AUTO PILOT
DAMPENING
SYSTEMS
TL. 113-56/10

SYMBOLS.

CG	a/c centre of gravity
H	high pass network 2S/(2S+1).
HM	Hinge moment limits
L'_p	Rolling accel'n due to roll rate, 1 per sec.
$L'_{\delta a}$	Rolling accel'n due to ail defl'n, 1 per sec².
M	Mach number.
N	Ratio of time const's of lead network
P_T	Total press., pounds per foot².
P_F	$= \partial p/\partial F_S$, roll rate command per unit stick force, degrees per sec per lb.
P_ϕ	$= \partial p/\partial \phi$, roll rate command per unit roll angle error, 1 degree per sec per degree
R	Radius of turn of a/c, feet.
S	Reference wing area, ft².
T	time constant, seconds.
U_1	True air speed, feet per second.
W	a/c wt., pounds.
T_{OL}	Open-loop transfer fcn.
a	Speed of sound

a'_y Lateral accel'n of a pt 13 ft forward of a/c CG, g's.

g Acceleration from gravity, feet per sec^2.

h Altitude, feet.

l_A a/c horizontal flt path accel, g's.

N Load factor, g's.

P Roll rate, degrees/sec.

P_ϕ $= \partial P/\partial \phi$, commanded roll rate per attitude error, radians/sec/radian.

$\bar{q}$ Pitch rate, degrees/sec.

q Incompressible dynamic pressure, psf.

q'_c Pitot differential press $= \frac{1}{2}\rho U_1^2$, psf.

r Yaw rate, degrees/sec.

s Laplace operator, $= \sigma + j\omega$, rads/sec.

t Time, secs.

t_{95} Time to reach 95% of a given command, secs.

y. Lateral displacement of the a/c from a ref line, ft.

α_0 Trim angle of attack, measured from free stream to fuselage datum plane, degrees.

β Sideslip angle, degrees.

δa Single aileron deflection, positive to give left roll, radians.

$\delta a_p = \partial \delta_a / \partial P_\varepsilon$, aileron command per unit roll rate error, secs.

δe Elevator deflection, +ve down, degrees.

δ_r Rudder deflection, +ve left, rads.

$\delta_{ra} = \partial \delta_r / \partial a'_{y_\varepsilon}$, rudder command per unit lateral accel'n error, rads/g.

$\delta r_{\delta a} = \partial \delta_r / \partial \delta a$, rudder command/unit ail deflection

$\delta r_r = \partial \delta_r / \partial r_\varepsilon$, rudder command/unit yaw rate error, secs.

ζ Damping ratio

θ Phase angle of transfer fcn, degrees.

$\bar{\theta}$ Pitch angle, degrees.

σ Real part of $S = \zeta \omega_n$, rads per sec.

ϕ Roll angle, degrees.

ϕ_ψ $\partial \phi / \partial \psi_\varepsilon$, roll angle command per unit heading error.

$\delta a_F = \partial \delta_a / \partial F$, commanded aileron/pound of force, radians per pound.

ψ Heading angle, degrees.

ψ_y = $\partial\psi/\partial y_\varepsilon$, heading angle command per unit lateral displacement error, degrees per foot.

ω = Imaginary part of s, radians/sec.

ω_n Natural frequency, rads/sec.

ω_B Breakpoint in frequency response asymptotes, radians per sec.

SUBSCRIPTS

$(\ )_c$ Command
$(\ )_{\delta a}$ Aileron loops closed
$(\ )_{\delta r}$ Rudder loops closed
$(\ )_\varepsilon$ Error
$(\ )_G$ Gust
$(\ )_g$ Gyro
$(\ )_L$ Limits.

FFS JONES

÷ DRAFT ÷

SUMMARY.

MH AERO REPORT 51252 - TR6

ARROW LATERAL AUTOPILOT ANALYSIS

17 MARCH 1958.

I.

INTRODUCTION

Definition: Automatic Flight Cont Syst:
a) Outer-loop or command systems
b) Couplers or tie-ins.
c) Damper System.

II Specs.

Performance: AFCS, in conjunction with other subsysts shall perform:
a) automatic attack
b) automatic navigation
c) automatic approach for landing
d) Pilot assist functions:
- Heading hold
- Bank hold
- Altitude hold
- Mach control by a/c control stick.

III. REQUIREMENTS & DESIGN OBJECTIVES.

BANK HOLD:
- stabilizes a/c to any bank $\angle \phi \leq \pm 60°$, irrespective of disturbances.
- A/P hold attitude existing 0.5 secs after lateral stick force is relieved.
- If $\phi \measuredangle > 60°$, system remains locked on C.S.S.
- Basic inner loop for all other autopilot modes.
- Design objectives are:
a) well-damped response to small step ϕ input ($\zeta = 0.9 \pm 0.2$)

b) 2-3 secs to be within 95% of final attitude
c) Overshoots less than 10%.
d) Simple gain scheduling.

Control parameter is:
GAIN: P_ϕ.

HEADING HOLD:

- stabilized on heading chosen by pilot, irrespective of disturbances.
- heading held within 0.5 sec's after pilot relieves lateral stick force, provided wings are within ±7.5° of level;
- Design objectives are:
  a) well damped response to small step heading $\angle\psi$ inputs ($\zeta = 0.9 \pm 0.2$)
  b) 10-14 secs to be within 95% of final position.
  c) overshoots < 10%.
  d) simple gain scheduling.

Control parameter is:
Gain, ϕ_ψ

NAVIGATION MODES:

Data Link:

- Modes are known as:
  i) AGCI CLOSE CONTROL.
  ii) RETURN-TO-BASE.
- a/c recieves specific info from ground station, which is introduced into the A/P thru a coupler.
- Info in form of discrete heading commands. (analysis → not consider any component dynamics outside of A/P/a/c syst.)
- @ termination of close control, a/c req'd to xecute large change in heading, ≈ 90° or >. Should complete maneuver as quickly as possible.

Design Objectives are:

a) well-damped response to large or small step heading commands. ($\xi = 0.9 \pm 0.2$)

b) large commands to be complete within ± 2° of desired heading in the min time consistent with opt. stab & a/c safety.

c) overshoot of hdg commands < 10% or 2°, whichever is smaller.

d) Simple gain scheduling.

Control Parameters are:

a) GAIN, Φ_ψ

Bank Limits, Φ_L.

Automatic Ground Controlled Intercept (AGCI) Broadcast.

- Command signals to a/c - A/P received from information processed in the dead reckoning computer. It, in turn, has derived this info from: a data link, airborne radar, & sensors contained in a/c.
- Commands in form of continuous corrections to a/c course. Dynamics? (not available)
- Design objectives - same as data link.
- outputs same as for data link.

Automatic Dead Reckoning:

- a/c solely under control of dead reckoning computer.
- problem dynamically identical to that of the broadcast mode.
- Design objectives same as data link.
- outputs same as data link.

AUTOMATIC GROUND CONTROLLED APPROACH (AGCA).

- a/c directed to align with the runway ℄ from a position on the downwind side of airfield.

- signals to A/P - continuous heading commands from ground station & are proportional to lateral displacement of the a/c normal to the runway ℄, this error being computed on the ground.
- system engaged by pilot upon receipt of a signal to do so from the ground.

Design objectives:

a) a/c travel along runway ℄ (extended) @ the breakoff from AGCA for any expected steady cross wind.

b) Bank limits 10° ~~max~~ during glide-slope phase, but larger values permissible ($\leq 30°$) for earlier phases.

c) Well damped response to small ~~so~~ lateral displacement step ($\zeta = 0.9 \pm 0.2$) & to gusts, both side & rolling. Well damped bracketing response ($\zeta = 0.9 \pm 0.2$); bracketing capability up to 40° heading from runway.

Control parameters:

Gain; ϕ_ψ
Gain, ψ_y
Integration time constant, T
Time constants of lead network (if req'd)
Bank limits, ϕ_L.

FIRE CONTROL:

- a/c maneuvered from predetermined area relative to target to a position where it can release its weapon. It will do so then break away, ~~automatically~~
- commands to A/P ∝ to ∠ar steering errors obtained from airborne computer. These are summed against the sine of the bank angle. A/P analysis is concerned only with response to a discrete step command. Thus, response req'ts for

fire control same as those for attitude hold mode. In addition, a/c A/P req'd whose response, ψ/ϕ_c, shows no peaks greater than 2 db below a frequency of 2.0 rads/sec & none greater than 4 db @ higher frequencies (up to 10 rad/sec.).
Control parameter is:
Gain, P_ϕ.

IV. ANALYSIS

AUGMENTED AIRPLANE CHARACTERISTICS:

- augmented a/c on NORMAL DAMPER.
- a/c basic characteristics altered by feedbacks to servos which operate rudder & aileron:
  feedback eq's are,

$$\delta_r = \delta_{r_a} a'_y + \delta_{r_r} \frac{2S}{2S+1} r_G + \delta_{r_{\delta a}} \frac{2S}{2S+1} \delta_a$$

$$\delta_a = \delta_{a_p}\left(1+\frac{1}{S}\right)\left(P - A_c P_c\right)$$

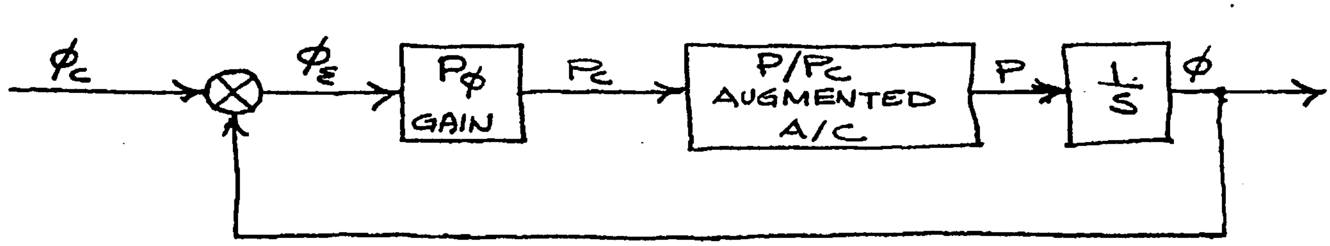
where $A_c = f(q'_c, a'_y)$

all freq'y responses P/Pc from Damper analysis.

BANK HOLD:

Analysis:

Basic block dia is:



Open-loop transfer function is:

$$T_{OL} = \frac{P_\phi}{S}\left(\frac{P}{P_c}\right)$$

The gain, P_ϕ, can be adjusted to give desired damping ratio or desired response time, but not necessarily both.

ω_B = break frequency → intersection of the asymptotes of the frequency response.

Result → $P_\phi \neq q_c'$ & altitude.

∴ these gains can be approximated by a constant @ average value of 1.0.

plots of resulting freq'y responses of closed loops (ϕ/ϕ_c) - computed from P_ϕ of 0.8.

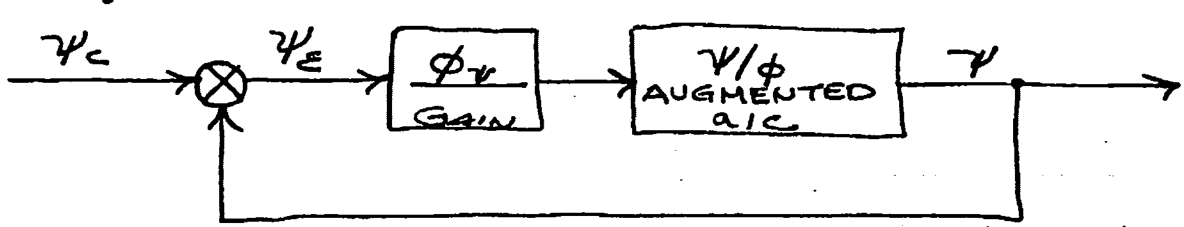
plot of transient response.

Conclusions

A constant value of the P_ϕ gain equal to 1.0 gives satisfactory bank hold performance throughout the flight regime.

HEADING HOLD:

Analysis: Block dia is:



-augmented a/c characteristics obtained from freq. responses of (ψ/ϕ_c) - plot. The gain, ϕ_ψ, can be adjusted to give desired damping ratio or the desired response, but not necessarily both. Frequency responses of (ψ/ϕ_c) presented in tabular form. - of Ruper.

- Inspection of freq. response (ψ/ϕ_c) shows that it can be approximated by an integration within 3db up to 0.7 rad/sec. Phase margin @ this frequency is 26°.

- Design obj. is to reach 95% command in 12 secs.
- Corresponds to a 4-sec time const. or an $\omega = 0.25$ rad/sec (where phase margin is 70°)

Thus, it seems likely that the approx to (ψ/ϕ_c) is justifiable for this analysis, so that gain, ϕ_ψ, can be computed & the exact frequency response used for checking purposes. The classical approximation is:

$$\frac{\psi}{\phi_c} \cong \frac{g}{U_1}\,\frac{1}{s}\,\frac{\phi}{\phi_c} \cong \frac{g}{U_1}\,\frac{1}{s}$$

$$\therefore \quad \frac{\psi}{\psi_c} = \frac{1}{\dfrac{s}{\phi_\psi (g/U_1)} + 1}$$

$$\text{\& so} \quad \phi_\psi = \frac{-0.25}{(g/U_1)}$$

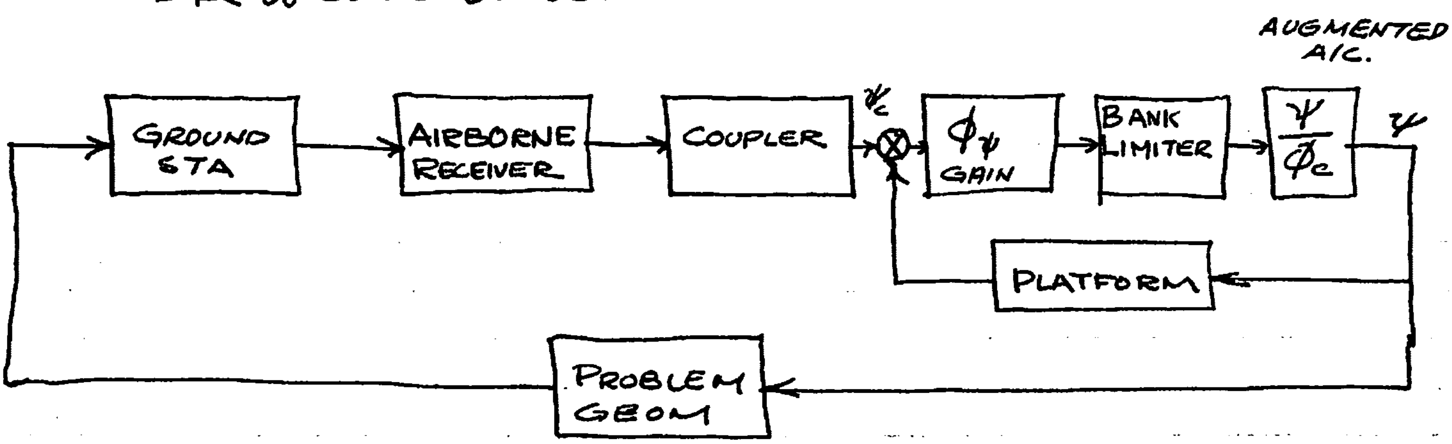
this gain plotted vs TAS. (Based on the availability of TAS as a scheduling parameter.)

Decision to use transient response as the criterion for acceptable gains was deliberate. However, in a sizable number of past AP's, this gain was limited by a roll coupling phenomenon in the gyro, which leads to an instability. The "roll-yaw" gimbal errors are eliminated in the gyro planned for Arrow by redundant gimbaling. A negligible error remains, a pitch-yaw coupling. The eq'n for this coupling is:

$$\psi_{indicated} = \tan^{-1}(\tan \psi_{true} \cos \Theta).$$

Conclusions:
The ϕ_ψ gain is scheduled with TAS to give about a 4-second time const. to the heading hold mode. The ϕ_ψ gains are ∴ higher than their counterparts in previous systems. The possibility always exists for limit cycle oscillations arising out of the small discontinuities present in the control system. The likelihood of oscillations is enhanced by high gains, but pessimism on this count is not warranted at present.

NAVIGATION MODES:
Data Link.
The block dia:



∵ commands to a/c are discrete steps, analysis of heading hold mode is directly applicable for small heading steps. Remaining problem is the determination of acceptable bank limits. Two considerations must be weighed:

1. safety of a/c (or pilot's concept of it)
2. completion of large heading changes in a time span acceptable to the attack mission.

The time to be within ε degrees of a large heading command is a fcn of:

U_1	true air speed
ϕ_L	bank limits
ϕ_ψ	bank-to-heading ratio
ψ_c	heading command size
ψ_E	heading change while on bank limits.

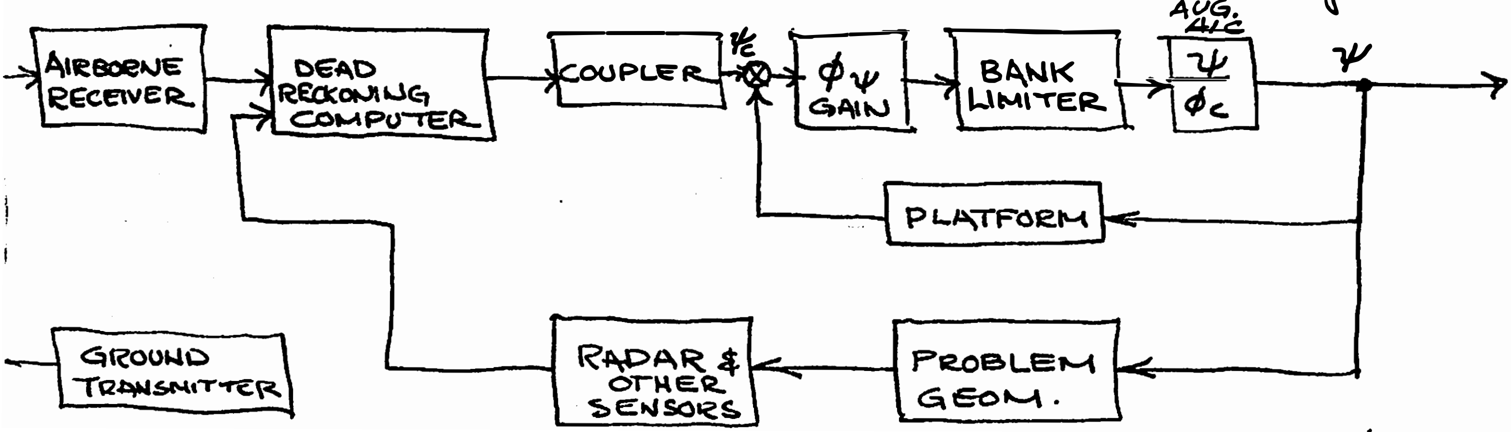
The xpression for this time is:

$$t(\text{sec}) = \underbrace{2.5}_{\text{time to roll up to bank limits}} + \underbrace{\frac{t_1}{\psi_E}\left(\psi_c^\circ - \frac{\phi_L^\circ}{-\phi_\psi}\right)}_{\text{time flown on bank limits}} + \underbrace{(t_2)\ln\left(\frac{1}{\varepsilon^\circ} - \frac{\phi_L^\circ}{-\phi_\psi}\right)}_{\text{time req'd after leaving bank }\angle\text{ limit to reduce heading error to }\psi^\circ}$$

Plots of t_1/ψ_2 & t_2.

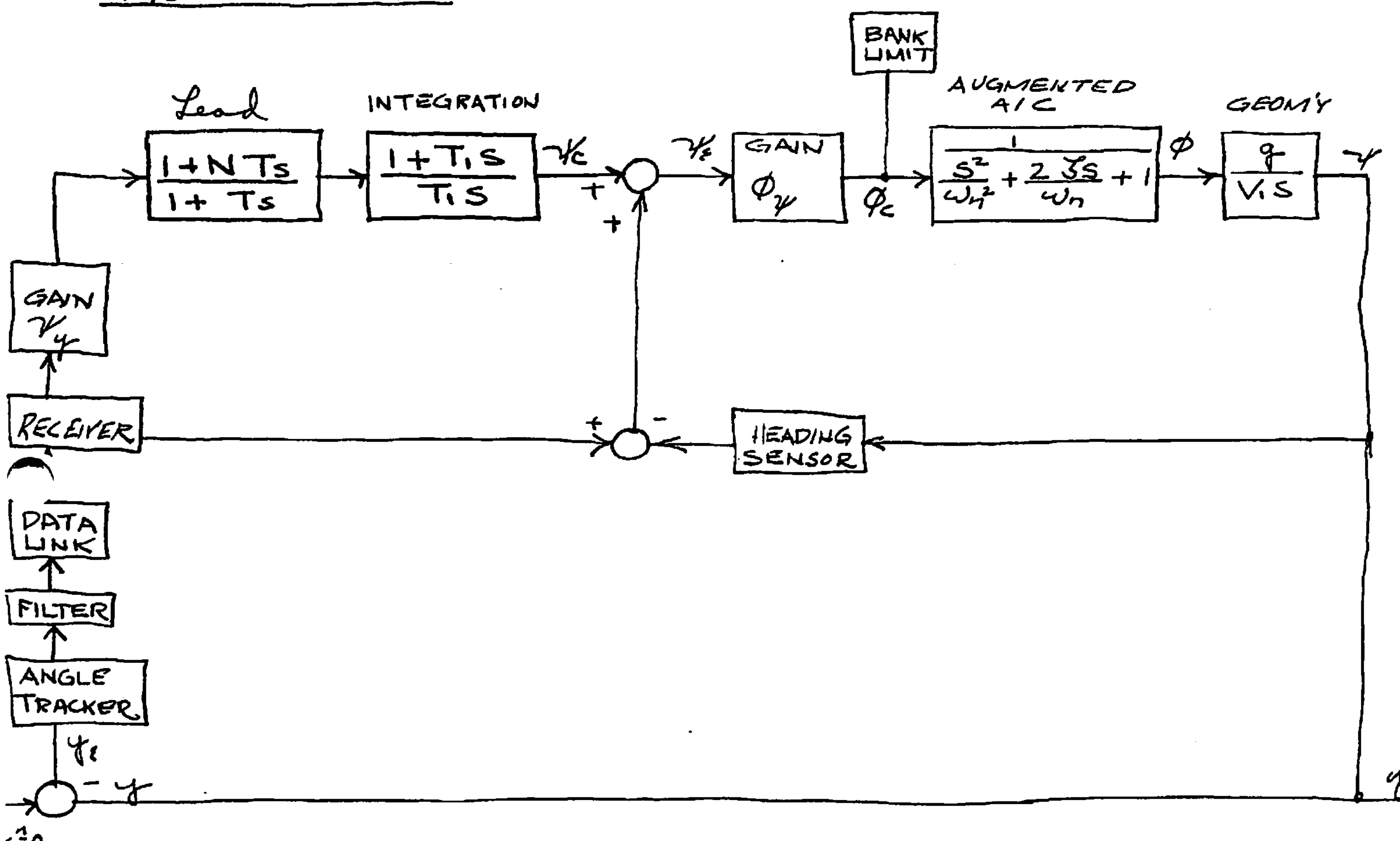
* Bank limit of ±60° is acceptable.

AGCI Broadcast & Automatic Dead Reckoning Modes.



· Block dia for dead reck. mode is same as for broadcast mode, except that no ground-transmitted signals are employed.
Insufficient info.

AGCA ANALYSIS:



LATERAL AGCA.

Ψ_y, N, T, & T_1 to be specified.

Previous investigations have shown that the system which has a feedback loop from the heading of the a/c to the turn control or bank circuits of the a/c is the most free of off-course errors due to rolling moments & false erection of the vertical gyro. However, in order to obtain a zero position error in the presence of a cross wind, an integration must be added to the system. If the integration rate is to be fairly high, a lead network must be used to obtain sufficient phase margin to achieve a reasonable system damping ratio and resonant frequency.

The roll ∠ response of the augmented a/c to a roll command was approximated by a 2nd order syst. The resonant f & damping were obtained by analyzing several analog computer traces, ~~and ref fig~~; obtained when complete a/c & a/p were simulated on the computer. Plot of transfer fcn ψ/ϕ_c. Bank to heading ratio ϕ_ψ chosen from plot. Value −4 chosen for ϕ_ψ yields a damping ratio of 0.8 & resonant freq'y of 0.4 rad/sec. Closed loop response for ψ/ψ_c was then obtained. Freq'y response of the ground-based eq't (ref. 3) in fig. Freq'y response of y/ψ_c + characteristics of ground based eq't plotted.

@ this point, integration rate $1/T_1$ was chosen. Normally the amplitude characteristic is used to select the int'n rate. However, this syst has the nonlinear ground-based eq't as part of the loop. It was ∴ better to use the phase curve as a guide in selecting the int'n rate. When choosing int'n rate, it should be borne in mind that a lead network will be chosen later. Trials, a value of $1/T_1 = 0.2$ selected. Fig shows y/y_c with & without the lead network. The N & T for the lead network were chosen to yield a gain range of 10 db for an M_p of 3 db. The outer-loop gain ψ_y was chosen from Fig. 9 & is equal to 1° of heading called for per 222 ft of lateral error. (On simulation, it was found desireable to set the bank to heading ratio from −4 to −3.5).

Beam Following:

Lead network with an N of 10 & time const of 3.18 sec's & the int'n with a time const. of 5 were simulated in the analog comp setup. A series of beam following runs was made by heading the a/c in direction of runway & displacing it laterally from runway.

The gain Φ_{ψ} & Ψ_y were adjusted to give satisfactory performances. $\Phi_y = -3.5$ & $\Psi_y = -0.004$. Raising the Ψ_y gain to -0.01 drove the system unstable @ approx 0.5 rads.

Bracketing:

Whereas beam following is concerned with the system behavior after small disturbances, bracketing is a trajectory problem - the study of the path taken by the A/C velocity vector from some position near the airfield to the point @ which it is tangent to the runway ℄ extended. - It was found that gains selected were satisfactory for bracketing; the only stipulation is that the integration not be started until ≅ 30 sec's after engagement. The max acceptable heading error at engagement is a fcn of the A/C T.A.S. & bank ∠ limits for a specified overshoot of the runway.

Assuming that the system is engaged @ about 1500' lateral displacement error, the following table lists the max permissible heading errors for near deadbeat alignment with the runway.

Heading Error @ Engagement

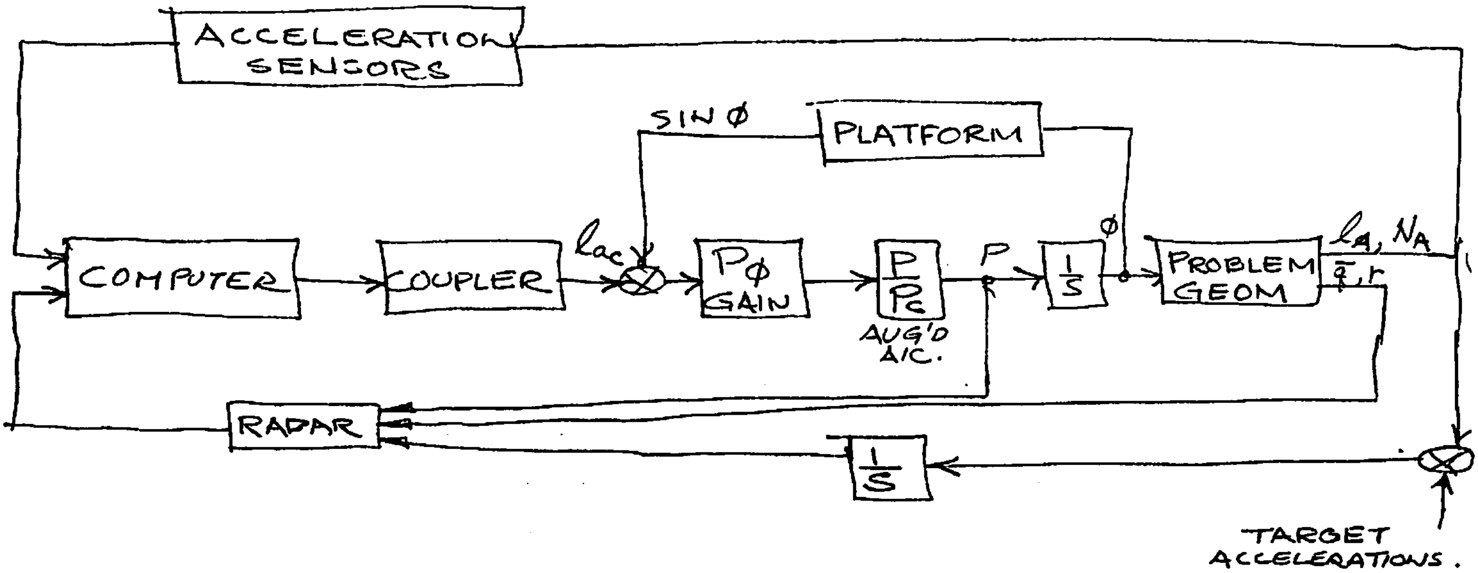
	$U_1 = 220$ fps	$U_1 = 330$ fps	$U_1 = 440$ fps.
30° Bank Limit	65°	40°	30°
40° Bank Limit	80°	50°	35°

@ this time, max hdg error ∠ expected is less than 30°, & no need exists for a bank limit > 30°.

Conclusions:

System designed to give satisfactory perf for both beam following & bracketing. However, selection of parameters is @ best a compromise & a different set of parameters would also yield a satisfactory system. In the present system, the H of the lead network may be reduced to any value desired or it may be set equal to one! In order to do this, the heading loop must be closed & the integration rate must be quite low. O.K on sim.

INNER LOOP ANALYSIS for FIRE CONTROL:



The behavior of the sin φ feedback is the subject of study. Cuz of the nonlinear nature of the problem, the primary effort was expended on an analog computer analysis.

Arrow AFCS has a req'd inner-loop feedback of the sine of the bank ∠ on this mode. In the interest of mechanical simplicity, it might be desireable to incorporate this mech'l signal as the basic inner loop for all A/P modes.

A short analog computer study was carried out to verify the belief that no unacceptable behavior stems from this nonlinear system. Possible prob's are:

a) system instability
b) difficulty in precise bank limiting.

Configuration Studied:

A/p signals are all directed thru the basic control stick steering system. A reasonably accurate representation of that system is necessary to the study if stability margins are to be looked into. Accordingly, aileron rate limits, damper position limits, and servo-actuator lags are included. The a/c is represented by a single-degree-of-freedom lag.

Transfer Fcn Req't.

The req't on the transfer function for the a/c-a/p was investigated. The "exact" frequency responses of ψ/ϕ_c & r/P_c were computed for all flight conditions & are listed. Formers is appropriate to automatic fire control, the latter to manual tracking.

The frequency response of ψ/ϕ_c for a representative flight condition was shown. also r/P_c.

Conc's

Studies verified that no unacceptable behaviour results from the use of the sin ϕ feedback.

ELECTRONICS

REF. "INTRODUCTION to INDUSTRIAL ELECTRONICS."
R. R. BENEDICT.

CH. 1. HIGH-VACUUM THERMIONIC DIODE & TRIODE

1.1 ——

1.2 INDUSTRIAL ELECTRONIC TUBES

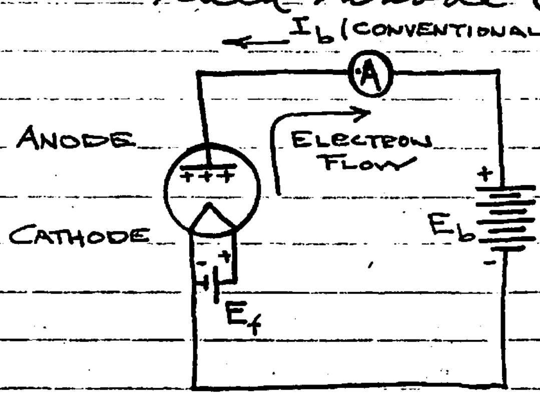
- high-vacuum tubes
- gas-filled tubes
  - inert gas, press = 1/10,000 – 1/100 ats.

- cold cathodes
- hot (or thermionic) cathodes
- pooltype cathodes

- diode
- triode
- tetrode
- pentode

1.3 DIODE:

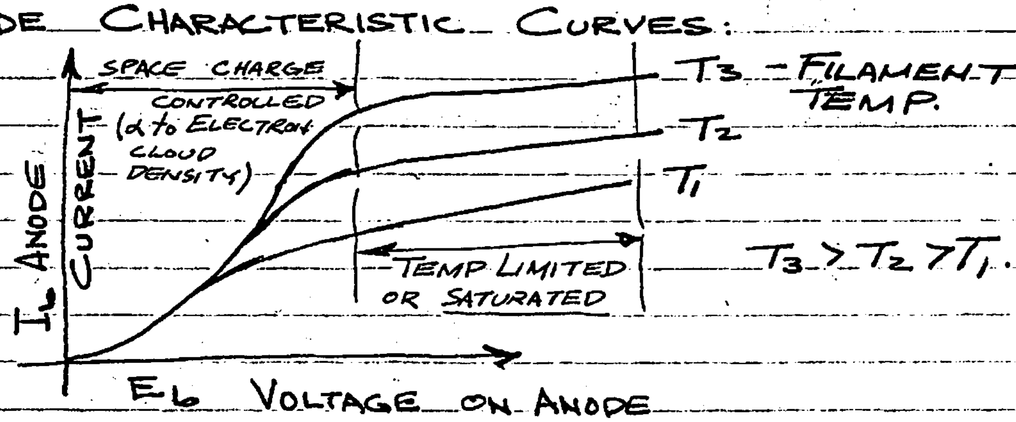
- hot cathode
- cold anode (or plate).



Tube acts as:
a.) insulator in direction
b.) conductor in the other.
- permits rectification of A.C.
(i.e., conversion of A.C. to D.C.)

- Chief use of diode is in RECTIFIER circuits.

1.4 DIODE CHARACTERISTIC CURVES:

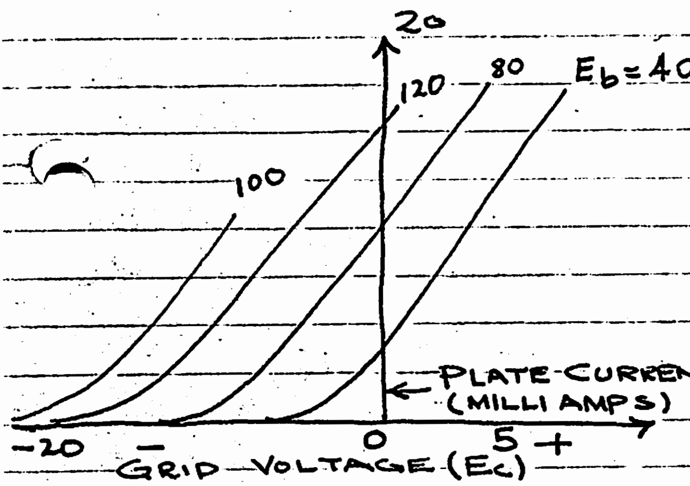


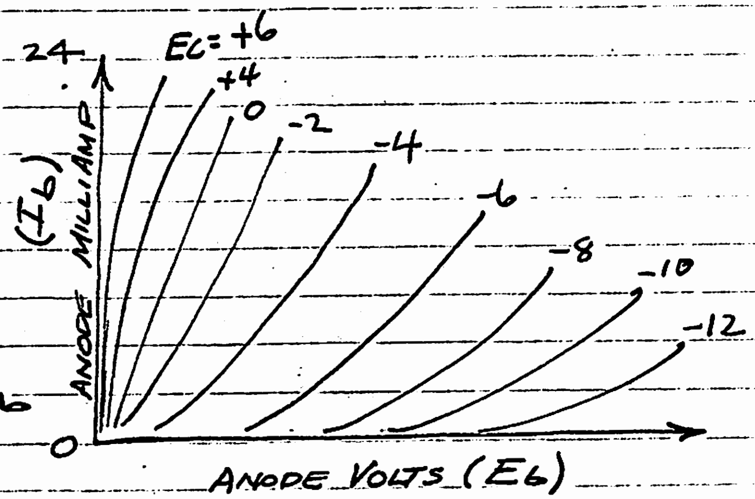
$T_3 > T_2 > T_1$.

DIODE ANODE CHARACTERISTIC CURVE

- With constant grid voltage, vary anode voltage → anode or plate characteristic curves
  (anode voltage & anode current, grid V parameter)
  * characteristic curves most important (these are published by manufacturer)

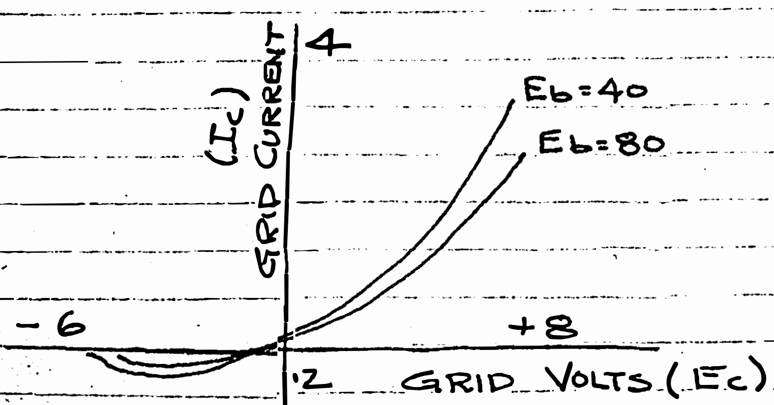
- Grid to cathode voltage E_c → algebraic quantity
  - called DIRECT GRID-BIAS VOLTAGE or GRID BIAS.
  - certain grid bias for particular anode voltage called CUT-OFF BIAS → reduces plate current to zero.





TRANSFER CHARACTERISTIC

ANODE CHARACTERISTICS.



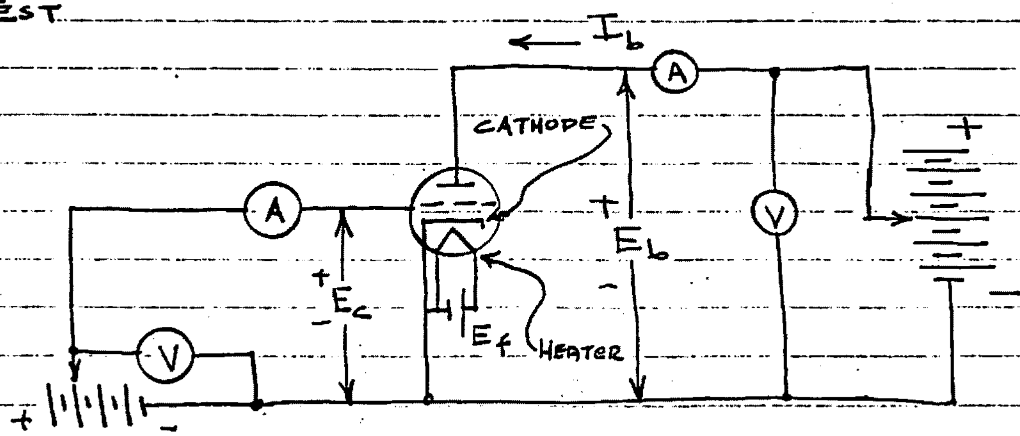
1.5. THE THERMIONIC TRIODE:

- hot cathode
- anode
- control grid.
  - +ve, accelerates electrons.
  - −ve, decelerates electrons:
    - only small prop'n of electrons collected by grid:
  - ie, controls anode current

(ex., the changing anode current, in turn, can perform a useful function such as to close the contacts of a relay.)

1.6. TRIODE CHARACTERISTIC CURVES:

EXP'L TEST CIRCUIT.



- For a constant cathode temperature, there are two factors that determine the anode current → anode voltage & grid voltage.
- For a fixed anode voltage, vary grid voltage E_c → changes plate current.
  Plot → TRANSFER CHARACTERISTIC for triode
  (E_c, abscissa; I_b, ordinates)
- When voltage drop from grid to cathode is +ve, there is a sizable grid current.
  when grid voltage −ve, grid current is a small fraction of a milliampere
  ∴ −ve grid, the grid absorbs practically no power from grid battery E_c, yet controls large power in anode cct.
  (∴ grid usually operated with −ve voltage.)

CH. 2. SPACE CHARGE, THERMIONIC ELECTRON EMISSION, and PRACTICAL CATHODES.

2.1. SPACE CHARGE RELATIONS IN THE DIODE:

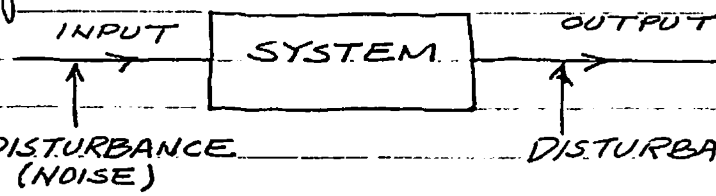
- Space charge limited – over ranges where the anode voltage can control current
- Temperature limited – over saturation range.
- Space charge limited – hot cathode → can emit more electrons than reach anode, but electrostatic repulsive action of electrons in transit control current.
- SPACE CHARGE LIMITED:
  - (+ve) charges on anode balanced by electronic space charge.
  - ∴ electric field strength = zero @ surface of cathode & electrostatic force on electrons = 0 @ this pt.
  - ∴ potential curve has horiz. slope @ cathode
- TEMP. LIMITED:
  - lines of force from anode end on charges on cathode
  - ∴ field of force urging electrons toward anode @ all pts in the gap.
  - ∴ pot. curve has +ve slope @ all pts.
  - increase anode voltage will not increase current appreciably; will increase electron vel & reduce number present in gap.

2.2. THE THREE HALFS POWER LAW:

SERVOMECHANISMS

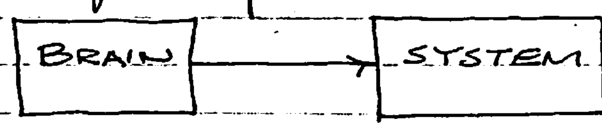
1. INTRODUCTION:

Purpose – to formulate the concept of a control mechanism.

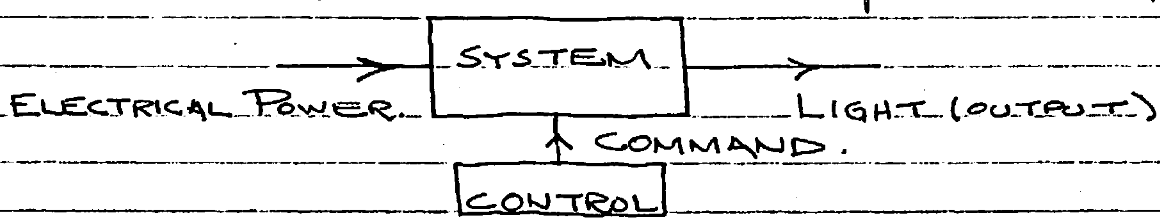


1.1 OPEN LOOP CONTROL SYSTEM:

Simple case controller:
ex. lighting controller – turns lighting system on and off at arbitrary time, regardless of lighting conditions.

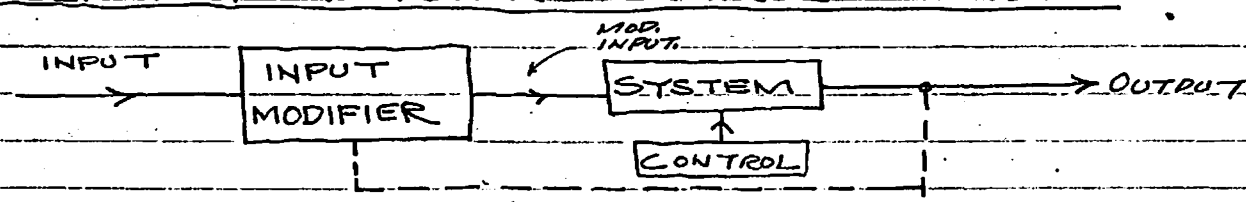


Open Loop Block Diagram for above system:

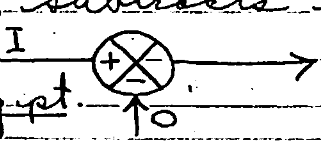


Disadvantage of open loop – extreme accuracy of components required.

1.2 CLOSED LOOP FEEDBACK CONTROL SYSTEM:



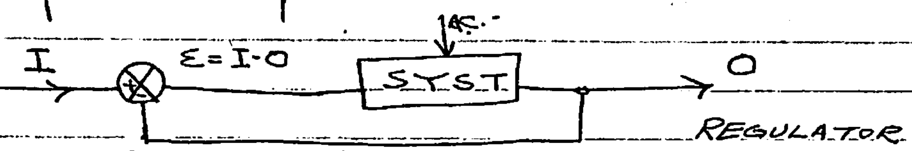
Requirement: output should vary directly with input – ∴ controller is eliminated.
Modifier: compares input & feedback fcns, i.e., subtracts output from input.



$I - O = \varepsilon$ where $I \triangleq$ input, $O \triangleq$ output, $\varepsilon \triangleq$ error.

summer or summing pt.

Modified Diagram:



i.e, the system is driven by the error signal (not input or output).

CASE 1:

Variables: - system performance
- power supply - subject to loading.
- system input is fixed.

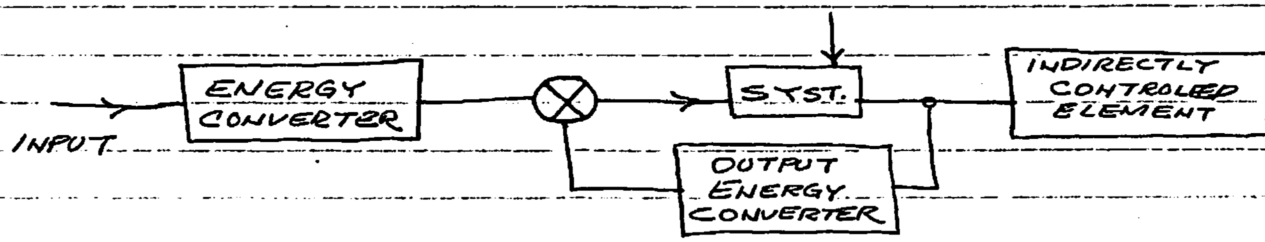
This is a REGULATOR system.

Dynamic range = O.

CASE 2:

Variables: - input
- ∴ variable
- this is a servomechanism.

CASE 3: Variables: - input + disturbance.

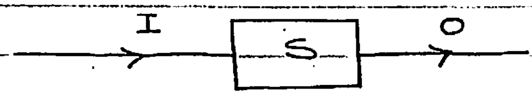


For other than electrical systems.

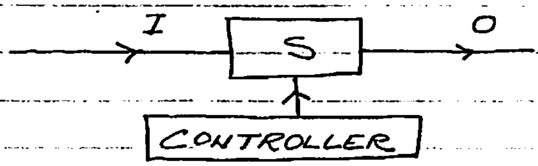
DEFINITION:

A servomechanism is a feedback control system in which the output is controlled to be equal to, or nearly equal to, Input, whereby the input is a variable quantity. So output disturbances are of secondary importance, it may be present and it will be corrected for by the servomechanism.

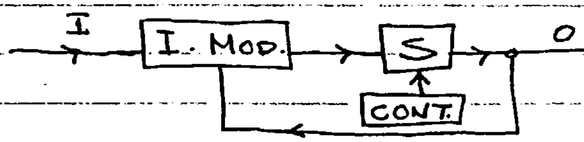
Resumé



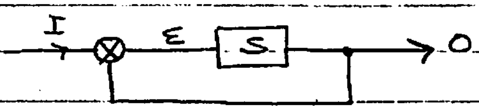
Open loop system.



Open loop control system
- not occurate enough.
- expensive.



Comparator
- control difficiencies in output.



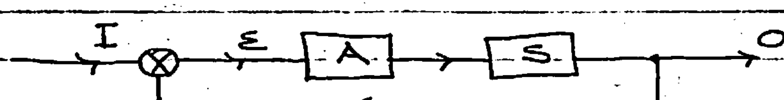
Control loop system:
a) Regulator
b) Servomechanism

This is a "POSITION CONTROL SYSTEM"

2. CONTROLLED ELEMENTS:
- speed; position; voltage, current, power, flux, flow, temperature.

3. MEASURING MEANS (Energy converter)
- temperature: bi-metallic strip, thermocouple.
- position of diff'l gear, governor, displ't press.

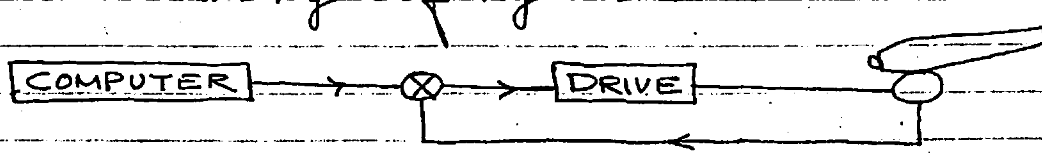
* ε should be as small as possible for sensitivity ∴ an amplifier is req'd.



types of amplifiers:
electronic, magnetic, hydraulic.

EXAMPLES:

1) Positioning of gun.



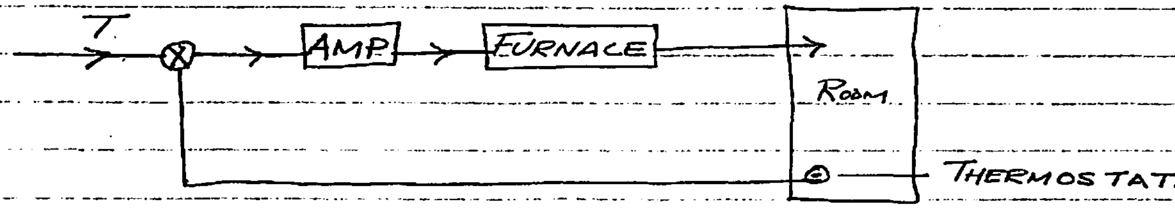
Typical position control system.

2.) Washing machine:

a) automatic washer – typical open loop.

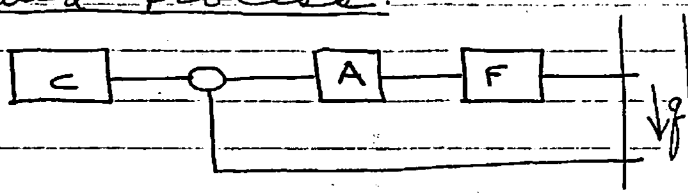
b) wash + women + labour → closed loop.

3.)



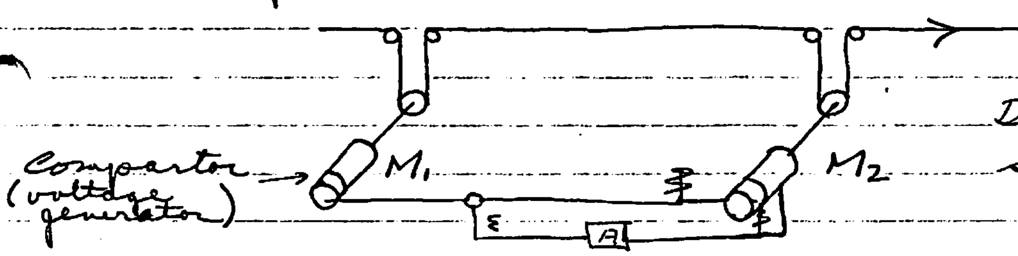
Typical regulator: "ON-OFF" system.

4) Liquid Process:



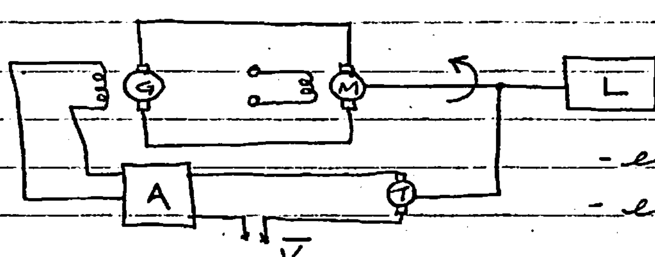
Servo Mech.

5) Paper Machine:



Drives M_2 @ same speed as M_1

6) Speed Controller (Regulator)

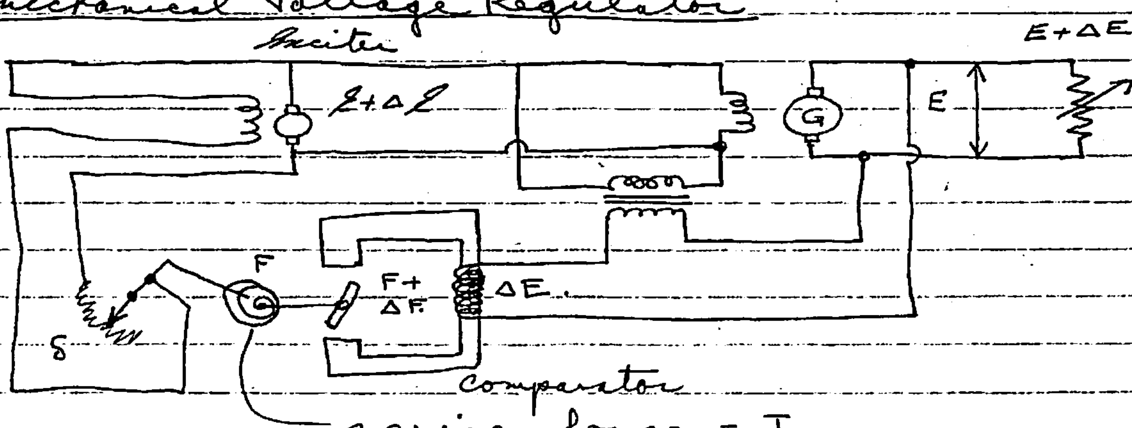


T = tachometer.

V̄ = ref. voltage.

- externally excited
- excitation field stays const.

7. Mechanical Voltage Regulator

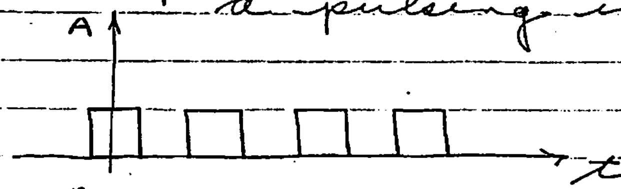


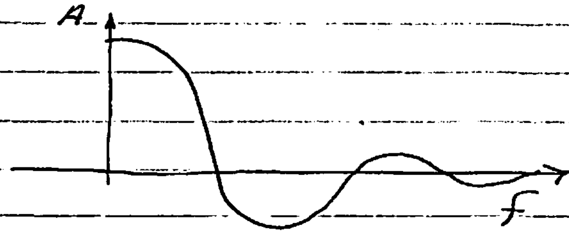
MATHEMATICAL FORMULATION:

Curve of system input may be represented by $A = f(t)$

Example of input waves:

a pulsing input





In actual systems there will be a delay of some form. System may delay some parts of the signal more than other points.

Dynamic characteristics of system:

NOMENCLATURE:

G - Transfer function is a function that describes those dynamic properties of a system that modify the input quantity in the process of transferring it to the output quantity.

$G = O/I$.

If assuming zero loading of sub-systems the effect of adding successive systems does not effect output of previous systems. Then $O = I G_1 G_2 \cdots$

R - Reference function (input).

C - Controlled function (output).

$E = R - C$ $\quad C = (R - C)G$

$$= GR - GC$$

$$C + GC = GR$$

$$C(1+G) = GR$$

$$C = \frac{GR}{1+G}$$

$$C = \frac{GR}{1+G}$$ = Fundamental equation of a feedback system.

This is a degenerative ~~system~~ equation of a closed loop system.

For an open loop system, $C = RG$

then $\frac{dC}{dG} = R$

$dC = R\,dG$

but $R = \frac{C}{G}$

then $dC = \frac{C}{G}\,dG$

$dC =$

$dC_{CLOSED} =$

$\boxed{G = A}$

Thus demonstrating advantage of feed-back.

Elements of Systems

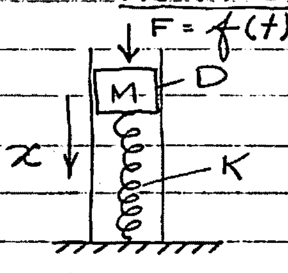
Mass, capacitance, resistance.

$E = IR$. R is considered constant within limits usually denoted by denoted by power factor or watts.

Assumptions:

Linear relationships - do not vary with time. Therefore we shall not consider tube outputs, etc.

In mechanical system:

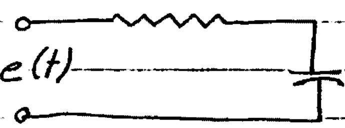


Associated forces due to F, D, K.

$$M\frac{d^2x}{dt^2} = \Sigma f = f(t) - f_K - f_D$$

$$M\frac{d^2x}{dt^2} + D\frac{dx}{dt} + Kx = f(t).$$

In electrical system:



$$e_R = iR$$

$$e_c = \frac{1}{C}\int i\,dt$$

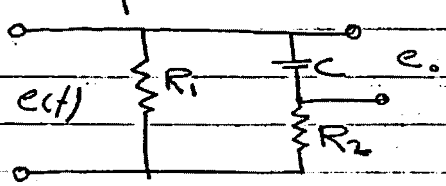
$$\therefore e(t) = iR + \frac{1}{C}\int i\,dt.$$

$$e(t) = iR + \frac{1}{C}\int i\,dt + L\frac{di}{dt}$$

Differentiating:

$$\frac{de}{dt}(t) = R\frac{di}{dt} + \frac{i}{C} + L\frac{d^2i}{dt^2}$$

This compares with the physical equation for mechanical system.

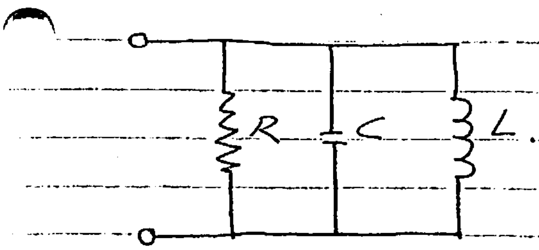


$$e(t) = e_c + i_2 R_2$$

$$e_o = \frac{1}{C}\int i_2\,dt$$

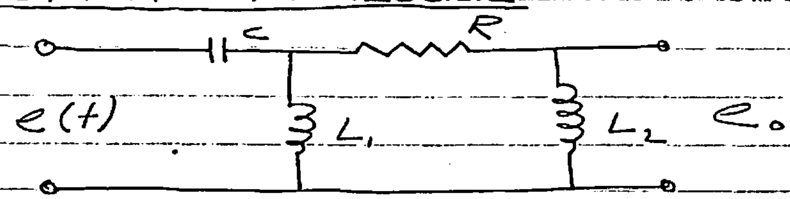
$$\therefore i_2 = \frac{de_c}{dt} \cdot C$$

Then $e(t) = e_c + RC\frac{de_c}{dt}$.



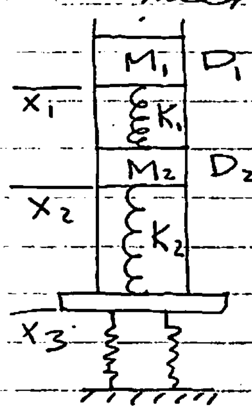
$$I = i_R + i_C + i_L$$
$$= \frac{e(t)}{R} + C\frac{de(t)}{dt} + \frac{1}{L}\int e(t)\,dt$$
$$\frac{di}{dt} = \frac{de(t)}{R\,dt} + C\frac{d^2e(t)}{dt^2} + \frac{e(t)}{L}$$

ELECTRICAL ANALOGUE:



$$\frac{de_1}{dt} = \frac{1}{C}i_1 + \frac{1}{L_2C}\int C_0\,dt + L_1\frac{d^2i_2}{dt^2} \qquad (1)$$
$$0 = \frac{R}{L_2}\int e_0\,dt + e_0 - L_1\frac{di_1}{dt}$$

Mechanical Analogue:



$$M_1\frac{d^2x_1}{dt^2} = -K_1(x_1-x_2) - D_1\frac{d(x_1-x_2)}{dt} \qquad (1)$$
$$M_2\frac{d^2x}{dt^2} = +K_1(x_1-x_2) - D_2\frac{d(x_2-x_3)}{dt} - K_2(x_2-x_3) \qquad (2)$$

from ①:
$$M_1\frac{d^2x}{dt^2} + K_1(x_1-x_2) + D_1\frac{d(x_1-x_2)}{dt} = 0 \qquad (3)$$

from (2)
$$M_2\frac{d^2x}{dt^2} - K_1(x_1-x_2) + D_2\frac{d}{dt}(x_2-x_3) + K_2(x_2-x_3) = 0 \qquad (4)$$

from (3)
$$M_1\frac{d^2x}{dt^2} + K_1(x_1-x_2) + D_1\frac{dx_1}{dt} = D_1\frac{dx_3}{dt} \qquad (5)$$

from (4)
$$M_2\frac{d^2x}{dt^2} - K_1(x_1-x_2) + D_2\frac{dx_2}{dt} - D_2\frac{dx_3}{dt} + K_2x_2 - K_2x_3 = 0 \qquad (6)$$

Solution of linear 2nd order differential Eq.

$$a\frac{d^2y}{dx^2} + b\frac{dy}{dx} + cy = a f(x)$$

$$\frac{d^2y}{dx^2} + \frac{b}{a}\frac{dy}{dx} + \frac{c}{a}y = f(x)$$

let $\frac{b}{a} = B$ & $\frac{c}{a} = C$.

let $y = u$ when $f(x) = 0$.

Then $\frac{d^2u}{dx^2} + B\frac{du}{dx} + Cu = 0.$

If $y = v$, $\frac{d^2v}{dt^2} + B\frac{dv}{dx} + Cv = f(x)$ ← part. int.

If solution is composed of u & v, $y = u + v$.

Then, $\frac{dy}{dx} = \frac{du}{dx} + \frac{dv}{dx}$

and $\frac{d^2y}{dx^2} = \frac{d^2u}{dx^2} + \frac{d^2v}{dx^2}$

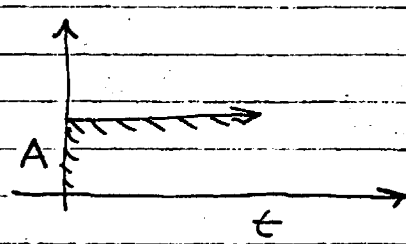
$$\left(\frac{d^2u}{dx^2} + \frac{d^2v}{dx^2}\right) + B\left(\frac{du}{dx} + \frac{dv}{dx}\right) + (u+v)C = f(x)$$

$$\frac{d^2u}{dx^2} + B\frac{du}{dx} + uC + \frac{d^2v}{dx^2} + B\frac{dv}{dx} + vC = f(x)$$

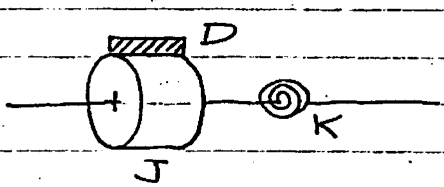
* $$\frac{d^2E}{dt^2} + 2\zeta\omega_n\frac{dE}{dt} + \omega_n^2 E = f(t) \qquad \text{(A)}$$

$E(0) = 0$

$\frac{dE}{dt}(0) = B.$



$t < 0$ $f(t) = 0$
$t = 0$ $f(t) = -$
$t > 0$ $f(t) = A.$



$$J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} + K\theta = T$$

$$\frac{d^2\theta}{dt^2} + \frac{D}{J}\frac{d\theta}{dt} + \frac{K}{J}\theta = \frac{T}{J}$$

In above equation Ⓐ, $\omega_n^2 = \frac{K}{J}$

$$2\zeta\omega_n = \frac{D}{J}$$

$$\zeta = \frac{D}{2J}\sqrt{\frac{J}{K}} = \frac{D}{2\sqrt{JK}}$$

For steady state (time independent)

$$\omega_n^2 E = A$$

$$E = \frac{A}{\omega_n^2}$$

if $t<0$ $f(t)=0$.
Then eq (A) $=0$.

$$E = e^{rt}$$

$$\frac{dE}{dt} = re^{rt}$$

$$r^2e^{rt} + 2\zeta\omega_n re^{rt} + \omega_n^2 e^{rt} = 0$$

$$r^2 + 2\zeta\omega_n r + \omega_n^2 = 0$$

$$r_{1,2} = -\zeta\omega_n \pm \omega_n\sqrt{\zeta^2-1}$$

$E = K_1e^{r_1t} + K_2e^{r_2t}$ $\Rightarrow$ sol'n to Ⓐ.

Possible solutions:

(1) $\zeta<1$, then $\sqrt{\zeta^2-1} = j\sqrt{1-\zeta^2}$
Conjugate complex roots.

(2) $\zeta>1$. Real roots.

(3) $\zeta=1$, $r_1=r_2=-\zeta\omega_n$.

③ $E = K_1e^{-\zeta\omega_nt} + K_2e^{-\zeta\omega_nt}$

$= \frac{A}{\omega_n^2} + (K_1+K_2)^{-\zeta\omega_nt}$

This represents a critically damped system.

② $r_1 = -\zeta\omega_n + A$, $r_2 = -\zeta\omega_n - A$.

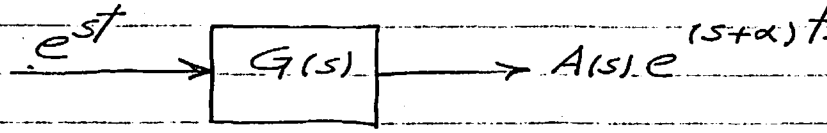
① $r_1 = -\zeta\omega_n + j\omega_n\sqrt{1-\zeta^2}$

$r_2 = -\zeta\omega_n - j\omega_n\sqrt{1-\zeta^2}$

Solution: $E = \frac{A}{\omega_n^2} + K_1e^{r_1t} + K_2e^{r_2t}$

"Root Locus" method of representation:

THE LAPLACE TRANSFORMATION CONCEPT:

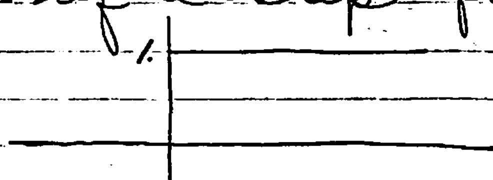


$$\int_0^\infty f(t)e^{-st}\,dt = \mathcal{L}\left[f(t)\right] \quad \text{where } s = a + jb.$$

This is the basic definition of the <u>LAPLACE TRANSFORM</u>.

$\int_0^\infty f(t)e^{-st} \to 0$ criterion for Laplace. i.e., a decaying function.

Laplace of a step function:



$t<0 \quad f(t)=0$
$t=0 \quad f(t)=0+$
$t>0 \quad f(t)=1.$

$$\int_0^\infty 1\times e^{-st}\,dt = -\frac{1}{s}e^{-st}\Big]_0^\infty = \frac{1}{s}.$$

<u>Typical Laplace transforms:</u>

$$\mathcal{L}\left[e^{-at}\right] \to \frac{1}{s+a}$$

$$\mathcal{L}\left[\sin\beta t\right] \to \frac{\beta}{s^2+\beta^2}$$

$$\mathcal{L}\left[e^{-at}\sin\beta t\right] \to \frac{\beta}{(s+a)^2+\beta^2}$$

$$\mathcal{L}\left[t\right] \to \frac{1}{s^2}$$

<u>Laplace transforms of Derivatives:</u>

$$\mathcal{L}\left[\frac{d f(t)}{dt}\right] \to sF(s) - f(0^+)$$

often $f(0^+)$ can be neglected for a true engineering case.

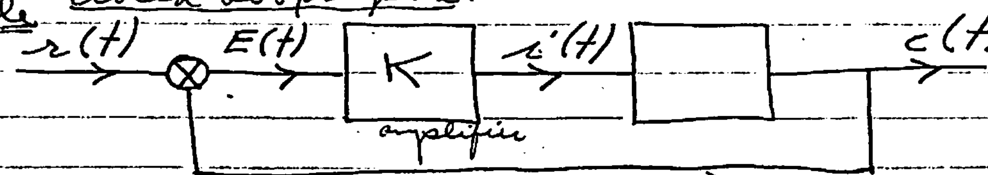
$$\mathcal{L}\left[\frac{d^2 f(t)}{dt^2}\right] \rightarrow s^2 F(s) - s f(0+) - \left.\frac{d f(t)}{dt}\right|_{t=0+}$$

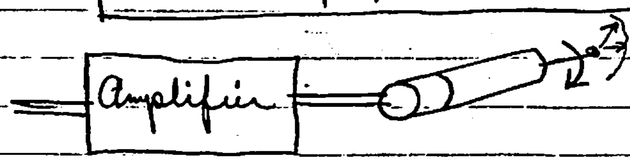
<u>Laplace Transform of Integral</u>

$$\mathcal{L}\left[\int f(t)\,dt\right] \rightarrow \frac{1}{s} F(s) - \frac{f^{-1}(0+)}{s}$$

where $f^{-1} \triangleq \int f(t)\,dt$ evaluated @ $t=0$.

<u>Example</u> <u>Closed Loop System</u>





$J \triangleq$ inertia of rotor of motor.
$D \triangleq$ friction.
$\theta \triangleq$ displacement.

$$J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} = K\{r(t) - \theta(t)\}$$

$$J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} + K\theta(t) = Kr(t).$$

Now, $\mathcal{L}[Kr(t)] \rightarrow KR(s)$

$$\mathcal{L}[K\theta(t)] \rightarrow K\theta(s)$$

$$\mathcal{L}\left[D\frac{d\theta}{dt}\right] \rightarrow Ds\theta(s) - \cancel{D\theta(0+)}^{\,0}$$

$$\mathcal{L}\left[J\frac{d^2\theta}{dt^2}\right] \rightarrow Js^2\theta(s) - \cancel{sJ\theta(0+)}^{\,0} - \cancel{J\frac{d\theta(t)}{dt}}^{\,0}$$

Assumption $\theta(0) = 0$, $\left.\frac{d\theta}{dt}\right|_{t=0} = 0$.

$\therefore\ Js^2\theta(s) + Ds\theta(s) + K\theta(s) = KR(s)$

This is the <u>FOURIER TRANSFORM.</u>

R(s) is known. $\Theta(s)$ unknown $\Rightarrow$ output fcn.

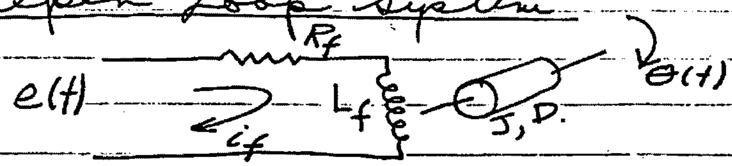
$$\Theta(s) \frac{[Js^2 + Ds + K]}{K} = R(s)$$

Since $R(s)\, G(s) = \Theta(s)$

Then $G(s) = \dfrac{K}{Js^2+Ds+K}$.

= transfer function of the closed loop.

Open Loop System



$\theta(t) \to G$ & $e(t)$

$$e(t) = R_f i_f + L_f \frac{di_f}{dt}$$

$$\phi(t) = K_f i_f$$

Torque $T(t) = K_2\, \phi(t)$

$$J\frac{d^2\theta}{dt^2} + D\frac{d\theta}{dt} = T(t)$$

$$E(s) = I_f(s) R_f + L_f s\, I_f(s)$$

$$\phi(s) = K_f I_f(s)$$

$$T(s) = K_2\, \Phi(s)$$

$$T(s) = Js^2\theta(s) + Ds\theta(s)$$

$$\frac{\phi(s)}{E(s)} = \frac{K_f I_f(s)}{I_f(s)(R_f + L_f s)} = \frac{K_f}{R_f + L_f s}$$

$$\frac{\theta(s)}{\phi(s)} = \frac{\frac{T(s)}{Js^2+Ds}}{T(s)/K_2} = \frac{K_2}{Js^2+Ds}$$

$$\frac{\phi(s)}{E(s)} \times \frac{\theta(s)}{\phi(s)} = \frac{\theta(s)}{E(s)}$$

$$\therefore \frac{\theta(s)}{E(s)} = \frac{K_f}{R_f + L_f s} \cdot \frac{K_2}{Js^2 + Ds} = G(s)$$

$$= \frac{\frac{K_f}{R_f} \times \frac{K_2}{D}}{\left(1 + \frac{L_f}{R_f}s\right)\left(1 + \frac{J}{D}s\right)s}$$

Let $\frac{L_f}{R_f} = \tau_f$ & $\frac{J}{D} = \tau_M$ & subst.

Stability Criterion:

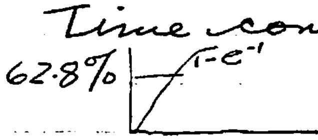
Instability when $G(s) \to \infty$.

i.e., $s = 0$; $\tau_f s = -1$ or $\tau_f M = -1$.

Let $K = \frac{K_f}{R_f} \cdot \frac{K_2}{D}$.

then $\theta(s) = \left(\frac{1}{s}\right)\left[\frac{K}{s(1+\tau_f s)(1+\tau_M s)}\right]$

Time const: time required to reach $e^{-1} \doteq 62.8\%$



INVERSE TRANSFORMATION:

$$G(s) = \frac{A(s)}{B(s)} = \frac{a_m s^m + a_{m-1} s^{m-1} + \dots + a_1 s + a_0}{b_n s^n + b_{n-1} s^{n-1} + \dots + b_1 s + b_0}$$

Partial fraction → $(s+a)(s+b)(s+c)\dots$

$$= \frac{C_1}{(s - s_k)} + \frac{C_2}{(s - s_{k-1})} + \dots + \frac{C_n}{(s - s_n)}$$

$$C_N = \left[(s - s_n)\frac{A(s)}{B(s)}\right]_{s = s_N}$$

$$\mathcal{L}^{-1}\left[e^{-at}\right] \to \frac{1}{s+a}$$

$$G = C_1 e^{s_k t} + C_2 e^{s_{k-1} t}$$

Example Closed Loop:

$$G(s) = \frac{1}{s}\,\frac{K}{(Js^2 + Ds + K)}$$

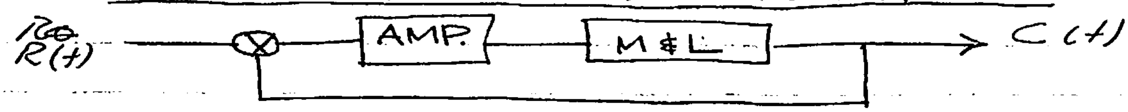
roots: $r_1 = a + jb$, $r_2 = a - jb$.

$$G(s) = \frac{1}{s}\,\frac{K}{(s + a + jb)(s + a - jb)}$$

$$G(t) = C_1 + C_2 e^{-(a+jb)t} + C_3 e^{-(a-jb)t}.$$

Next - general solution and compare with classical mathematical methods.

INVERSE LAPLACE TRANSFORMATION:



$$G(s) = \frac{K}{Js^2 + Ds + K}.$$

$$G(s) = \frac{1}{s}\,\frac{K}{(s+a+jb)(s+a-jb)}$$

$$\mathcal{L}^{-1}\left[\frac{a_0}{s(s+a+jb)(s+a-jb)}\right]$$

$$\frac{C_1}{s} + \frac{C_2}{(s+a+jb)} + \frac{C_3}{(s+a-jb)}$$

In time domain this can be represented by:

$$C_1 + C_2 e^{(-a-jb)t} + C_3 e^{(-a+jb)t}$$

$$= C_1 + e^{-at}\left[C_2 e^{-jbt} + C_3 e^{+jbt}\right]$$

From previous eq's:

$$C_1 = \frac{a_0}{(s+a+jb)(s+a-jb)}\Bigg|_{s=0.}$$

$$\therefore C_1 = \frac{a_0}{a^2+b^2}.$$

$$C_2 = \frac{a_0}{s(s+a-jb)}\Bigg|_{s=-a-jb}$$

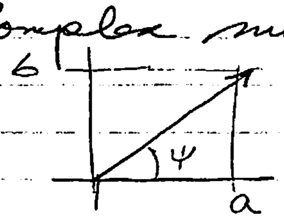
$$= \frac{a_0}{(-a-jb)(-2jb)}$$

$$C_3 = \frac{a_0}{(-a+jb)(2jb)}$$

$$c(t) = \frac{a_0}{a^2+b^2} + e^{-at}\left[\frac{a_0}{(-a-jb)(-2j)}\,e^{-jbt} + \frac{a_0}{(-a+jb)(2j)}\,e^{+jbt}\right]$$

$$\sin\beta t = \frac{e^{j\beta t} - e^{-j\beta t}}{2j}$$

Complex number $a+jb$ can be represented by a vector:



$$\tan\psi = \frac{b}{a}$$

$$\psi = \tan^{-1} b/a$$

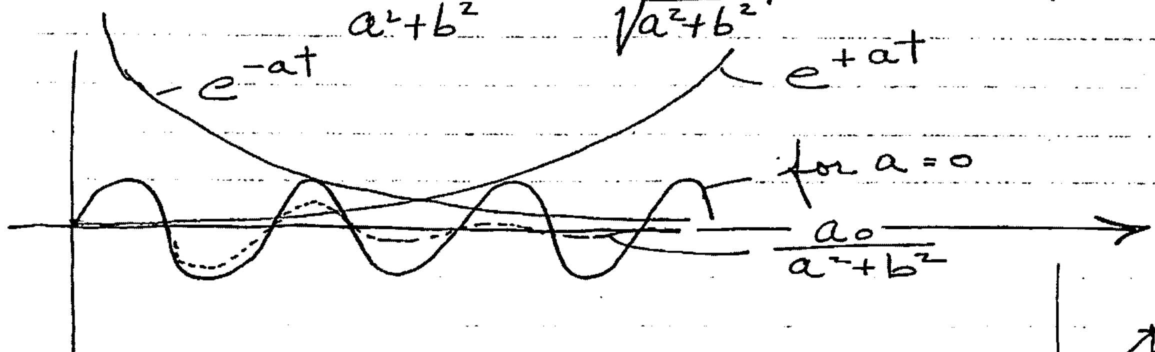
$$a+jb = \sqrt{a^2+b^2}\cdot e^{j\psi}$$

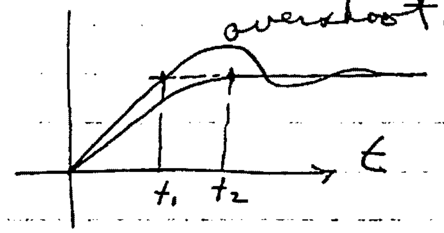
$$\therefore \frac{a_0}{\sqrt{a^2+b^2}}\, e^{-j\psi} = \frac{a_0}{-a+jb}$$

$$\& \quad \frac{a_0}{\sqrt{a^2+b^2}}\, e^{-j\psi} = \frac{a_0}{-a-jb}.$$

These can be defined into the final equation:

$$G(t) = \frac{a_0}{a^2+b^2} + \frac{a_0}{\sqrt{a^2+b^2}} e^{-at} \sin(bt+\psi)$$





STABILITY:

$$\frac{c}{r}(s) = \frac{K\,G(s)}{1+KG(s)}.$$

An instability will result when:

$1+KG(s) = 0$, or $KG(s) = -1$. i.e., phase = 180°.

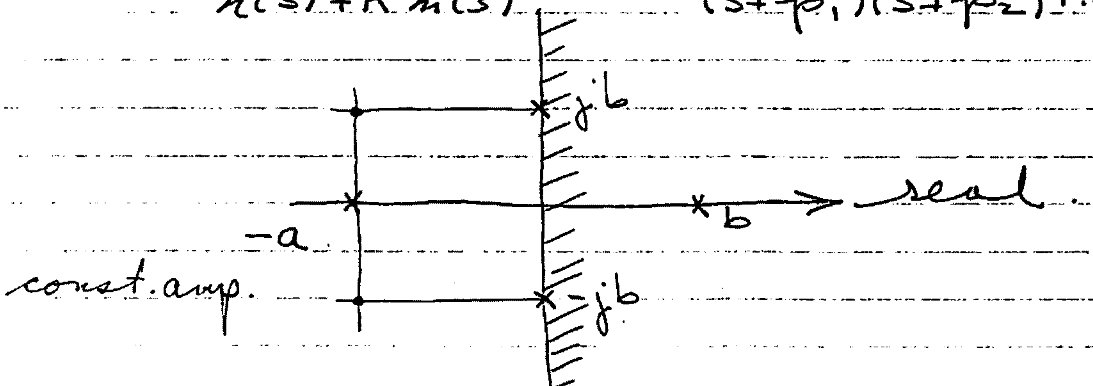
$$G(s) = \frac{m(s)}{n(s)}$$

Say $G(s) = \frac{1}{s}\,\frac{1}{(s+a)(s+b)}$

$$\therefore \frac{c}{n}(s) = \frac{K\frac{m(s)}{n(s)}}{1+K\frac{m(s)}{n(s)}} = \frac{Km(s)}{n(s)+Km(s)}.$$

then $n(s) + Km(s) = 0$.

$$\frac{Km(s)}{n(s)+Km(s)} = \frac{K(s+z_1)(s+z_2)\cdots(s+z_n)}{(s+p_1)(s+p_2)\cdots(s+p_m)}.$$



for $G(s) = \frac{1}{s}\,\frac{1}{(s+a)(s+b)}$

There is a pole where the roots = 0.

i.e., where $s = -a$.

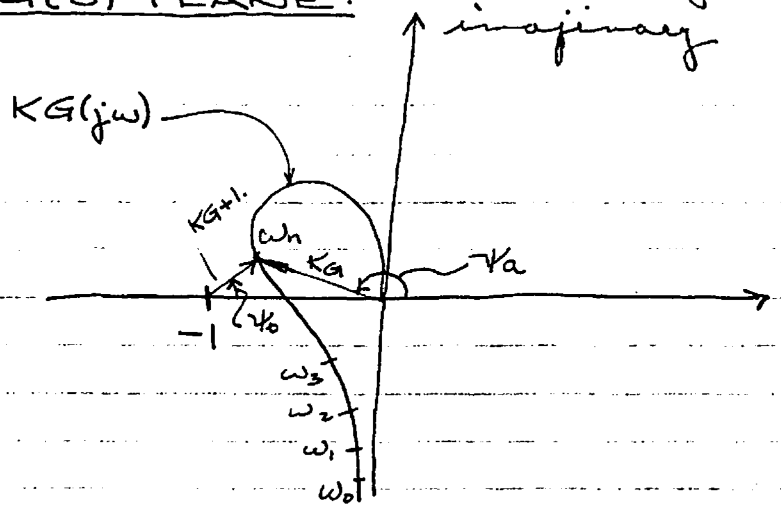
e^{-at} (decaying time fcn)

$s = -a + jb$

Must get a pair of complex conjugate roots.

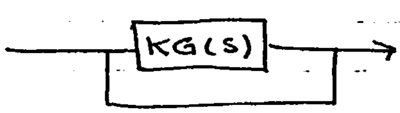
For a case +b, e^{-bt}
∴ causes instability.
The RH side of S-plane is definitely out for stable systems.
i.e., a real negative part of the root is req'd.

KG(S) PLANE:



test results.

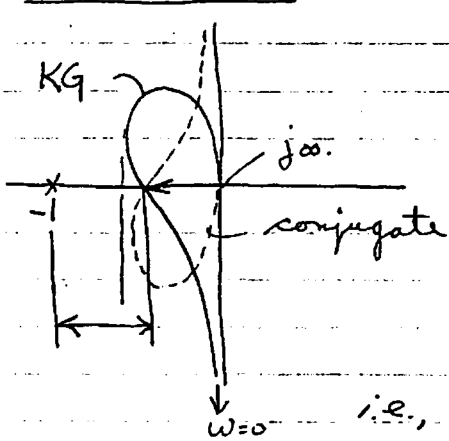
$KG(s) = R(s) + jI(s)$
$(A + jw) = e^{jwt} = \cos wt + j \sin wt.$
We are interested in $s = jw$ in this plane.



If we close loop we have
$$\frac{KG(s)}{1 + KG(s)}.$$
→ adds vectorily 1.

Then: $\dfrac{|KG|}{|KG+1|} e^{\Psi a - \Psi b}$

KG Plane: frequency plot:

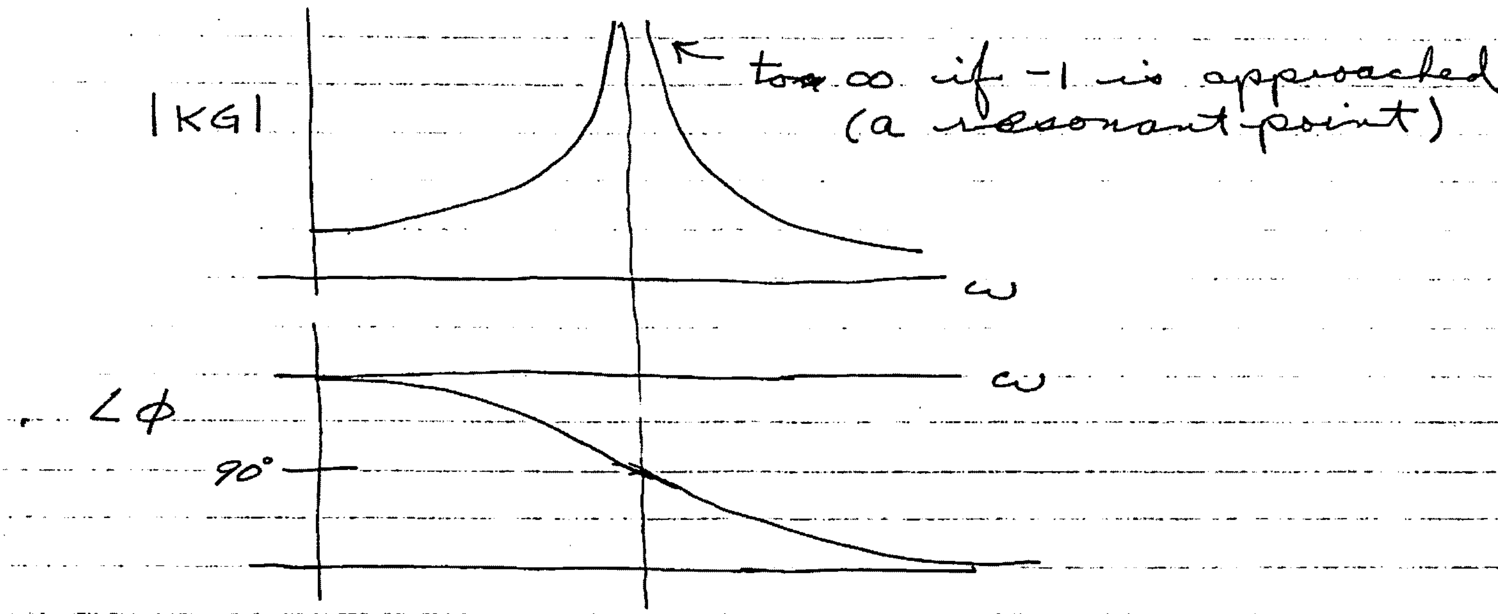


This system is stable:
It will always be stable provided KG<1.

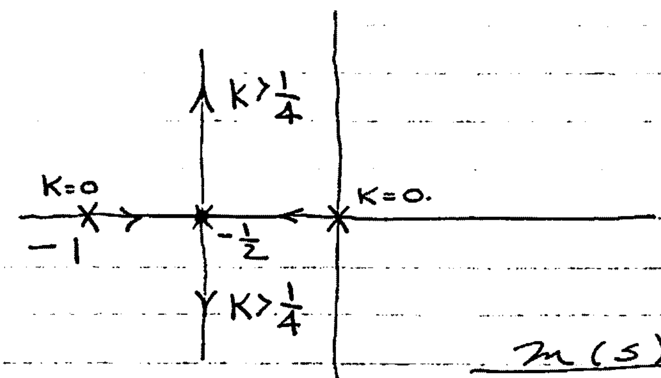
K — G(S)

Limiting value = KG = -1.
∴ the transfer fcn must never exceed -1 to be stable.
i.e., 1+KG=0 can only be satisfied if KG<-1.

If curve twists around −1 several times, there is more than 1 pole or $KG = -1$ more than once.



ROOT LOCUS METHODS:



Transfer fcn.:

$$G(s) = \frac{K}{s(s+1)} = \frac{m(s)}{n(s)}$$

$$\frac{m(s)}{m(s)+n(s)}$$

$m(s)+n(s)=0$

$K + s^2 + s$

$S_{1,2} = -\frac{1}{2} \pm \sqrt{\frac{1}{4} - K}$ roots of quadratic eq.

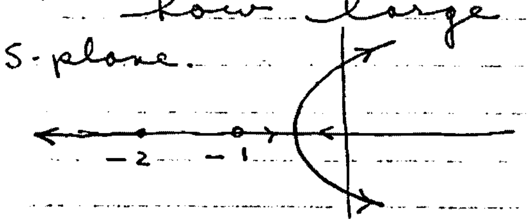
examine roots which are poles.

for $K = 0$, $S = -1, 0$

for $K = 1/4$, $S = -\frac{1}{2}$

$S_{1,2} = -\frac{1}{2} \pm j\sqrt{K - \frac{1}{4}}$ for all $K > 1/4$.

This is a stable system, no matter how large the gain is.



$$G(s) = \frac{K}{s(s+1)(s+2)}$$

$s = j\omega$:

Transfer function: $G(s) = \frac{K}{s(s+1)}$ stability.

Fundamental Eq. $\frac{C}{R} = \frac{G(s)}{1+G(s)}$ closed loop feed-back.

$$= \frac{m(s)}{n(s)+m(s)}$$

$$= \frac{K(s+z_1)(s+z_2)\cdots}{(s+0)(s+p_1)(s+p_2)\cdots}$$

$1 + G(s) = 0$

$n(s) + m(s) = 0$

$G(s) = \frac{m(s)}{n(s)}$.

$G(s) = \frac{K}{s(s+1)(s+2)}$ instability.

$(s+z_1) = B e^{j\angle B}$

$(s+p_1) = A e^{j\angle A}$.

To find ratio of a given point in the s-plane:

$$\frac{C}{R} = \frac{KB_1 e^{j\angle B_1} \times B_2 e^{j\angle B_2}}{A_2 e^{j\angle A_2} \cdot A_3 e^{j\angle A_3}}$$

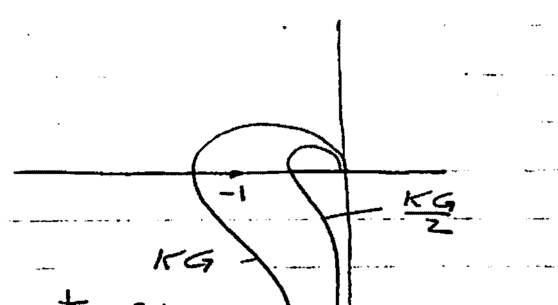
$$= \frac{KB_1B_2 \cdots e^{j\Sigma\angle B_n}}{A_1A_2\cdots e^{j\Sigma A_n}}$$

$G(s) = -1 = 1 \times e^{j180}$.

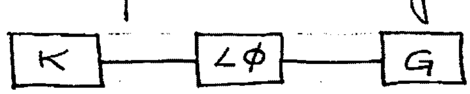
$\frac{KB_1B_2\cdots B_n}{A_1A_2\cdots A_n} = 1.$, $\Sigma\angle B_n - \Sigma\angle A_n = \pm 180 + n\,360.$

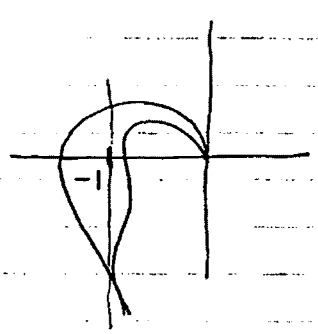
Instability: KG Plot:

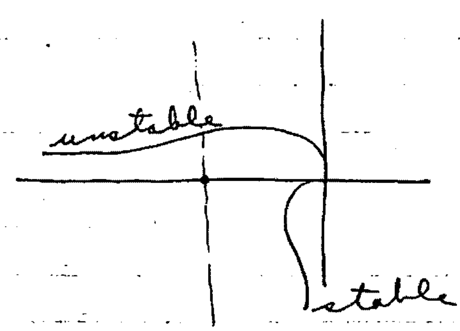
Decrease gain, increase stability.



Sometimes reducing gain is not poss. Then shape of curve must be changed, which can be accomplished by phase shifting.



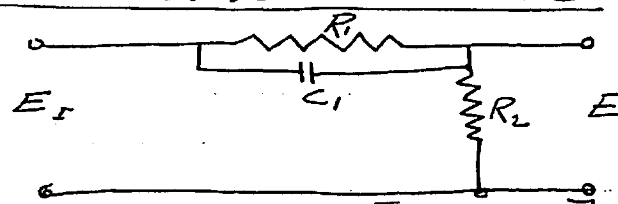




when $K(\omega)$ & $\angle\phi(\omega)$ } Use series or parallel
output $K(S)\,G(S)$ } compensation.

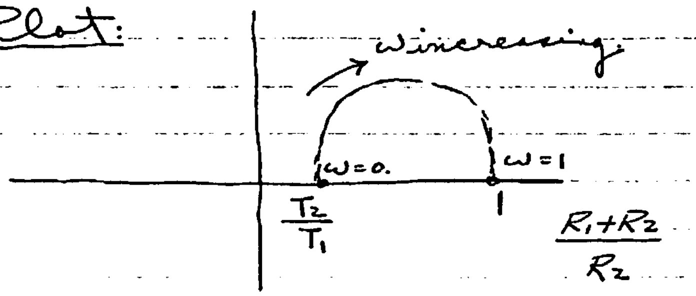
We have such networks mainly cuz change of gain produces change of phase.

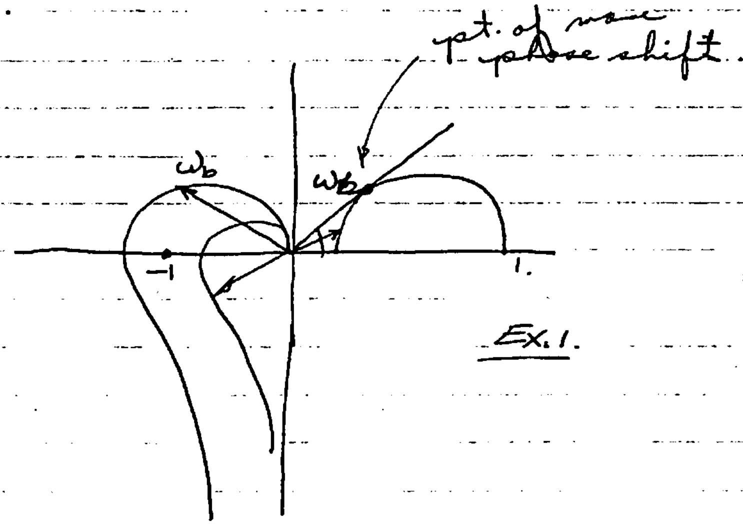
Phase lead network:



$$\frac{E_o}{E_I} = \frac{T_2}{T_1}\left[\frac{T_1 S + 1}{T_2 S + 1}\right].$$

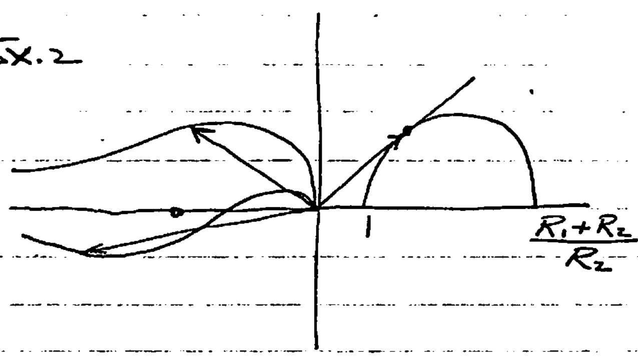
Plot:





Ex. 1.

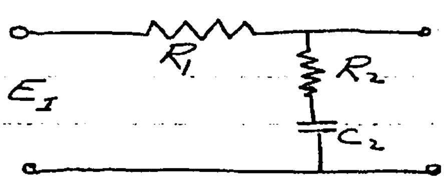
Ex. 2



with pre-amp after comp. network.

The closer to -1, the more osilations are present & the longer they will last.

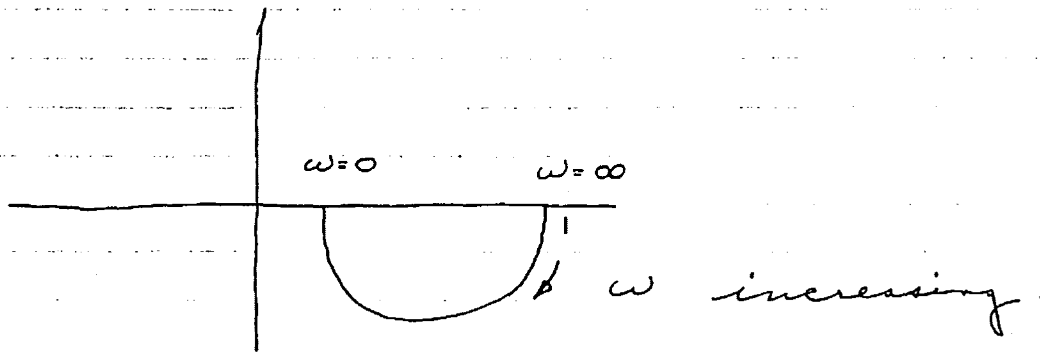
Phase Lag Network:



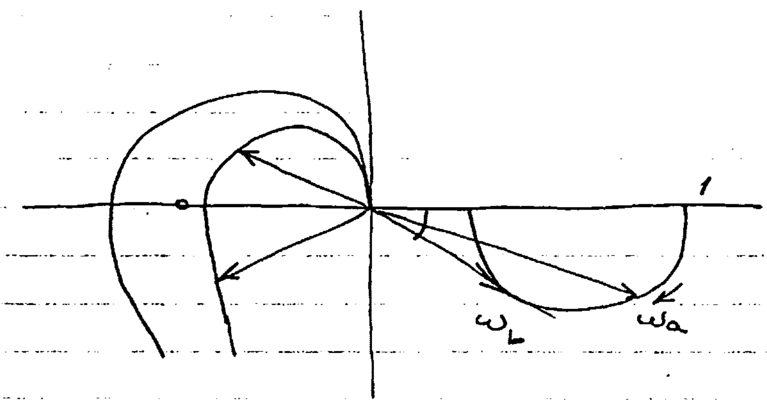
$$\frac{E_o}{E_I} = \frac{T_1 S + 1}{T_2 S + 1}$$

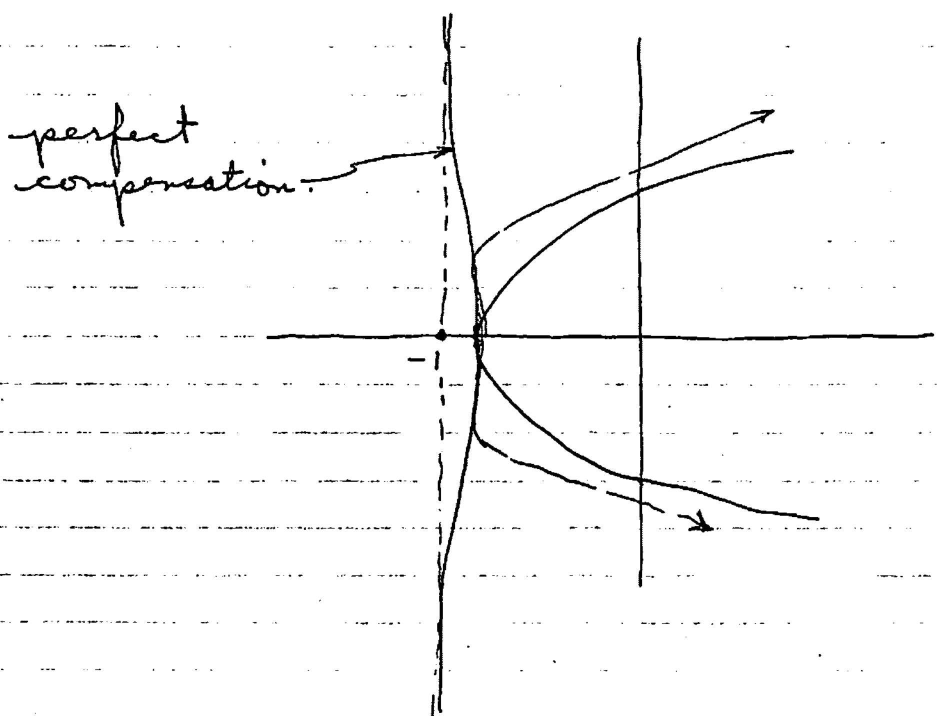
$T_1 = R_2 C_2$

$T_2 = (R_1 + R_2)\,C_2$



Ex.





$$\frac{K(s+\beta)}{s(s+a)(s+b)}$$ if perfect.

MB-3 AUTOPILOT
MH FIELD TRAINING MANUAL

I. AUTOPILOT FUNCTIONS:

1. GENERAL INFORMATION:

- installed in F-100D.
- provides the following fcns (modes):
  1. Pitch and yaw stability augmentation (on either automatic pilot or manual control)
  2. Attitude hold (Pitch, Roll, and Heading)
  3. Control stick steering.
  4. Altitude hold.
  5. Mach hold.
  6. Heading select.
  7. Automatic Pitch Trim.
  8. "G" Limiting.
  9. Tie-in to autolabs.
  10. Possible Future Tie-in to M-1.
  11. Possible Future Tie-in to APW-11.

- Synchronization of input signals provided before engagement to eliminate objectionable transients. A time delay is provided before engagement is possible, in order to allow gyros to come to operating speed and amplifiers to warm up.

- After engaging, automatic trim to stabilizer is used to reduce the long term output of the pitch servo to a null. This insures that there will be no sudden pitch attitude change upon disengaging the autopilot. Automatic trim is inoperative during control stick steering, and during damper mode of operation.

- When the damper switch is closed, the Pitch and Yaw Stability augmentation mode is energized. In this mode, part of the MB-3 system is utilized to damp oscillations and increase stability of the aircraft in the pitch and yaw axes. These stabilizing control movements are effected by differential servos, hence are not reflected back to the pilot's stick or rudder pedals. The pilot flies the plane manually in this mode, but in making turns he needs to use the stick only, the rudder being positioned automatically by the damper circuits.

- When the autopilot is engaged, control is now in the attitude hold mode, with the Pitch and Yaw stability mode still functioning. If the autopilot is engaged within ±7.5° of level in roll, the autopilot will automatically level the plane, hold it on a constant heading, level in roll, and in whatever pitch attitude the plane had before engaging. If, however, the autopilot were in a bank attitude of greater than ±7.5°, the autopilot would maintain that bank attitude and the plane would continue to turn rather than hold to a heading. The autopilot can be engaged in any aircraft attitude.

- If now, the pilot desires a change in attitude or heading, he engages the Control Stick Steering mode. To do this, he merely applies pressure on the stick in the desired direction. Heading control will be disengaged and the stick force transducers will supply command signals to the Autopilot to maneuver the plane according to the pilot's desires. When the desired attitude is reached, the pilot releases the stick force and the attitude hold mode is automatically resumed. NOTE: If the Control Stick Steering is released at a bank angle of less than ±7.5°, the plane will be automatically leveled and be held to a fixed heading with wings level.

- If, however, CSS is released at a bank angle greater than ±7.5° but less than 60°, and a pitch angle less than ±50°, the Autopilot will maintain that bank and pitch angle and the plane will continue to turn. If CSS is released at Bank Angles greater than ±60° or Pitch Angles greater than ±50°, the Autopilot will provide damping only for stability but the attitude the aircraft maintains will be a function of the aerodynamic characteristics of the airframe.

- The aircraft heading may be changed in another way, by use of the Heading Select Mode. To do this, the pilot needs only to "dial" the desired heading change on the Heading Select Dial, located on the Function Selector Panel. The Autopilot will then provide a coordinated maneuver to turn the plane to the chosen heading and will then maintain that heading. It is recommended that heading changes in this mode be limited to new headings within ±90° of present headings. A reason for this recommendation is to lessen the possibility of dialing a heading change of greater than 180°. Dialing a heading change of greater than 180° from the present a/c heading may cause the a/c to suddenly reverse the direction of bank. Obviously, the autopilot will always control the airplane to fly to the newly selected heading thru the smallest angle.

- The <u>Altitude Hold</u> mode is engaged by the "altitude" switch on the Function Selector. In this mode, the a/c is held at the Pressure Altitude at which this mode was engaged. The pilot should fly the plane and adjust power to arrive at the desired altitude before engaging the Alt. Control mode.

- If the Mach Hold mode is selected by use of the "Mach" switch, the Autopilot will control a/c pitch attitude to provide constant Mach number. As in the case of Alt. Control, <u>the pilot should fly the plane & adjust power to arrive at the desired Mach number before closing the Mach switch</u>.

- Constant attitude, constant altitude, and constant Mach are separate exclusive conditions, <u>so only one of the three may be selected at any one time</u>. During either altitude or Mach control modes, roll and yaw control is permitted thru the control stick, the rudder pedals, or the heading selector.

- Acceleration limiting circuitry is provided to prevent the autopilot from applying control that would cause the a/c to exceed its normal accelerations limits, because of either autopilot malfunction or during normal operation of the autopilot. Interlocks are provided to prevent engagement unless both A.C. & D.C. power are present and also to prevent engagement prior to a pre-set delay time, thus insuring proper gyro speeds, and adequate amplifier warm-up time. Another interlock will prevent engagement if hydraulic pressure of less than 1500 pounds is applied. An emergency disconnect switch, mounted on the pilot's stick, is able to disengage both autopilot and damper. It is possible for the pilot to manually override the autopilot in any or all axes at any time.

- In the autolabs mode, the autopilot is commanded by the labs system to provide exactly and automatically the desired maneuver.

- The M-1 tie-in mode operates similarly, and causes the plane to respond automatically to the M-1 controller demands. (This mode presently not being used.)

- Provision may be made for a tie-in to the APW-11 system for automatic guidance in response to that system.

- The Autopilot is designed to automatically control the a/c throughout its range and under all environmental conditions and aircraft configurations, such as external stores, encountered in operational use of the plane.

- The altitude design range is from −1000 ft. to 80,000 ft., and the mach design range is from M = 0.2 @ S.L. to M = 1.7 @ 23,000 ft. The control range of the basic Autopilot is 360° in pitch, roll, and heading. The range for Labs & M-1 control is adequate for the required maneuvers.

2. STABILIZER DAMPER:

Ref. FIG. 1.1 & 1.11

A. GENERAL:

1. Purpose:
   - to damp pitch oscillations so as to stabilize the flight attitude in the pitch axis.

2. Utilization:
   - hyd. press. is ported to damper servos thru Differential Servo Valve in supply line.
   - valve closed prior to engagement of damper.
   - removes hyd. press. from servo rams & control valves, preventing servo operation.
   - servo ram spring restrained @ its neutral position & acts as a rigid link in the control system prior to engagement.

   - Damper engaged by placing "Damper - Standby" switch on fcn selector @ Damper.
   - This energizes "Differential Servo Valve", porting hyd press to servos.
   - Application of hyd press slowly removes the spring restraint on servo action of a hyd. time delay mechanism.
   - ~~Th~~ This prevents abrupt maneuvers at time of engagement.
   - After ≈ 2 - 5 secs, servos have limited stroke capability (Ref. § III - J)

   - After engaging, pitch rate gyro detects pitch oscillations & feeds signals ∝ to pitch rate to the pitch damper amplifier.
   - Servo ram extends or retracts (depending on signal polarity), deflecting the stab to eliminate the disturbance.
   - Feedback signals ∝ to servo ram displ't are summed with pitch rate signals @ the amp. input to maintain stab

deflection ∝ to pitch rate.

- Stick position transmitter develops signals ∝ to st. pos. during maneuvers.
- Stick pos'n signal balances resulting pitch rate signal, thus preventing the damper from resisting pilot initiated maneuvers.

- Mech travel limits in pitch Diff Servo variable as fcn of alt. → permits larger limits of control surface deflections @ high alts.

B. INPUTS TO THE STABILIZER DAMPER AMPLIFIER:

1. Stick Position:
   - voltage ∝ to position of control stick from neutral (neutral ≐ 2 1/2° L.E.D.)
   - allows pilot a certain control of the pitch damper by the use of his stick.
   - i.e., pilot can, with damper on, use control stick to aid the Stabilizer Damper in damping pitch oscillations.
   - stick position voltage also tends to nullify the Pitch Rate voltage so that Pitch Rate will not oppose the pilot's initiated maneuver.

   - Stick position voltage → thru a lag network → so as to filter out too abrupt movements of Pilot's Control Stick.

   - After lagging stick position voltage, stick position input is hi-passed. This lag network filters out abrupt & erratic inputs from stick position pot; thus, it helps to prevent erratic movements of the Stab. Diff. Servo.

2. Pitch Rate:

- pitch rate voltage developed by pitch rate gyro is ∝ to the <u>rate</u> of pitch attitude change & of such a phase relationship that it asks for elevator surface deflection in a direction to oppose this <u>rate</u> of pitch displacement.
- Pitch rate is A/S scheduled so that less pitch rate voltage is utilized at higher I.A.S.
- Pitch rate voltage thru lead network before it is high-passed.
- Effect of the hi-pass network: to block out steady-state stick & pitch rate voltages.
- i.e., stick position & pitch rate inputs must be varying in order to be felt by the Stabilizer Damper Amp, but once they become steady state, they are no longer felt by the Stab. Damper Amp.

  <u>Note</u>: lag network on output of pitch rate gyro was a recent mod. Added to filter out the hash and noise of this input, & thus prevent surface jitter.

- ∴ effect of hi-pass network is to produce pitch damping action only when the pitch rate is varying. Whenever pitch rate is const, as in a constant pull-up maneuver, the hi-pass crct prevents pitch rate voltage from producing surface movement that would oppose the pilot or Auto-Lobs initiated maneuver.

3. Pitch Damper Servo Feedback.
- Pitch Damper Servo Feedback is a voltage ∝ to the displacement of the Damper Servo from center & is of such a phase relationship that it balances the summation of the sensing element inputs at the Stab. Damper Amp.
- i.e. with no inputs from the sensing elements to the Stab. Damper Amp., the Pitch Damper Servo Feedback, if any, would be such as to drive (via the servo amp.) the Pitch Damper Servo to neutral (centre).

- Pitch Damper Servo Feedback is not scheduled according to Mach or A/S cuz the sensing element input has already been compensated by A/S, and since the Pitch Damper Servo Feedback cancels the sensing element input, necessary A/S sched'g is already completed.

C. HYDRAULIC SERVO DAMPER MECHANISM:
Ref. § III - J.

D. IRREVERSIBLE LINKAGE:
Ref Fig 1.2; Two servo actuators -- one parallel for Autopilot (ref-later) one differential for Damping.
Damper servo: connected so that its movement does not reflect at the control stick but only alters the position of the North American A/C (NAA) Power Actuator which in turn positions the horizontal stab. No elevators conventional, all-moving tail-plane. ~~a~~ more stable form of maneuvering in pitch axis (@ high M) than conventional el.

- On damper operation, the diff actuator adds to or subtracts from pilot's control stick action which in turn ultimately alters the position of the Horizontal Stabilizer but no action of the damper should be felt @ the control stick. This is an irreversible linkage.

- On manual mode, Damper off, the diff'l actuator is spring loaded to center. For info, ref § III-J.

3. RUDDER DAMPER:
ref. FIG. 1-3 & 1-10.

A. GENERAL:

1. Purpose:
- To dampen Yaw oscillations so as to stabilize the flight attitude in the Yaw axis.
- To coordinate pilot-initiated man's.

2. Utilization:
- Hyd. press ported to the damper servos thru the "Differential Servo Valve" in the hydraulic supply line.
- Servo is closed prior to engagement of the damper.
- This removes hydraulic pressure from the Servo Rams and Control Valves, thus preventing servo operation.
- Servo Ram is spring loaded (restrained) @ its neutral position & acts as a rigid link in the control system prior to engagement.

- Damper engaged by placing the DAMPER-STANDBY switch on the fcn selector at DAMPER.
- This energizes the "Differential Servo Valve", porting hydraulic pressure to the servos.
- Application of hydraulic pressure slowly removed the spring restraint on the Servo by the action of a hydraulic time-delay mechanism.
- After ≈ 2 to 5 secs, servo has full stroke capability.

- Rudder Damper becomes engaged when the damper switch is placed "ON", providing certain AC & DC sequences have been accomplished. (Refer to AC & DC sequencing § II.)
- From AC & DC flow dia, (§ II) it is possible to engage the Rudder Damper without engaging the Autopilot.

- After engaging the damper, the Yaw Damper fcns to provide yaw damping, eliminate sideslip, & coordinate turns.
- Yaw damping produced by Yaw Rate Gyro.
- Yaw rate signals are fed to Yaw Damper Amplifier & the Servo Ram extends or retracts (depending upon signal polarity), deflecting the rudder to eliminate the disturbance.
- Servo Feedback maintains rudder defl'n ∝ to Yaw Rate.
- Yaw Rate signals are fed thru a high pass filter which passes signals due to yaw accel'n only.
- This filter is provided to eliminate yaw rate signals during steady-state turning rates, thus allowing the damper to coord turns.
- Turn coord'n is produced by combination of aileron position, roll rate, and lateral acceleration signals.

- Hi-passed aileron position & hi-passed roll rate signals provide rudder defl'n to overcome yawing moments due to aileron deflection & roll rate resp'y.
- A lagged roll rate signal balances yaw rate signals during turn entry & recovery. (This is necessary cuz hi-pass yaw rate filter passes yaw accel'n during turn entry & recovery)
- If turn not fully coordinated, resulting side-slip is detected by the lateral accelerometer & the rudder is deflected to increase or decrease turning rate as req'd to coord the turn.

- Pilot operate rudder pedals to provide intentional side-slip.
- Switches in Yaw Damper actuated by the rudder pedals to cut out lateral accel'n signals.

B. INPUTS TO THE RUDDER DAMPER AMPLIFIER:

1. Yaw Rate:
   - Yaw rate voltage developed by yaw rate gyro is ∝ to rate of heading change & is of such a phase relationship that it asks for rudder surface deflection in a direction to oppose this rate of heading change.

   - Yaw rate hi-passed before reaching Rudder Damper Amplifier.
   - Hi-passing is to prevent steady state yaw from from opposing steady-state turn.
   - ∴ only time yaw rate can produce Servo movement is while yaw rate is chging amp.
   - Once it becomes steady state amplitude no further servo movement will be produced by Yaw rate.

2. Aileron Position:

- Ail pos'n voltage ∝ to aileron displacement from S/L.
- Asks for rudder surface def'n in a direction to aid the maneuver being produced by Ail defl'n.

- At low A/S, down ail normally produces more drag than up aileron.
- At high A/S, this relationship is usually reversed.
- ∴ down aileron @ low air speeds drags most, it produces a yawing tendency which is in opposition to the desired yaw that is being produced by the bank angle that is being produced by the deflected ailerons.
- ∴, to nullify this adverse yaw prod'd by the drag of the deflected ailerons, a voltage ∴ to aileron pos'n is fed to the Rudder Damper Amplifier of such a phase as to ask for rudder deflection to aid the turn entry or turn exit being produced.

- Aileron pos'n voltage is A/S scheduled before being hi-passed. (∴ blocking steady-state voltages).
- ∴ we eliminate steady state aileron position as an input to rudder damper amplifier (as long as ailerons are not streamlined they do produce an adverse yaw which can, if not nullified, produced a slipping or skidding steady-state turn).
- ∴ we have a lateral accelerometer input that will reposition rudder via the Rudder Damper Amplifier until turn is coord't.
- ∃ if ail's not streamlined, the adverse yaw created by miss-trim, will be cancelled by the lateral accelerometer action.

Ref. § III, addendum.

3. Lateral Accelerometer:
- Lat. Accel'r voltage by lateral accel's ∝ to the side-slip of the A/C.
- Input sent thru a lag network which essentially filters out high frequency inputs from the lateral accelerometer.
- High frequency inputs are usually produced by vibrations &/or oscillations.

- voltage is input to the Rudder Damper Amplifier if engaged, but is not an input to the Amp ~~if damper~~ while pilot is producing any yaw manouvers by rudder pedals.
- ∃, when pilot pushes rudder pedals to produce deliberate slip, pressure on pedals will close the rudder bungee switch, energizing K-5 (relay), applying 45ᵛ 400ᴴ to relay K-37, which cuts out lat. accel. input.

- Pressure released from the rudder pedal, relay K-5 de~~e~~ energized, K-37 remains energized for 4 secs (nom).
- ∴, lat. accel does not appear as an input to Rudder Channel for nom. 4 secs after press. is released from rudder pedals.
- 4 secs allows accel'r to settle out to zero before applying it to Rudder Channel.

4. Rudder Trim:
- Rudder Trim Pot usually adjusted @ time of installation of lat'l accel's to null out any unbalance of the lat'l accel's due to its position on installation.

5. Roll Rate:

- Roll rate voltage developed by roll rate gyro is ∝ to rate of roll displacement & is of such phase relationship that asks for rudder surface deflection in a direction to aid the turn entry or turn exit.

- As A/C rolls into a turn, downward going wing produces a forward lift vector & upward going wing produces backward lift vector.
- These vectors → adverse yaw while A/C is rolling. (ref. § III, Addendum).
- To nullify this adverse yaw on entry & turn exits, roll rate voltage, after being A/S scheduled, is hi-passed & fed into the Rudder Damper Amplifier.

- ∴ yaw rate is varying in amplitude as the turn entry or turn exit is executed, yaw rate appears as an input to Rudder Damper Amp. on turn entry & turn exit.
- We remember from the discussion ¶1 above, Yaw Rate opposes any rate of heading change, except the steady-state rate of heading change.
- ∴ we must cancel this yaw rate during the turn entry & turn exit.
- on turn entry or exit, A/C begins to roll (→ roll rate) before A/C begins to yaw (→ yaw rate).
- To cancel this yaw rate during turn entry or exit, we put roll rate thru a lag network, (after having 1st scheduled it according to A/S) & feed this input to the Rudder Damper Amp.
- Effect of this lagged roll rate signal is to nullify yaw rate signal during turn entry.

- @ steady state bank angle condition, yaw rate is a constant & roll rate = 0.
- ∴ roll rate = 0 in steady state, there is no adverse yaw being produced by roll rate.
- ∴ we do not need any more hi-passed roll rate. (hi-passed roll rate eliminated as Roll Rate = 0)
-
- ∴ Yaw Rate in steady state turn = constant, it does not appear as an input to the Rudder Damper Amplifier cuz of yaw rate hi-pass network.
- ∴ lagged roll rate is no longer needed to cancel yaw rate.
- Obviously roll rate in steady-state turn = 0 ∴ lagged roll rate disappears also.

6. <u>Rudder Servo Feedback:</u>

- Rudder Servo Feedback = voltage ∝ to displacement of Rudder Servo from centre, & it is of such a phase relationship that it balances the summation of the sensing elements inputs at the Rudder Servo Amplifier.
- ∃ with no inputs from sensing elements to the Rudder Damper Amplifier, the Rudder Damper Feedback, if any, would be such as to drive (via the Servo Amplifier) the Rudder Damper Servo to neutral (centre).

- Rudder Damper Feedback is Mach scheduled so as to produce less feedback @ higher Mach numbers.
- Less feedback, of course, produces greater surface deflection per unit of input to the Rudder Damper Amp.
- Mach no. increases @ higher alts (assuming constant I.A.S.).

- after Mach scheduling, the feedback is A/S scheduled such that a greater %age of feedback voltage is utilized @ higher A/S.
- Utilizing a higher %age of the feedback voltage at high airspeeds, of course, means that less surface deflection is produced at high A/S.

- Combination of M & A/S scheduling on Rudder Damper Feedback voltage produces a scheduling closely approximating T.A.S. scheduling.

C. HYDRAULIC SERVO DAMPER MECHANISM.
ref § III - J.

D. IRREVERSIBLE LINKAGE:
Ref FIG 1.4.
- Yaw axis has diff'l actuator only.
- As in pitch axis, Yaw Damper Differential Servo adds to or subtracts from the pilot's rudder pedal command.
- Any movement of Diff'l Servo will ult'y produce rudder surface movement, but movement of Diff'l Actuator should not be felt at rudder pedals.

4. AILERON (AUTOPILOT):

Ref. FIG. 1-5, FIG. 1-10.

A. GENERAL:

1. Purpose:
   - Aileron channel of Autopilot must provide all fcns (on autopilot operation) that the pilot would provide on manual operation. Including:
     - a.) roll damping
     - b.) heading control
     - c.) control stick steering
     - d.) attitude stabilization
     - e.) certain specified bombing functions.

2. Utilization:
   - Damper engaged before autopilot can be engaged.
   - Autopilot engaged by placing "ENGAGE-STANDBY" switch on function selector at "ENGAGE"
   - The Aileron & Stabilizer channel of autopilot become engaged at this time, providing certain AC & DC sequences have been accomplished. (§ II.)
   - It is impossible to engage Aileron channel without engaging elevator channel.

   - Engaging the autopilot energizes the Servo Engage Solenoid, porting the servo Rams to the metered (Moog Valve) pressure.
   - At same time, autopilot trim circuits are de-energized.
   - The system is fully operational @ this pt. (Pitch & Yaw Damper fcns previously described)

   - If autopilot engaged within limits of ± 50° in pitch & ± 60° in roll, vert gyro roll & pitch signals together with bank & pitch synchronizer signals switched into roll &

pitch channels, respectively.
- ∴ synchronizer signals exactly balance the gyro signals, there will be no bump @ engagement, & a/c will maintain existing attitude.
- If the a/c is in a bank angle of 7.5° or less @ engagement & the pilot is not applying stick force, heading control will be engaged & a/c will roll to wings level on a constant magnetic heading.
- If a/c exceeds ±50° pitch @ engagement, Autopilot will provide attitude stabilization thru lagged pitch rate signals although no fixed attitude will be held.
- If a/c exceeds ±60° in roll engagement, a/c will remain in turn without pitch or roll attitude stabilization but with Autopilot supplying roll & pitch damping.

B. INPUTS TO THE AILERON SERVO AMPLIFIER:

1. Autopilot Trim:
- Prior to engaging Autopilot, autopilot trim feeds back enough voltage to Aileron Servo Amplifier to balance (null) the input.
- As long as input to Servo amp is unbalanced (not nulled) it is impossible to engage the Autopilot.
- ∴ purpose of Autopilot Trim prior to engaging the Autopilot is to balance the input to the Aileron Servo Amplifier so that the Autopilot can be engaged.

- ~~@ pre-~~ During engaged period, autopilot Trim does not appear as an input to Aileron Servo Amp. Relay K-2A ~~open~~ cuts it out.

- When Autopilot Trim circuit was operating, trim switches were acting to place a charge across the (Lag.) condenser (C-23) in the roll autopilot trim circuit.
- From point of engagement, no additional

charge is placed on this condenser.
-∴ this charge gradually discharges to zero.
- as it does, the voltage input, (which originally was synced out by the charge on this condenser) now takes over & produces control surface movement.

2. Roll Rate:
- Roll Rate voltage developed by the roll rate gyro is ∝ to rate of roll displacement & is of such a phase relationship that it asks for aileron deflection in a direction to reduce this rate of roll displacement to zero rate.

- Roll rate is A/S scheduled so that roll rate produces less aileron deflection at higher A/S.

- Roll rate hi-passed (in a/c with BG-38B-2 Calibrator or subsequent series).

- A/S scheduled roll rate is also hi-passed & sent to an Aileron Solenoid Amplifier which acts upon the Hyd. Ram (WAAA) directly.
- The fcn of this hi-passed roll rate thru the Aileron Solenoid Amplifier to the Hyd Ram is to produce damping of hi-frequency roll rate directly without having to go thru the Aileron Servo Amp & Servo fcns which inadvertently have a certain amount of system lag.
- This roll-rate signal, directly from the roll rate gyro, is also utilized for fcns in the Rudder Damper.

3. <u>Roll Control Stick Steering:</u>

- Control stick steering voltage ∝ to force on the pilot's control stick in the roll axis.
- Zero (neutral) pos'n of CSS is obtained any time force is removed from grip, or if force applied is less than ≈ ½ LB.

- Roll CSS part of input to Aileron Servo Amplifier @ all times Xcept on Labs Maneuver from time of pull-up (+4 sec. or − 0.0 sec.) thru roll-out, & until such time that pilot switches from LABS ALT or NORMAL back to normal autopilot. In other words, on Labs maneuver @ pull-up, Roll CSS is switched out & does not tie back into aileron channel until pilot switches OFF of Labs.

- Roll CSS lagged to prevent maneuvers being applied too suddenly in CSS mode.

4. <u>Vertical Gyro Roll Displacement & Bank Sync.</u>

A. <u>Autopilot Disengaged:</u>

- Prior to engaging, relay K-10 is energized.
- K-10 energized, output of vert gyro roll displ't feeds into Bank Sync Ampl'r.
- Bank Sync Amp will drive the Bank Sync motor which drives the bank sync pot until the summation of these two voltages = 0.
- When summation = 0, no input to Bank Sync Amp.
- Bank sync amp & motor combination is capable of maintaining the summation of Vert Gyro Roll displ't & Bank Sync @ zero within limits of ± 75° roll attitude (bank ∠).

- vert gyro roll displ't & bank sync = 0, no input to Ail Servo Amp from this source @ instant of engagement.

B. Autopilot Engaged:
- @ instant of engaging autopilot, it is assumed that the summation of VG roll displacement & bank sync = 0.
- Any deviation of a/c in roll from the attitude it was in @ the instant of engagement, will produce a change in VG roll displacement.
- ∴ the summation of VG roll displ't & bank sync. will no longer be zero.

- Diff. between VG roll displacement & bank sync, will feed to Ail Servo Amp, asking for aileron surface defl'n to return a/c to attitude that it was in @ instant of engagement.

NOTE: There are 2 exceptions to this rule.

1.) a/c ±60° or more in roll attitude @ the instant of engagement, relay K-10 remains energized & the Bank Sync Amp continues attempting to maintain vert. gyro roll displ't + bank sync = 0.
  - Not until roll displ't is reduced below ±60° roll attitude will relay K-10 deenergize.
  - ∴ VG roll displ't + bank sync is not part of input to Aileron Servo Amp, @ roll > ±60°.

2.) Bank ∠ < ±7½°, pilot desires to maintain const. heading, action as follows:
  - Bank sync voltage removed from Aileron Servo Amp.
  - Roll displ. (without bank sync) is fed to Ail Servo Amp.
  - Roll displ. alone makes a/c roll to wings level.
  - Roll displ. + bank sync goes to Bank Sync Amp.
  - Roll displ goes to 0 as A/C rolls wings level.
  - So, roll displ't + bank sync → 0.

NOTE: Compass sync holds a constant heading (§5)

- Purpose of lag network in bank sync output is to prevent a sudden maneuver when bank sync suddenly disappears as an input to the Aileron Servo Amp. When K-3 energizes.
- K-3 energizes when bank ∠ → < ±7½° if CSS is off.

- i.e., Relay K-3 cannot be energized if Roll or Pitch CSS is on.

- When A/C → wings level, output of VG roll displacement = 0 & roll displ + bank sync ⟹ 0.

c. Control Stick Steering:
- When pilot actuates CSS mode (by applying force to grip in either roll or pitch) relay K-10 energized & action of Bank Sync Amp & motor combination is same as if A/P were disengaged.

5. Compass:
a.) Autopilot Disengaged:
- flux-gate compass is fed into heading synchro, & then fed into Compass Sync Amp.
- Compass Sync Amp drives compass sync motor to reposition the rotor of heading synchro until input of Compass Sync Amp = 0.

- ∴ Compass Sync Amp & motor combination can maintain hdg synchro rotor @ a null, it is assumed that @ the instant of engaging the Autopilot, input to aileron Servo Amp from transmitter (hdg) synchro rotor = 0.

b.) Autopilot Engaged:
- @ inst. of engaging, output of compass demodulator = 0.
- ∴ no input from compass demod to ail. Servo Amp.
- after engaging, any deviation of A/C hdg → an output from the compass demod that will ask for aileron surface deflection in a direction to reduce hdg deviation → 0.
- Max bank ∠ compass demod can produce is limited by diodes to ≈ ±30°.

- § 4 b (2) above, Autopilot engaged & A/C turning.
- If bank ∠ < ±7½°, relay K-3 will energize.
- Ties compass demod into Aileron Servo Amp.
- Remember: comp demod output = 0 when K-3 couples.

- When K-3 energizes, K-3A & K-3B also energize
- When K-3A energizes, compass sync amp & motor stops operating.
- ∴ rotor of Heading Synchro is now standing still.
- Remember also: A/C is turning; so output of compass demod will not remain = 0, but will increase as A/C deviates off heading.
- This input to Ail Servo Amp from Compass demod will ask for aileron defl'n to return the A/C the heading present when K-3 was energized.

- When A/C finally settles out wings level & on heading present K-3 energized, output of compass demod = 0.

6. Aileron Bridge Centre:
 - adjusted @ installation to balance out errors from roll rate gyro or CSS. (autopilot engaged).

7. Directional Gyros (Roll & Yaw):
 - gyros electrically tied to input of Ail Servo Amp @ Labs Pull-up.
 - However, Y/R gyro will not have any electrical output until uncaged electrically (via cage solenoid).
 - Y/R gyro completely uncaged @ pull-up only if A/C wings are within ±.5° of level.
 - If not within ±.5° of level, a 4 sec (max) delay is set in motion.
 - ∴ Y/R gyro is completely uncaged when the wings become level or within 4 secs after pull-up, whichever comes first.

 - Fcn of yaw & roll: to ask for ail defl. to reduce heading (yaw) & roll deviations → 0 during labs manoeuver.

 - @ roll-out, yaw is removed completely from Aileron Solenoid Amp.
 - @ same time yaw removed, Roll Pot polarity

is reversed.
- Enables roll pot output to ask for aileron deflection to roll a/c to right side up, wings level!

8. Asymetrical Loading Pulse:
- Injected into Ail. Servo Amp (via relay K-6) @ time of pull-up on auto labs manoeuver.
- Amplitude of pulse is dependent on amount of charge on Asymetrical Loading condenser C-38.
- Charge on this condenser depends on how far off center the Ail Servo Feedback pot is @ the instant of pull-up. (when K-6 energizes)
- Purpose of Asym'l pulse is to deflect the Ail's (@ pull up) α to asym'l loading of a/c (in roll axis) & in a direction to counteract the Asym'l loading.
- i.e., asym'l ldg pulse tries to get wings level.
- Remember: wings must be level (within ±.5°) before Y/R gyro will become full uncaged.

9. Roll-out Pulse:
- Input switched into aileron Servo Ampl. @ time of roll-out from Labs manoeuver. This roll-out is usually performed @ 185° pitch ∠.
- Roll-out pulse utilized only to start a/c rolling out of Labs manoeuver.
- Once roll initiated, K7L energized, direct roll gyro will act to bring a/c to wings level, a/c right side up, & maintain a/c in this position until pilot places his LABS NORMAL ALT. switch to "off".

10. Aileron Servo Feedback:
- AIS scheduled & then hi-passed as input to ail servo amp.
- AIS scheduling ÷ to increase %ge of feedback voltage @ higher AIS.

- ∴ @ higher A/S, less control surface movement is necessary to balance inputs to ail Servo Amp.

- Hi-pass network tends to block out steady-state Aileron Servo Feedback.
- This action will in turn produce a trimming action by Ail. Servo.
- i.e, any error input to the Ail. Servo Amp must be reduced to zero before the Ail Servo Feedback can be reduced to steady-state condition.
- ∴, necessary for Ail Servo to assume a position other than streamline in order to maintain error inputs to aileron Servo Amp = 0, it will assume that position necessary to do so.

- Special network in ail Feedback cict (prior to hi-pass network) is there to prevent hyd servo from tending to oscillate @ approx 14 c.p.s.
- Oscillation @ ≈ 14 cps when high inertial loads are applied to servo.
- Network attenuates this frequency so that servo will not oscillate.

- Assuming asym'l ldg of a/c, necessary for the Ail Servo to assume a posi'n other than streamlined to maintain wings level.
- When aileron off streamline, ail servo feedback will charge the condenser in lag circuit (asym. ldg) via K-6 relay contact to ground.
- @ instant of pull-up on an automatic Labs manoeuver, relay K-6 energizes & allows the discharge of the condenser in the lag network to discharge into the Ail Servo Amp, thus producing an ail defl'n in the direction to counteract the asym'l loading @ that instant.

- This is necessary since vert. stability is switched from vertical gyro roll displacement to the direct yaw & roll gyros by the action of relays K-4L & K-10. Ref. Table III & IV.

11. Vertical Gyro Roll Displacement to the Labs Meter:
- Prior to pull-up on a labs maneuver, vert. gyro roll disp't voltage feeds to the Labs meter vert. pointer.
- after pull-up, input to Labs meter is derived from a combination of direct roll & yaw gyro outputs. at release, the sensitivity of the Labs meter (Vertical pointer) is greatly reduced by the action of relay K-5L.

C. HYDRAULIC ENGAGE & DISENGAGE MECHANISM:
Ref. § III - J.

D. PARALLEL ACTUATOR LINKAGE:
Ref. FIG. 1.6.
- Parallel actuator parallels the pilot's control stick action.
- any movement of C.S. prior to engaging must move the ‖'l actuator plungers.
- Since, after engaging the Autopilot, the ‖'l actuator movements can be felt @ pilot's control stick.
- Means of over-powering ‖'l actuator actuator must be provided for pilot's C.S. when on Autopilot op'n.
- ∴, force limiter valves are built into Servo actuator. Ref III - J.

5. STABILIZER AUTOPILOT:

FIG. 1.7 & 1.11.

A. GENERAL:

1. Purpose:

- Elevator channel of Autopilot must provide all fcns (on Autopilot operation) that pilot would provide on manual operation. Including:
  - a.) pitch C.S.S.
  - b.) pitch damping
  - c.) attitude stabilization
  - d.) altitude control
  - e.) mach control &
  - f.) certain specified bombing fcns.

2. Utilization:

- Damper must be engaged before Autopilot can be engaged.
- Autopilot engaged by placing ENGAGE switch on fcn selector to ENGAGE.
- Elevator channel of Autopilot becomes engaged @ this time providing certain AC & DC sequences have been accomplished. Ref II.
- It is impossible to engage the elevator channel without engaging the aileron channel.

- Engaging Autopilot energizes Servo Engaging Solenoid, which ports Servo Rams to metered pressure from the Moog Valve.
- @ same time, autopilot trim circuits are de-energized.
  - Servo is fully operational @ this point.

- If autopilot is engaged within the limits of ±50° in pitch & within ±60° of wing's level, the vert gyro pitch signal together with the pitch sync signal exactly balances the VG pitch displacement signal, there will be no bumps @ engagement & the a/c will maintain the existing attitude.

- If A/C exceeds ±50° in pitch or ±60° in roll @ moment of engagement, pitch sync & VG pitch displacement signals will not be switched into the Stab Servo Amp; ∴, the autopilot will only provide attitude stabilization thru lagged pitch rate signals
- No fixed attitude will be held.
- The attitude held will depend upon aerodynamic characteristics of the airframe.

B. INPUTS TO THE STABILIZER SERVO AMPLIFIER:

1.) Autopilot Trim:

- Autopilot trim of this channel operates same as the autopilot trim of the aileron channel.
- Prior to engaging, autopilot trim is actuated by the hydraulic unbalance of the Stab Servo, & feeds voltage to Stab Servo Amp to balance inputs of the Amp.
- When the inputs to the Amp are balanced (null or zero) servo hydraulic forces will be balanced & the Autopilot trim switches will return to off (neutral).

- After engaging, autopilot trim is no longer fed to the Stab Servo Amp. Relay K-2A is the relay that cuts out autopilot trim during engaged period.

- During the time that the autopilot trim cRct was operating, the trim switches were acting to place a charge across the (Lag.) condenser (C-11) in the pitch autopilot trim cRct.
- From the pt of autopilot engaged, no additional charge is placed on this condenser
- ∴ this charge gradually discharges to zero.
- As it does, voltage input (which was originally nulled out by the charge on this condenser)

now takes over & produces control surface movement.

2. Pitch Rate.

- pitch rate voltage developed by pitch rate gyro ∝ to rate of pitch attitude change & is of such phase relationship that it will ask for stabilizer surface movement in a direction to reduce rate of pitch displ't to "0".

a) Autopilot Disengaged:
- Pitch rate goes thru lag network & is added to pitch C.S.S. input (which goes thru lead network) prior to engaging.
- These 2 feed into Stab Servo Amp thru another lag network.
- @ instant of engaging, summation of pitch rate & pitch C.S.S. is no longer an input to the Stab Servo Amp.
- This summation will reappear only when pilot actuates pitch C.S.S. or if Autopilot is again disengaged.

b) On control stick steering, summation of C.S.S. & pitch rate again appear as an input to Stab Servo Amp.
- this input combination will call for stab deflection sufficient to maintain pitch rate equal to C.S.S.
- i.e., CSS commands rate of pitch.
- If pilot desires to increase pitch rate, all he needs to do is increase C.S.S. (Remember, C.S.S. is voltage ∝ to press. applied to stick: CSS is not ∝ to stick displ't.)
- In other words, pressure applied to control stick commands pitch rate.

c) Pitch rate (A/S scheduled & mach scheduled, which closely approximates true A/S scheduling) is ~~speed~~ sent thru a lead network, a hi-pass network, & an A/S adjusted lag network to Stab Servo Amp.

- This input is input that calls for surface deflection in a direction to reduce the rate of pitch displ't to zero.
- Hi-pass network blocks any steady state pitch rate which will prevent pitch rate from opposing any steady-state maneuver such as a pull-up on a Labs maneuver.
- Lead network helps to nullify any lags in cct.
- Lag network lags pitch rate input to produce flt path damping.
- Lag network A/S compensated so that @ higher A/S amount of lag is reduced.

3. <u>Pitch Control Stick</u>:
- Prior to engaging autopilot, relay K-11 is energized so that combination of pitch control S.S. & pitch rate are fed into Stabilizer Servo Amp.
- ∵ Autopilot not engaged, only action needed is autopilot trim feedback to cancel this input.
- After engaging, K-11 de-energizes, & pitch C.S.S. no longer an input to Stab Servo Amp.

- When pilot desires to re-position the stab surface (autopilot engaged) movement of pilot's C.S. in pitch axis causes K-11 to be energized & summation of pitch rate + pitch C.S.S is once again fed to stab ~~to~~ Servo Amp.
- Pitch C.S.S. voltage to Stab Servo Amp produces stab surface movement in direction to produce pilot command.
- Pitch Rate will continue to build up until Pitch Rate = & opposite to Pitch C.S.S.
- From this pt on, CSS commanding Pitch Rate Ref 2-6 above.

- On Auto Labs maneuver @ pull-up K-6 energizes which cuts out pitch CSS during Labs maneuver, thru roll-out period;

& until such time as pilot puts Labs Selector switch off of Labs positions.

4. Vertical Gyro Pitch Displ't & Pitch Synchro.

a.) Autopilot Disengaged:

- Prior to engaging autopilot, K-11 is energized, which allows summation of vert gyro pitch displ't & pitch sync to feed to Pitch Sync Amp.
- Pitch Sync Amp & motor comb'n is capable of maintaining summation of V.G. pitch displ't & pitch sync @ zero within limits of ±50° pitch att.
- If pitch att @ moment of engaging Autopilot exceeds ±50°, or if roll attitude exceeds ±60°, relay K-11 will remain energized until A/C attitude is brought within limits spec'd.
- ∴ V.G. pitch displ't is not utilized in pitch axis to stab pitch axis outside of limits spec'd.

- V.G. pitch displ't is also utilized as an input to Labs meter (horizontal needle) on automatic Labs maneuver prior to pull-up.

- V.G. pitch displ't input is characterized to make this input approx = to sine of the pitch ∠.
- This input (pitch displ't + pitch sync.) goes thru some A/S Compensated Lag network as Pitch Rate & C.S.S.
- Lag network helps prevent sudden inputs from producing sudden maneuvers.

b.) Autopilot Engaged:

- @ inst. of engaging Autopilot, K-11 de-energizes if pitch attitude is < ±50° & roll att < ±60°.
- Assuming pitch sync + V.G. pitch Displ't = 0, no bump will be produced upon engagement of autopilot.

c.) Control Stick Steering:

- When CSS mode is activated, K-11 is energized

causing V.G. pitch displ't & pitch sync voltages to be taken away from Stab. Servo Amp & fed to Pitch Sync Amp in same manner as before engaging Autopilot.
- Thus, when C.S.S. is released, a/c attitude (V.G. pitch displ't) will be maintained unless, of course, pitch or roll attitude of a/c is outside of pitch or roll limits specified.

d.) Auto Lobs Maneuver:-
On Auto Lobs Maneuver, from pull-up thru pull-out, summation of V.G. pitch displ't & pitch sync no longer appears as input to Stab Servo Amp & will not appear until such time as pilot goes back to Autopilot NORMAL operation.
- Action produced by K-6 causing Relay K-11 to energize.

e.) Altitude & Mach Control:
On alt & mach control, K-65 energizes & connects summation of V.G. pitch displ't + pitch sync. into Pitch Sync Amp & motor combination.
- Speed of Pitch Sync Amp. & motor comb'n is greatly reduced during these modes of operation.
- This input to Pitch Sync Amp & motor combination slowly trims out V.G. pitch displ't so that when pilot goes off of alt or mach control, a/c will not tend to return to flt attitude it was in prior to going on alt or mach control.
- i.e., Pitch Sync Amp is allowed to slowly assimilate any new flt attitude imposed by the alt or mach controller so that when pilot goes off of alt or mach control, Autopilot will continue to maintain a/c @ same att. the mach or alt controller was maintaining.

5. Up-Stabilizer:
- up-stab pot mech'ly positioned by Bank Sync Amp & motor comb'n to produce up-stab defl'n ∝ to bank ∠ to nullify the effect of loss of lift in a bank.

- Input not utilized if bank ∠ > ± 7½°, unless bank angle produced is created by something other than C.S.S. initiation.
- i.e., input would not be utilized if pilot initiated (thru C.S.S.) a bank ∠.
- If pilot initiates a turn by means of Heading Select knob, this up-stab voltage will produce stab defl'n to help prevent loss of vert. lift in a turn entry.

NOTE: This input is high ~~speed~~ passed, ∴ it cannot aid in a steady state Heading Select turn.
- It is assumed that if const alt is desired, Alt Control should be engaged.
- In other words, this up-stab voltage is only helpful during turn entry of a Heading Select turn.

This input not utilized while on mach control.

6. Stabilizer Servo Feedback:
- Stab. S.F. is compensated by stick pos'n, A/S sched'g, & mach scheduling.
- Stick pos'n scheduling compensates for non-linearity of NAA Control System.

- A/S & mach scheduling produce scheduling approx'g true A/S scheduling.

- This input as well as up-elevator input is hi-passed as an input to Stab Servo Amp to block steady state inputs.

- Hi-pass network acts to block steady state signals so that any error input to Stab Servo Amps will produce continuous movement of Stab Servo until that error has been reduced to zero.

- The hydraulic servo will tend to oscillate @ approx 10 cps with high inertial loads applied.
- Special network shown in Stab Autopilot feedback crct (just prior to hi-pass network) will prevent this oscillation by attenuating frequencies in 10 cps range.

7. <u>Altitude Rate & Altitude Displacement:</u>
- Alt rate = 400 cycle signal & ∴ must be demodulated before it is summed with alt displ't which is a D.C. voltage.
- Sum of these 2 voltages is fed to the input of Stab Servo Amp on Alt Control mode (K-8 & K-8A energized).
- Action of alt rate is to seek for surface defl'n in a direction to nullify any <u>chge</u> in pressure alt.
- The alt rate voltage ∝ to rate of chge in press. alt up to max ≈ 24,000'/min.
- Alt. rate asks for stab surface defl'n in a direction to reduce the alt rate to zero.

- Alt displ't is ∝ to alt press chge up to a max of ≈ 525 feet displ't from control alt.
- As long as alt displ't exists as an input to Stab Servo amp, Stab Servo will continue to move until a/c returns to control alt.
- @ control alt, alt displ't → 0 but Stab Servo may or may not be streamline.
- i.e. due to hi-pass network of Stab Servo feedback, Stab servo has acted to trim a/c so as to maintain a/c @ control alt.

- Alt control input is controlled by a limiting crct to prevent excessive "g" loading.
- This "g" loading = 2 g's max.

- Summation of alt rate (demodulated) & alt displ't is lagged slightly as an input to Stab Servo Amp.
- Lag network helps to prevent bumps created by sudden inputs from these sources.

8. Mach Rate & Mach Displacement:
- Same as alt rate, mach rate must be demodulated.
- Summation of mach rate & mach displ't is fed to Stab Servo Amp thru a lag network when on mach control. (K-12 energized)
- Action of this combination is to maintain mach no constant.
- Action of mach rate is to dampen & prevent mach no from over-shooting.
- Mach displ't acts to pos'n Stab Servo (via Stab Servo Amp) to maintain proper pitch attitude to maintain const. mach no.

- Lag network reduces effect of sudden inputs from mach rate or mach displ't.

9. Normal Accelerometer 4"G" or 1"G":
- On Labs maneuvers @ pull-up, normal accel'r minus 4 G's is fed to Stab Servo Amp thru mach schedule pot & lag network.
- Produces constant "G" pull-up for Labs man's.
- Lag network reduces effect of sudden inputs from normal accel'r minus 4 "G"s.
- i.e., oscillations & vibrations acting on the normal accel'r will not produce surface movement.

- @ pt where Alternate sector switch (in V.G.) closes, K-11L energizes & alters "G" command from 4 "G"s to ≃ 1.2 "G"s.
- Causes A/C to reduce its "G" forces so that it does not get into a buffet zone.
- Buffet zone can be detrimental to airframe.

- @ roll-out, the 1.2 "G" command is switched out by K-7L & a 1 "G" command switched in.
- Action produces no pull-up after roll-out.
- i.e., A/C is allowed to fly nose level.

- This 1 "G" cmd'n will exist until Autopilot is automatically switched to Alt Cont.

- On Labs maneuver, @ pull-up, input to Labs meter (horizontal pointer) becomes summation of normal accelerometer minus 4 "G"s.
- @ alternate release point, it becomes normal accel minus 1.2 "G"s.
- @ roll out, it becomes normal accel minus 1 "G".

10. <u>"G" Droop:</u>
≃ 4.5 secs after pull-up, "G" crct injects a voltage to Pitch Servo Amp to alter the "G" Command ∝ to mach number to take out "G" droop.

C. <u>HYDRAULIC ENGAGE & DISENGAGE MECHANISM.</u>
Ref. § III - J.

D. <u>PARALLEL ACTUATOR LINKAGE:</u> FIG. 1-8.
- parallels pilot's control stick action.
- movement of C.S. prior to engaging moves servo plunger.
- engaged, servo movements can be felt @ C.S.
- means of overpowering ∥ servo provided, if pilot wishes to do so during autopilot operation.
- ∴ force limiter valves built into servo.
Ref Sect <u>III</u> - J.

II. AC & DC SEQUENCES:

AUTOMATIC PILOT:

A. 28V DC ON AIRCRAFT (A/C CIRCUIT BREAKERS "ON"):

1. 28V DC is applied to the following (FIG. 2-1).

a.) Contact of K-21, Negative Monitor to Damper Power Supply. Before K-21 will close, Damper Power Supply must be "on". This channel of 28V DC is eventually used to operate the Time Delay Relay K-30.

b.) Two contacts of K-30. Before contacts will close, Damper Power Supply must be "on" & Thermal Time Delay bi-metal contact must be closed. One contact controls power to Autopilot engaging ccts, other contact controls power to Damper engaging ccts.

c.) K-20 Relay coil, Low Press Cutout Relay. Before relay will energize, a/c hyd. press must be above 1500 psi. Relay prevents engagement of Damper if hyd. press < 1500 psi. Also disengage if hyd press drops below 1500 psi. If Damper not engaged, impossible to engage Autopilot. ∴ this relay prevents engagement of Autopilot as well as Damper, if hyd press is low.

d.) Contact of K-27, Alt. Switch relay closes @ alt (± 20,000') if damper is engaged. Contact controls length of stroke of pitch diff servo to med stroke length. For info re amount of surface movement this stroke length can produce, ref. Table 1.

e.) Contact of K-28, another Alt. switch relay that closes @ alt (± 35,000') if Damper engaged. Controls length of stroke of diff (pitch) servo to a long stroke.

f.) Two contacts of K-3, the ±7.5° bank angle relay. These contacts will be closed when Autopilot is engaged if bank ∠ < ±7.5° of wings level. (2 exceptions)

1.) If C.S.S. engaged, Relay K-3 will not energize until C.S.S. is released, & only if bank angle < ±7.5°

2.) If bank ∠ < ±7.5°, to begin with, & then is caused to xceed ±7.5° due to aero forces or due to heading select maneuver, relay K-3 will remain energized in spite of fact tant ∠ may exceed ±7.5°.

- One contact of relay K-3 is used to energize relay K3-A & K-3B which kills Compass Sync while energized.
- The other contact passes 28VDC thru a contact of Relay K-4 to coil of relay K-10 (Roll C.S.S.). Also 28VDC eventually gets to coil of relay K-11 (Pitch C.S.S.)

g.) Contact of K-7, Autolabs wings level relay. Contact is closed @ pull-up (+4.0-0.0 secs) while on Autolabs maneuver.
- K-7 (& K-6) energized @ pullup on Autolabs to make Roll Sync & Pitch Sync operative. ∴ when pilot returns to Normal Autopilot, autopilot will maintain new attitude.

h.) Contact of K-14, Roll & Pitch CSS Relay. Is energized whenever pilot Xerts force on control stick in either Roll or Pitch direction. Action of contact is to energize relays K-10 & K-11 thus activating Roll & Pitch C.S.S. Mode.

i.) Contact of K-6. Autolabs relay. - energized @ pull-up.
- Ref 2-1, appears K-6 actuates K-11 which initiates Pitch C.S.S. However, ref Fig 1-11, shows K-6 prevents C.S.S. operation. ∴ fcn of K-6 actuating K-11 is to prdce Pitch Sync operation during pull up & roll-out maneuver.

j.) Contact K-10, actuates ECO relay. Opens contact on Roll CSS operation & de-energizes the E.C.O. relay. Whenever E.C.O. relay de-energizes, roll erection to the vert gyro is cut-off, preventing false erection of vert gyro while in turns.

k.) Contact of K-2 & → ECO relay. opens on engagement of autopilot. When this relay energizes, auto trim relay is energized. Auto trim relay energizes auto trim ccts during engaged period. Fcn of Auto trim is to position Stab bungee so that Stab will not move to some other attitude @ instant Autopilot disengaged.

l.) 2 other contacts of K-2, autopilot engage relay. One passes 28VDC to relays K-3 & K-4 that limit Autopilot fcn in Bank & Pitch attitudes. Other passes 28VDC later used to engage Alt. Control or Mach Control.

m.) Contacts on relays K-40 & K-41 of Aileron Solenoid Amp. → utilized to produce Roll Damping.
Relays K-40 & K-41 actuated by Aileron Solenoid Amp which receives its info from Roll Rate Gyro via a hi-pass network. Action of this crct is to by-pass Autopilot system & allow Roll Rate voltage to pulse a/c hyd Ram ~~to~~ dampen high freq. Roll Rates.

B. <u>115ᵛ 400~ on a/c (Autopilot crct breakers "on")</u>:

1. <u>115ᵛ 400~ applied to following (FIG. 2.2)</u>:

a.) To Autopilot Calibrator (BG-38A). From this calibrator, 115ᵛ supply used to energize Autopilot bridge power supply. As soon as Autopilot Bridge Power Supply is operating, Relays K-36 (+ve Monitor) & K-1 (-ve Monitor) are energized within Calibrator, used to energize B+ Power Supply for Autopilot.

b.) From autopilot Calibrator, 115ᵛ 400~ sent to Bank Sync Motor, Pitch Sync Motor, Trim Interrupter, Vert. Gyro Rotor, & Lobe Calibrator.

c.) From Lobe Calibrator 30ᵛ 400~ sent thru Lobe ECO & Yaw rate ECO Relay contacts to Vert Gyro to be utilized as Roll Erection Voltages. 30ᵛ 400~ sent <u>directly</u> to VG for pitch erection.

d.) Autopilot Bridge Power Supply Voltages utilized for Autopilot Bridge Sensing Elements with Xception of those sensing elements used on Damper operation. Ref. to MB-3 Autopilot Syst. Schematic in appendix will indicate damper bridge sensing elements receive their power from Damper Bridge Power Supply.

e.) Autopilot B+ Power Supply provides voltages to Pitch Servo Amp, Ail Servo Amp, Bank Sync Amp, & pitch Sync Amp.

f.) Voltage supplied to Pitch Sync Motor controlled by relays K-65 & K-11.

g.) Same transformers that supplies voltage to Bank & Pitch Sync motors, also supplies power to Autopilot Chopper Coils.

h.) Power to Auto Trim Interrupter Motor controlled by K-2, A/P Engage Relay.

C. 115V 400~ on A/C (Damper Crct Breakers "ON"):

1. 115V applied to: (FIG 2.3).

a.) 115V 400~ to Damper Calibrator (BG-36A).

b.) Within Damper Calibrator 115V 400~ utilized to energize Damper B+ Power Supply, Transformer 27T1. This Power Supply provides voltages to Rudder Servo Amp, Pitch Servo Amp, Signal Characterizing Amp, & Compass Coupler Amplifier.

c.) 27T1 also supplies voltage to compass sync motor, compensator motor, choppers, relay K-37 coil via K-5 contacts.

d.) From Damper Calibrator, 115V sent to Pitch Rate Gyro, to Roll Rate Gyro, & to Yaw Rate Gyro.

D. Damper Power Supply Operative (K-21 & K-35 energized) (Ref FIG 2.4)

1.) When Damper Power Supply becomes operational, K-21 (-ve Monitor) & K-35 (+ve Monitor) are energized allowing 28V DC to pass thru Up Contact of relay K-30. 28V DC thru this contact energizes heating element of K-29, Thermal Time Delay Relay.

2.) After 60±6 secs, Thermal Time Delay bimetal strip (K-29) is actuated. K-29 in turn energizes relay K-30, the Time Delay Control.

Once K-30 becomes energized, pulls contact above Relay coil to down position. This acts as a holding contact to maintain K-30 energized. K-29, the Thermal Time Delay bimetal strip heater is allowed to de-energize.

K-30 controls engaging of Autopilot & Damper crcts. i.e., if K-30 is not energized it is impossible to engage Damper or Autopilot.

E. Relay K-30, Time Delay Control Energized, 28V D.C. applied:
1. To htg element of K-18 via contact of relay K-16.
(Ref. FIG. 2-5A).

Approx 13.5 secs, K-18 closes & applies 28V to Vert Gyro Uncage Solenoid via NAA cage button located on throttle quadrant.

Once VG uncages, 28V goes to relay K-16.

K-16 when energized removes 28V from htr of relay K-18.

K-16 sends 28V onto contacts of relay K-17

NOTE: K-2A, once energized, will bypass K-16 contacts such that V.G. can be caged or uncaged & not cause autopilot to disengage.

NOTE: As long as NAA Gun Sight Missile Switch is ON, it is impossible to cage V.G. with NAA Cage Switch.

K-17, Damper Engaged Relay, energizes when Damper comes engaged. Before Autopilot can be engaged, Damper must be engaged so that K-17 is energized.

Once Damper is engaged, contact of K-17 closes, & passes 28V D.C. to Aileron Anti-engage contact.

If Ail Bridge is balanced, Ail Anti-engage contact will be closed, passing 28V to the Stab Anti-engage contact.

The Stab Anti-eng cont closed if Elev. Bridge is balanced.

For more info on how Ail & El bridges are balanced, Sec I, Autopilot fcns, par. B.1, P.

If ail & Stab Anti-eng conts both closed, 28V DC will pass on to Autopilot Diseng Switch. If Autopilot Diseng switch closed as it should be, power → "G" Limiter Control Relays K-2G, K-4G, K-3G

Under normal op'g conds, "G" Lim Cont Relays are de-en'd (conts open) until after 115V is applied to 'G'-Lim Cal. Then, 'G' Lim control Relays are energized (conts closed) until 'G' forces exceed pre-set limits. (Ref. add. § III-O re adjustments of limits.

If G Lim Conts closed, Power passed on to K-1 (-ve Monitor for Autopilot Bridge Power Supply). K-1 energized if Autopilot Bridge Power Supply ON.
Normally, if K-1 energized, Autopilot Bridge Power Supply is operating, ∴ Relay K-36 (+ve Mon of A/P Bridge Pow. Sup.) should be energized.
With K-1 & K-36 energized, power is applied to Autopilot Eng. Switch. With power to A/P Eng Sw., the A/P is ready to be engaged. ref § G & H.

2. Power from K-30 also applied to A/P Diseng Sw. (FIG 2-6): If A/P Diseng Sw is closed, power passed on G Lim Control Relays K3G, K1G, K2G & K4G. Also to Extend side of Pitch Diff Servo "G" Switch.
K3G, K1G, K2G & K4G closed unless G forces exceed prescribed limits. K1G & K3G control +ve G lims i.e., G of pull up. K2G & K4G cont -ve G (dive).
Pitch Diff Servo G Switch acts to prevent G Lim Relays from diseng'g Damper whenever displ't of Pitch Diff Servo from neutral pos'n is in a dir to reduce G of man being performed. i.e., K-1G & K-3G might open on pull-up man but if Pitch Diff Servo G Sw. is in extend pos'n (down el), then this switch by-passes K-1G & K-3G, preventing them from diseng Damper. Obviously down elev. will reduce G forces of pull-up man. i.e. relieved.
Relays K-1G, K-3G, K-4G & K-2G closed, or by-passed by Pitch Diff Servo G Switch, Power passed to ½ of Damper Eng Sw & to contact of K-20, the L/P relay.
K-20 energize off 28V DC bus if A/C Hyd Press > 1500 LB.
K-20 energized, power → other half of Damper Eng Sw.

F. Damper Engage Switch ON (FIG 2-6) 28V Applied to:
1. Holding Solenoid of Damper Eng. Switch.
2. To coil of K-17 (Damp Eng Relay). K-17 controls power to Yaw C.S.G. Relay, Y/P Diff Servo Valve Sol, & the Eng of A/P. For complete A/P DC flow dia FIGS 2-5A, 2-6 & 2-7.

3. To Altitude Switch. @ ≈ 20,000', alt switch eng's K-27. Eng'g K-27 closes a contact that passes 28VDC to Stab Med Stroke Sol. (FIG 2-7). Eng'g this sol. limits Stab Damper Servo to med lims of control. Prior to energizing relay, Stab Damp Servo, if eng'd, had Short Stroke Limits imposed upon it.
4. @ ≈ 35,000', K-28 energized. Energizing this relay passes 28VDC to Stab Long Stroke Sol. (FIG 2-7). Energ'g this Sol opens Stroke Lims of Stab Damper Servo to its max lims.
5. Second ½ of Damp Eng Sw (FIG 2-6) passes current to contact of K-17. K-17 energ'd ∴ cont closed & power is passed to Y/P Diff Servo Valve Sol. Energizing this valve will allow hyd press to be applied to Pitch & Yaw Diff Servos.
6. Power to K-5 (Yaw C.S.S. relay) from K-17. Relay cont does not energize K-5 unless Bungee Switch is closed. (FIG 2-7) by pilot applying press to one of his rudder pedals. Applying press to rudder pedal will mech'y close Bungee Switch.
7. Effect of K-17 Relay Cont on A/P eng process was discussed in ¶ E-1.
8. Damper Syst (Yaw & Pitch) completely eng'd.

G. <u>Autopilot Engage Switch ON - 28VDC applied to</u>:
1. A/P Eng Switch holding sol'd (FIG 2-5). Holding Sol will hold A/P Eng Sw in ON pos'n.
2. K-2, A/P Eng Relay, & K-2A A/P Aux Eng Relay (FIG 2-5). K-2 controls fcns of 28V D.C. & K-2A controls fcns in A/P bridges.
   K-2 energized closed a contact shown in FIG 2-5 that by-passes aileron & stab anti-eng switches. Once these switches are by-passed by K-2, during the engage period, any unbalance of ail or el bridges may open anti-eng switches but will not cause A/P to diseng. Another contact of K-2 (FIG 2-5) passes power from A/P eng sw, closed, to stab & ail servo eng sols.

H. Relay K-2, Autopilot Engage, Energized 28VDC to:

1. Ail & Stab ll'l servo engage solenoids (FIG 2-5). Sols allow hyd press to be applied to ail & el servo eng sols. ∴ servos engaged.

2. to ±7½° Roll Switch on bank sync motor (FIG 2-8) Bank sync, Sect 1, A/P fcn, keeps in step with VG Roll Displ't. Positioning of Bank sync posn's ±7½° Roll Sw. If A/C is within 7½° of wings level switch should be closed. ∴ power is passed to K-3, ±7½° Bank Relay. Ground return for this relay is thru conts of K-10 & the J-4 Compass Slew Relay & Hdg Eng Sw. (FIG 2-8)
   - Assuming A/P engaged, wings within ±7½° of level, & C.S.S. off, K-10 de-energ'd. Thus ground return to
   - K-3 completed thru contacts of K-10.
   J-4 Comp Slew Relay normally closed Xcept when slewing the J-4 Comp syst. (rely K-2002 in J-4 syst.)
   - Head Hold Sw on fcn selector. When pilot desires to utilize head hold mode of A/P switch would be in closed pos'n. (FIG 2-8).
   - K-10 closed, slew relay closed, & Head Hold Sw closed, K-3 will have a ground. Now K-3 can energize from 28V coming thru 7½° roll sw.
   - Energizing K-3 affects many crcts.
   - One contact of K-3 causes K-3A & K-3B to energize. (FIG 2-7) another controls compass input to A/P, & another turns compass sync on or off. another places bypass around 7½° roll sw as long as K-3 energ'd.

3. K-14, C.S.S. Slow Release Relay. Before this relay can be energized, pilot must apply force on his stick in either pitch or roll axes. Energizing K-14 closes contact (FIG 2-9) that bypasses conts of K-3 & K-4 which serves to energize K-10. Also energizes K-11, providing K-65 (Mach or Alt Relay) is de-energized & providing A/P is not on Autolabs maneuver.

- Once K-14 becomes energized, resistor condenser network (FIG 2-8) charges. When stick force switches open, the discharge of this network maintains K-14 energized for approx 0.4 secs. "Slow Release".
- Energizing K-10 introduces Bank sync op'n. Energizing K-11 introduces Pitch sync op'n.
NOTE: K-16, when de-en, causes K-14 to en. This action puts A/P into C.S.S. fcn while V.G. is caged.

4. ±60° Roll Sw. in Bank sync. This switch will be closed if bank ∠ is less than 60° from wings level. With this switch closed, power is passed to Relay K-4, the ±60° Bank Relay. The gnd return for K-4 is thru the V.G. ±50° Pitch att. sw. This switch is pos'd by the V.G. & is closed within limits of ±50° of nose level.
   - With ±60° Roll sw. & ±50° Pitch sw. closed, K-4 will be energized, if A/P is eng'd.
   - K-4 energized, contact (FIG 2-9) is opened that cuts out Roll & Pitch C.S.S. Relays K-10 & K-11, if A/P is eng'd.
5. To contact of K-4 (FIG 2-10). If conds prev'ly descr'd exist, K-4 energized, ∴ contact in FIG 2-10 closed. Power then passed thru contact of K-6 (normally closed xcept during pull-up & roll-out on Lobs). With K-6 closed, power is passed to alt & Mach Cont. Sw.
   - Impossible to engage Mach Control & Alt Cont @ same time. Fcn of K-15, Alt & Mach Slow Release Relay, is to prevent switching from Alt Control to Mach Control without first allowing ≈ 3 secs delay between the 2 fcns.
   - K-65 energized on either Mach or Alt Control. The fcn of this relay prevents energizing of the Pitch C.S.S. & it allows the operation of Pitch Sync during Mach or Alt Control Operation.

Note FIG 2-10 ground return for Mach-Alt Hold Sol is thru a Mach Switch. Between the Mach numbers of ≈ 0.96 to 1.04. switch is open. This means that it is impossible for the Mach or Alt Controls to become engaged within this range of Mach No's or to remain eng'd within that range.

6. To Auto trim (A/T) (FIG. 2-11) Engaging A/T Relay energizes the A/T ccts & produces an A/T fcn such that stab is trimmed mechanically to hold the att of the a/c @ same ~~time~~ position the A/P has the a/c. i.e., if A/T ccts fcn, when the pilot switches from A/P operation to Manual Control, the a/c should continue to hold the same Pitch att.
7. When K-2 energizes, only path for 28V D.C. to the ECO Relay (K-9) is thru closed contact of Relay K-10. (FIG 2-11). E.C.O. Relay is energized at all times Xcept during C.S.S. or when Yaw rate xceeds 0.53°/sec. At 0.53°/sec, ECO switch opens, de-en. K-9. On C.S.S., K-14 is energized which in turn energizes K-10. which turns off K-9. ∴ in turns or on CSS the ECO Relay K-9 de-ens & turns off roll erection to the V.G.
   - The reason for cutting off Roll Erection during CSS or turns is to prevent false erection of VG in the direction of the turn due to the mercury in the Merc sw's being thrown outboard to the turn by cent. force.

AUTOMATIC TRIM (FIG. 2-12):

A. 28V D.C. on a/c, ail-stab trim cct bkr ON.
   1: Ref Fig. 2-11: as long as A/P Eng. Relay (K-2) is de-en, auto trim is off. Ref FIG. 2-12: as long as A/T is off, 28V D.C. from ail-stab trim cct bkr passes ~~thru~~ to pilot's manual trim button located on pilot's c.s. By manually actuating this trim button, it is possible to energize

nose-up or nose down field windings to the trim actuator motor. It will also be noted that action of Trim Impulse Relay prevents the energizing of Up & Down Field Windings sim'y
- When A/P engaged, (FIG 2-11) shows that A/T relay is energized, (FIG 2-12) shows that pilot's manual trim button has no control over the Trim Actuator.

B. 28V on a/c A/P A/T Cict Bkr ON.
1. FIG. 2-12 shows that with A/P trim crt bkr ON & the auto Trim relay energized the pilot's manual trim button has no control over the Trim Act. motor.
2. Power thru A/T relay conts is applied to a/c trim switch in stab servo. It is applied to this switch via contacts of K-10 & K-6.
   - Fcn of K-10 is to prevent A/T while on C.S.S.
   - Fcn of K-6 is to engage Auto trim when on a Labs pull-up manoeuver.
   - Action of a/c trim switches located in the Stab servo is to energize a nose-up or nose-down relay. These 2 relays can never be energized simultaneously. Energizing one of these relays allows power to pass from the Trim Interrupter Conts to Trim Actuator.
3. Fcn of Trim Interrupter is slow down A/T fcn. If A/T fcn is allowed to operate ~~continuously~~ continuously without interruption, it may over-trim or trim to rapidly.
   - The centrifugal switch in Trim Interrupter is a safety feature to insure that power is available for driving the trim actuator even if the trim Interrupter motor is stalled. It is conceivable that without the cent sw, the Trim Int. motor could stall in a pos'n where the Trim Int Conts are open. This would prevent any Trim Act. motor operation on Auto Trim.

4. Trim Impulse Solenoid Valve:

The purpose of these 2 trim impulse sol valves is to produce a lead in the trim fcn. These valves are built ~~$~~ into NAA actuator such that a small amount of trim (in direction of needed or commanded trim) is introduced by these valves.

5. Trim Impulse Relay:

Relay helps to prevent energizing of trim actuator in both field windings at once.

SECTION III

ADDENDUM

A. BRIDGE POWER SUPPLY: (FIG 3-A-1)

- Simplified diag of Damper & A/P bridge power supplies. They are identical in theory of operation.
- Rectifiers are Selenium, connected in push pull to give full wave rectification. This helps filtering.
- Filter network is a choke input - provides better regulation than a condenser input filter.
- +ve & -ve monitoring relays are energized by current from +ve & -ve sides of power supplies resp'y. Any failure of power supply will cause one or both of the monitoring relays to de-energize.
- De-energizing one or both of the Damper Bridge power supply monitor relays (K-1, K-36) will disengage and/or prevent engagement of A/P.
- De-energizing one or both of Damper Bridge power supply monitor relays (K-21, K-35) will disengage &/or eng. of both A/P & Damper
- The A/P Bridge power supply provides power for:

Aileron:

1. Aileron servo feedback pot.
2. Roll CSS pot
3. Direct Gyro roll pot
4. Direct Gyro yaw pot
5. Roll out pulse
6. Aileron bridge center pot.
7. Vert. Gyro roll displ't pot.
8. Bank sync. follow-up pot.

Elevator:

11. Stabilizer servo feedback pot
12. Pitch CSS.

13. Pitch rate pot.
14. Vert gyro-pitch displ't pot.
15. Pitch sync. pot.
16. A/P Trim switch
17. Mach Displ't pot.
18. Altitude Displ't pot.
19. Normal accelerometer pot
20. Two +ve accel command pots
21. "G" Droop pots.

Bias:

22. +ve voltage to all filaments in plug-in amplifiers.
23. -ve Bias to all discrimiter plug-in amps.

The Damper Bridge power supply provides power for the following:

Stabilizer:

1. Pitch damper servo feedback pot.
2. Stick position pot.
3. Pitch Rate pot.

Rudder:

4. Rudder servo feedback pot.
5. Yaw rate pot.
6. Two Aileron position pots
7. Roll rate pot
8. Rudder Trim pot
9. Lateral accel pot.

Bias:

10. +ve voltage to all filaments in plug-in amps.
11. -ve bias to all discriminator in plug-in amps.

"G"-Limiter Bias:

12. Bias (+ve & -ve).

- The theory of operation of this power supply is not different than the other power supply.
- The output of each supply should be a total of 100ᵛ ± 7ᵛ. Diff'l should not Xceed 3ᵛ. i.e., +50 & -47 (not +50, -46). Output of power supply can be adjusted by moving the tap on the input to the transformer.

- Load resistance to A/P power supply (measured end to end) ≃ 570 Ω.
- Load resistance to Damper power supply (") ≃ 700 Ω.

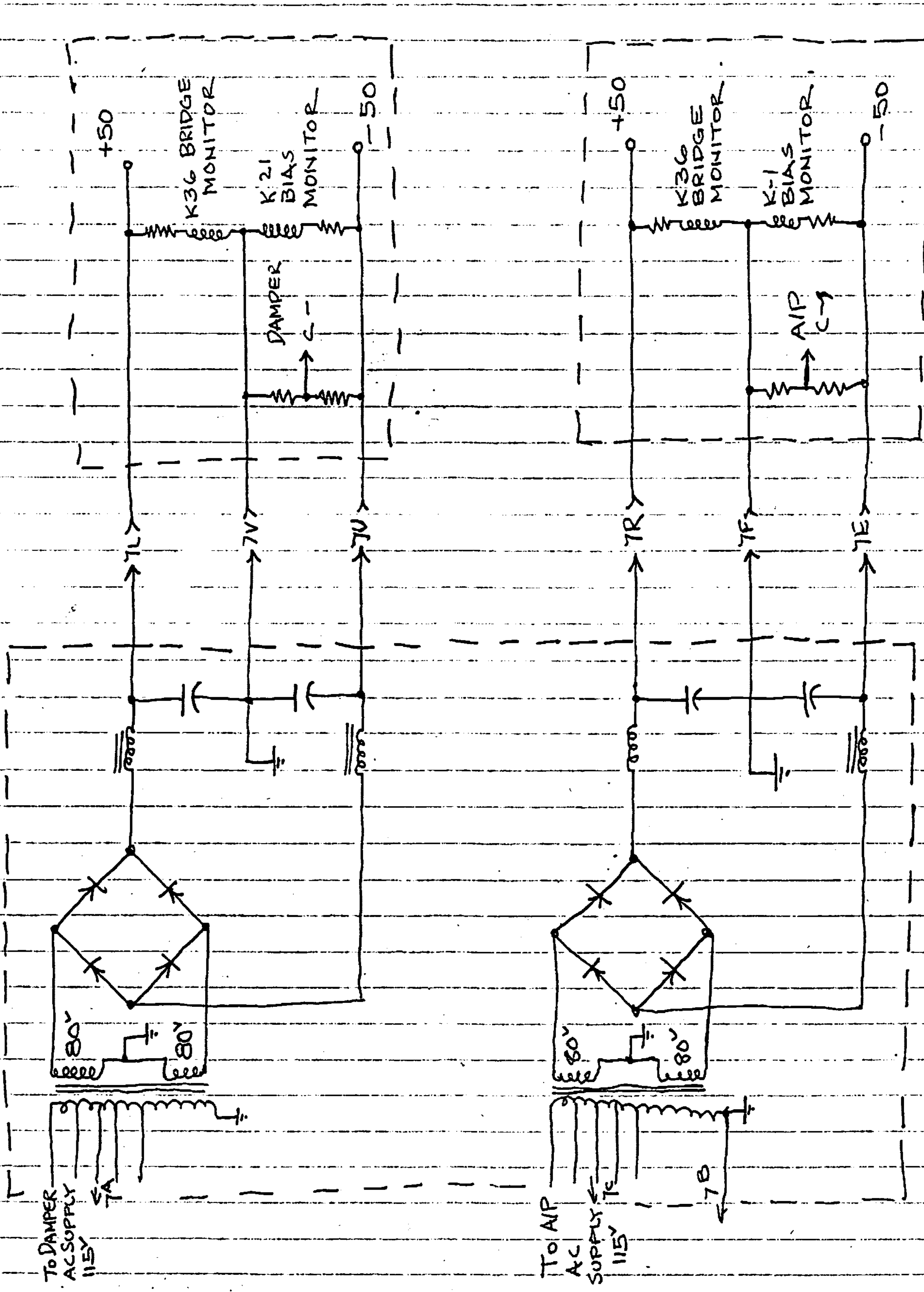


FIG. 3-A-1
BRIDGE SUPPLY AND MONITOR.

B. DC BRIDGE AND PARALLEL SUMMING:

GENERAL:

- Various amp input signals from the gyro and other pickoffs may be either series summed or parallel summed. Each method has certain adv's & disadv's. A Series Summing crct is quite susceptible to hardover signals produced by open circuits, or complete loss of all control in the case of certain specific locations of open crcts. Difficulty is not present with ||'l summing, however there is some attenuation of input signals.
- MB-3A/P uses ||'l summing cuy:

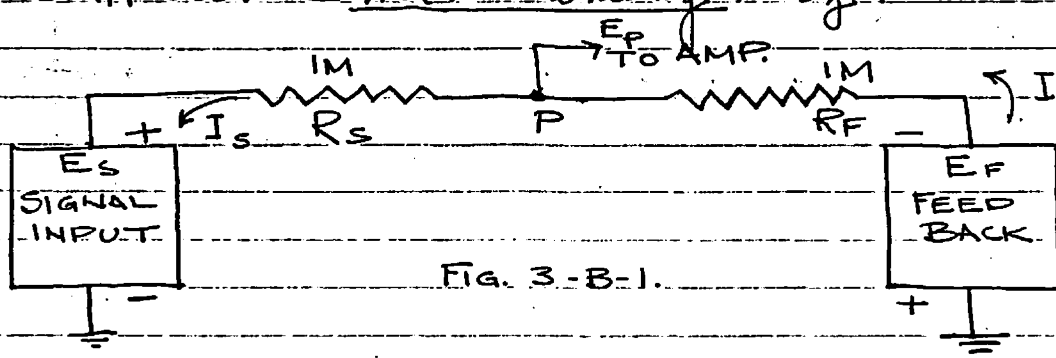


FIG. 3-B-1.

- Signal input to voltage point 'P' & feedback to P. P tied to amplifier & motor comb. Feedback pot driven by motor ~~to~~ in correct direction & proper amount to null out amp. input.
- Impedance of Signal Source is low in comp to R_s, & feedback impedance is low c.f. R_f, ∴ assume 0. Their effect is very small.
- Assume: Signal Input is +ve & Feedback is −ve w.r.t gnd. @ balance, input to amplifier = 0. Let us analyze the prob. to find what the input to the amp is:
- Electron flow → +ve, currents as in 3-B-1.

1.) $I_S = \left(\frac{E_S - E_P}{R_S}\right)$ & $I_f = \left(\frac{E_P - E_f}{R_f}\right)$

at balance, $I_S = I_f$, so

2.) $\left(\frac{E_s - E_P}{R_s}\right) = \left(\frac{E_P - E_f}{R_f}\right)$ @ balance.

3.) or $\left(\frac{E_s}{R_s} - \frac{E_P}{R_s}\right) = \left(\frac{E_P}{R_f} - \frac{E_f}{R_f}\right)$

4.) or $\left(\frac{E_s}{R_s} + \frac{E_f}{R_f}\right) = \left(\frac{E_P}{R_s} + \frac{E_P}{R_f}\right) = E_P\left(\frac{1}{R_s} + \frac{1}{R_f}\right)$

But $\frac{1}{R_s} + \frac{1}{R_f}$ is general form for formula for the reciprocal for // resistance. Let R_P = // resist.

5) Then $\frac{1}{R_s} + \frac{1}{R_f} = \frac{1}{R_P}$.

∴ from 4 & 5,

6) $\frac{E_s}{R_s} + \frac{E_f}{R_f} = E_P\left(\frac{1}{R_P}\right)$

Now, E_P ≙ input voltage to the amplifier. From 6,

7.) $E_P = R_P\left(\frac{E_s}{R_s} + \frac{E_f}{R_f}\right)$.

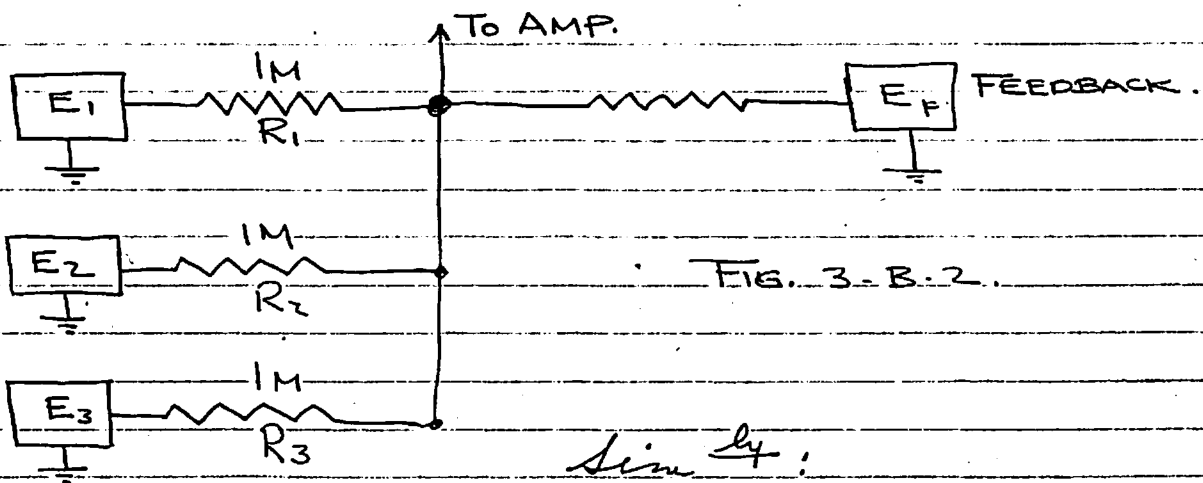


FIG. 3-B-2.

Sim'ly:

8.) $E_P = R_P\left(\frac{E_1}{R_1} + \frac{E_2}{R_2} + \frac{E_3}{R_3} + \ldots + \frac{E_f}{R_f}\right)$

R_P ≙ eq. resistance $R_1, R_2, R_3 \cdots R_f$ in //.

E_P ≙ input voltage to Amplifier.

This analysis is far from complete.

N.B. ① Size of the series dropping resistor for any one signal input does have a direct bearing on the inputs from the other signal input sources. If the size of any one dropping resistor is changed, it <u>does</u> materially affect all signal inputs.

(2) It is obvious from 8, that all signal inputs are reduced by the ratio of the total ‖ resistance to the series dropping resistor.

In some instances in MB-3 A/P, an additional resistor is connected from summing point P directly to ground. When this resistance is small c.f. to any of the summing resistors, its value may be taken as R_p, cuz its value will be the chief determining factor in the comp. of R_p.

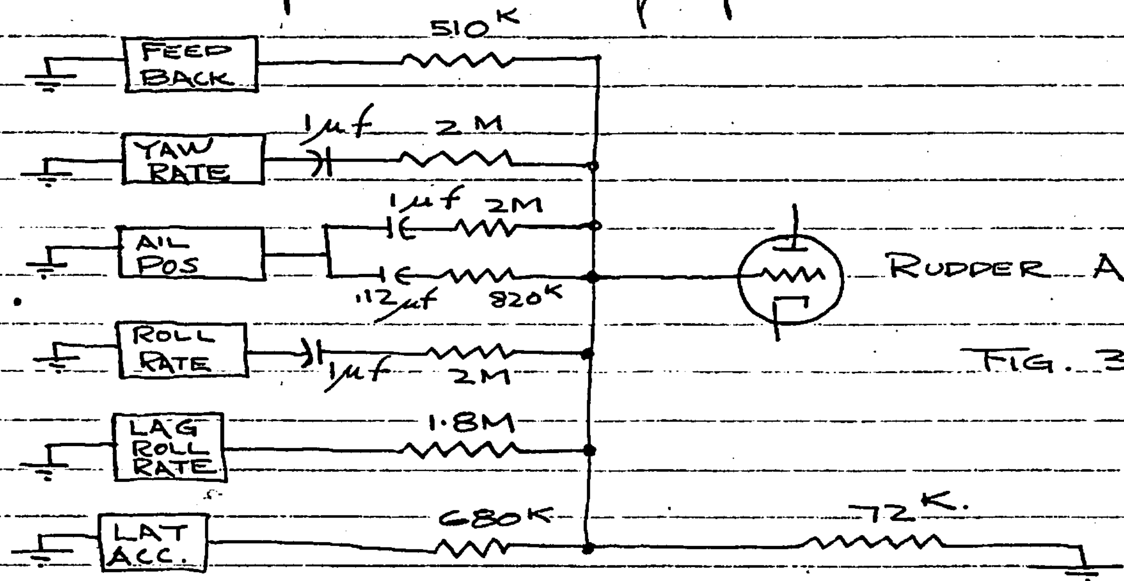


FIG. 3-B-3.

Ex. - Assume +10ᵛ from lagged roll rate, −2ᵛ from lat accel. R_p is ‖ resist = 72K, 680K, 1.8M, & 510K.

$\therefore R_p \doteq 56^K$.

$$\therefore E_p = 56{,}000\left(\frac{10}{1{,}800{,}000} - \frac{2}{680{,}000}\right)$$

$$= 56\left(\frac{1}{180} - \frac{1}{340}\right)$$

$$= \frac{56}{180} - \frac{56}{340}$$

$$= .31 - .165 = +.145^V$$

Effect of +10ᵛ from Lagged Roll Rate alone is:

$$E_p = 56000\left(\frac{10}{1{,}810{,}000}\right) = .31^V.$$

Feedback voltage req'd to balance 2 inputs would be given by:

$$\frac{E_f}{510{,}000} = \frac{10}{1{,}800{,}000} - \frac{2}{680{,}000}$$

$$\frac{E_f}{510} = \frac{1}{180} - \frac{1}{340}$$

$$E_f = \frac{510}{180} - \frac{510}{340}$$

$$= 2.8 - 1.5$$

$$= +1.3^v$$

TYPICAL D.C. BRIDGE:

A typical signal input source is:

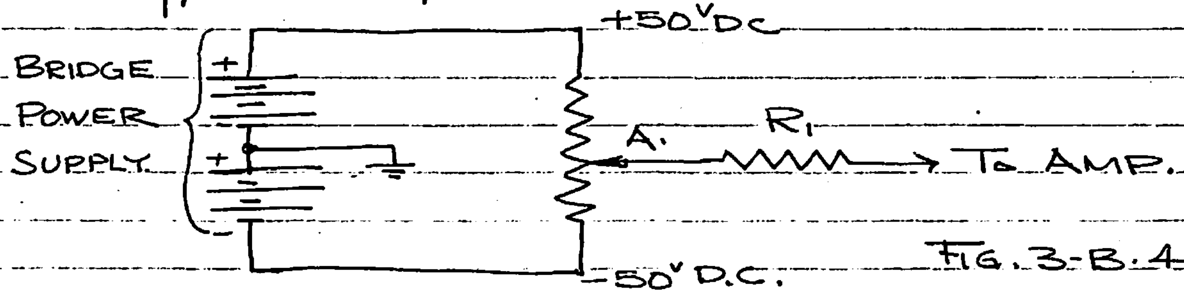


FIG. 3-B.4.

- Pot & wiper shown in FIG 3.B.4 could be any of several signal input sources in the control system. As long as the wiper is in centre, the pot @ A in resp. to gnd = 0. If wiper is moved off centre upwards, output is +ve w.r.t. gnd. with max ±50^v. Sim'ly ↓ -ve, -50^v max.
- Impedance of pot & wiper system is usually small in comparison to impedance of series dropping resistor R_1 & is usually ignored in most calcs.
- Polarity of signal source determines direction of A/P Servo movement. As A/P Servo moves, wiper on feedback pot moves. (FIG. 3.B.5.). When summation of signal source & feedback @ amp = 0, servo stops. If sensing device returns to centre (zero), the amp will make Servo drive feedback wiper to centre (0). Only time the amp is satisfied is when its input is zero.

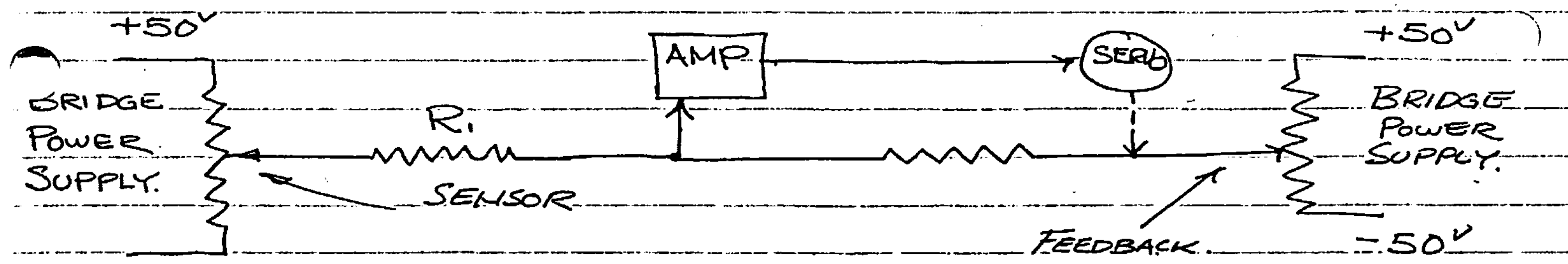


FIG. 3-B-5.

HI-PASS NETWORK:

- Sometimes it is advantageous to trim an air foil until it is aerodynamically stable so that it will hold a certain attitude. By placing a condenser (C_1) FIG. 3.B.6. in the feedback line, we can accomplish a trimming action.
- As long as feedback wiper is moving, the condenser is charging, & thus feedback tends to null the amplifier input. If the servo stops, the condenser soon stops charging. Then the only thing the amplifier sees is the signal from the sensing device (vertical gyro roll displacement in FIG. 3-B-6)

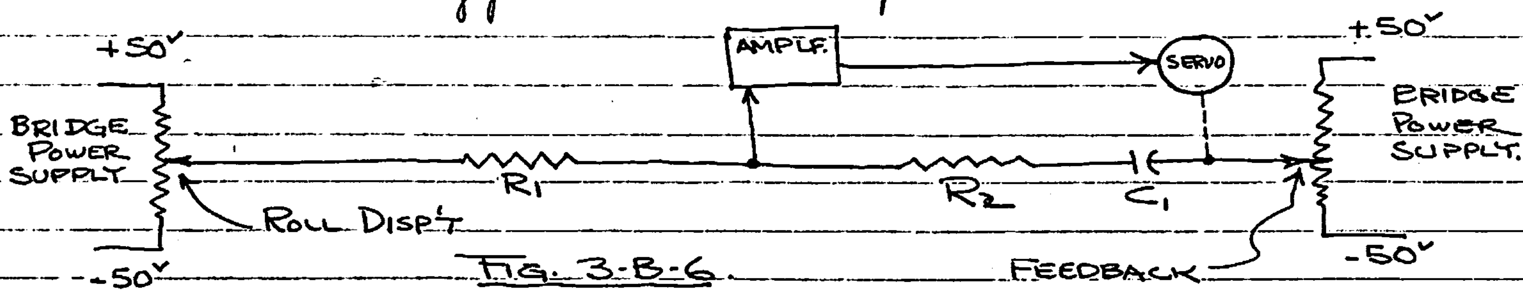


FIG. 3-B-6.

- As long as the amp. has any input @ all, the servo will cont to run. When input from VG roll disp. → 0, servo stops driving & condenser stops chging. Servo stops @ any position within its extremes.
- Should roll displ't ever change, servo pos'n will again be chged to by roll displ't back again to null posi'n
- Condenser shown is "High pass network".

LAG NETWORKS:

- Sometimes it is necessary to filter signal inputs to prevent lash, noise, & abrupt manoeuvres from over controlling a/c or from causing instability of a/c. FIG. 3.B.7 shows typical resistor and condenser network (C_1 & R_1) that filters these undesired inputs. "Lag network"

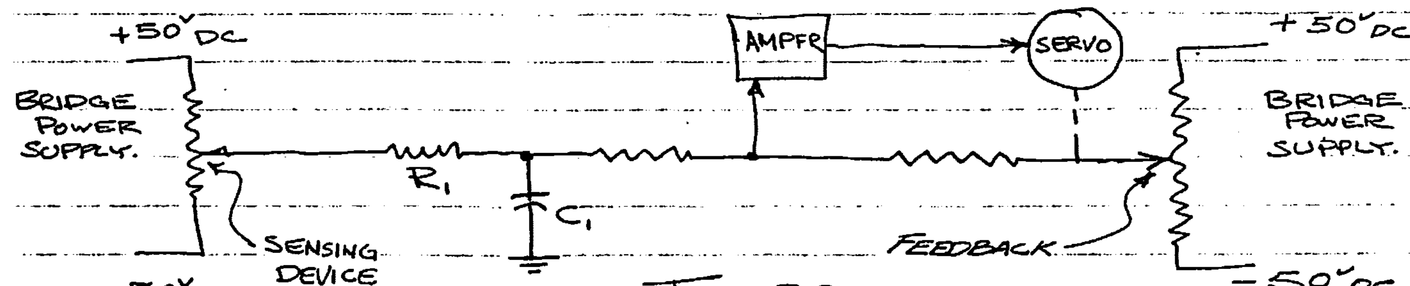


FIG. 3B.7.

LEAD NETWORKS:

- Sometimes necessary to lead certain inputs to take care of cert. lags. Typical lead network (C_1, R_1, R_2) FIG. 3-B-8. Lead networks tends to lead high frequencies more than low freq's.

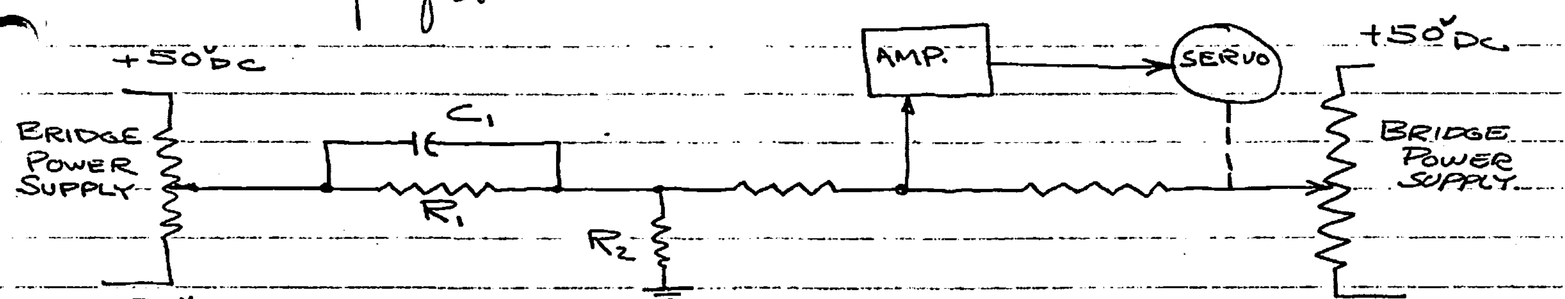


FIG. 3-B-8.

RATIO ADJUSTS:

- Sensing device designed so that it can be utilized in many systems. ∴ to make sensing device fit specific a/c syst, often necessary to modify max output of sensing device with adjment ref'd to as "ratio adjustment." FIG. 3-B-9.

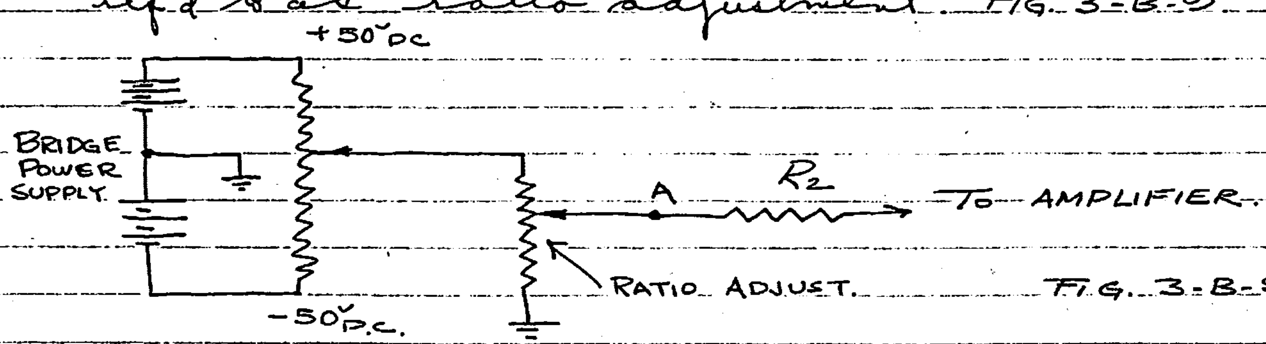


FIG. 3-B-9.

with ratio adjust @ centre, max output @ point "A" is 25V. Sensing device may have 50V output, but ratio adj will reduce this by 50% if it is set @ centre.

- ∵ input to amp. ulty cancelled by servo feedback voltage, it is obvious that the setting of this ratio adj determines amount the control surface must move before input to amp nulled. Thus, adj is appropriately named, "RATIO ADJ." for it literally controls ratio of control surface movement to sensing device movement.

<u>Rule of Thumb</u> "Turning ratio adjustment clockwise always produces a greater ratio, thus greater control surface movement."

AIRSPEED AND MACH SCHEDULING:

- Once max output of sensing device has been set with a hand adjusted ratio pot, it is sometimes necessary to further modify the max output of a sensing device to make it more nearly follow the aero char's of the airframe @ all airspeeds &/or M no's.
- Type of A/S scheduling used in this A/P syst varies as diff between dyn. & static pressures.
- Whenever A/S & M sched are both used on same output, it produces sched'g that closely simulates true A/S sched'g.
- A/S or M sched'g pot is connected just like the ratio pot of FIG. 3-B-9. Only diff being, the wiper on the pot is automatically adjusted by the A/S or M control device.

C. LEAD, LAG, and HI-PASS NETWORKS:

- R-C networks are found in many of the signal input paths to the amplifiers. They are also shown as separate blocks on the block diagrams of the diff'l A/P & D channels.
- a channel of the A/P with its signal inputs, its amplifiers, motor & feedback circuit, constitutes a servomechanism. An A/P servomech operates a/c control surfaces in response to signals from gyros & other signal sources which sense a/c attitude, rate of attitude change, & other flight parameters. This remote control of the a/c involves in many cases a long change of electrical & mech'l crct units. Ex, a/c yaw rate is first sensed by mech'l part of rate gyro, leaves the rate gyro as an electrical signal, passes thru a hi-pass network, is amp'd, drives electrical torque motor in a hydraulic actuator, is converted to mech'l motion of actuator shaft, operates a/c power actuator unit, moves surface in response to which a/c corrects yawing condition. Each of the links may add a small amount of lag or delay. The delays may be small, but the total sum may be large. Such delays may make the A/P-a/c combination unstable. Yaw rate signal is able to damp a/c oscillations cuz of its 90° phase lead w.r.t yaw displ't signal. If now, due to lags in control mechanism, rate signal is delayed by an amount $\geq 90°$, it will no longer be able to damp oscillations and may even increase oscillation tendencies. It becomes necessary, ∴, to compensate for these lags to make the A/P & a/c stable for all signal inputs ∴ Lead network req'd.

Circuit for lead network:

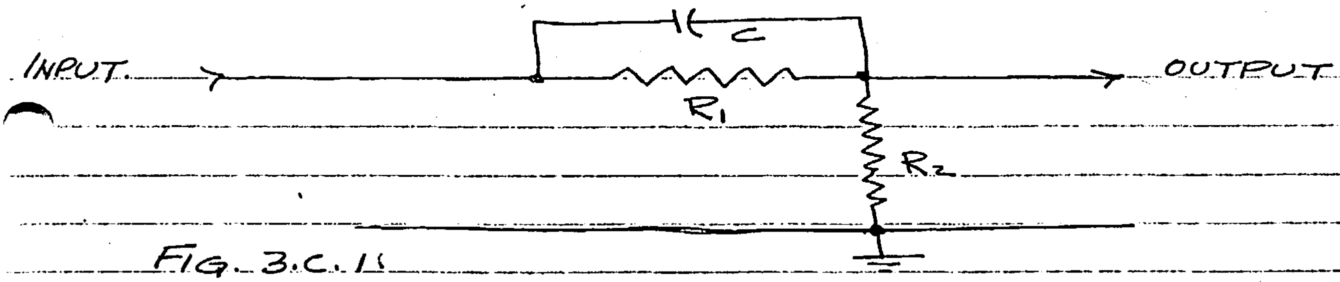


FIG. 3.C.1

- Input; slowly varying D.C. as the error signals fcn.
- Output; taken from voltage drop across R_2.
- Current flowing from R_1 is in phase with input as this path contains only resistance. Current thru condenser will be leading. Ex, current flow into a condenser is a max when voltage across it = 0. When condenser becomes fully charged, current is zero as no more charge enters condenser. Current into condenser i reaches its peak 90° before v reaches it peak. i.e., current thru condenser leads applied voltage by 90°. If there is a resistor in series with condenser, the current still leads applied voltage but by lesser amount than 90°.
∴ R_2 is supplied with in phase current from R_1 & with leading i from C, net current thru R_2 will lead applied voltage by an amount that depends on the relative amount of current supplied by C as compared to amount supplied by R_1. Adj't of sizes of R_1 & C will also then adjust amount of lead provided to input signal.
- Block dia of § I refers to lead network as:

$$\frac{T_1S+1}{T_2S+1} \quad \text{for } T_2 < T_1$$

This can also be expressed as:

$$\frac{T_1S+1}{T_1S+A} \quad \text{where}$$

$$\frac{T_1S+1}{T_1S+A} = \frac{1}{A}\left(\frac{T_1S+1}{T_2S+1}\right) \qquad \text{i.e., } T_2 = T_1/A$$

In second form, T_1 is the time constant $= R_1C$. expressed in seconds

$$A = \frac{R_1+R_2}{R_2}.$$

- When slowly varying D.C. is applied to this network, the output is affected in both ampl't & phase.
- amount of phase & amp change ∝ of freq of input.
(Input is D.C., but a regular variation of a/c attitude such as an oscillation produces the effect of a very low freq. a.c. input)
- FIG. 3.C.2, illustrates φ & ampl. response of a typical lead network. Upper trace shows amount of phase lead & lower trace shows amp. reduction (output over input). Absciss is frequency axis & is plotted in radians. To convert to c.p.s. divide by 2π. Note that at 0 freq. (steady state D.C. input) output is reduced to 0.2 because of the voltage divider action of R_1 & R_2. Also, @ φ=0, there is no phase lead. At f of 3 rad (≈ ½ cps) phase lead is ≈ 40° & amp. has risen to ≈ .32. Beyond 4 or 5 rads, lead ∠ begins to decrease.
- We are concerned, however, only with low freq (2-6 rads/sec) the phase lead remains between 35°-45°. If other values of C, R_1 & R_2 were chosen, diff't freq response curves would result.
- ∴ in many cases a control syst is unstable over only a small freq. range, values of C, R_1 & R_2 can be chosen to provide compensating lead over that range & thus stabilize the system.
- In general, whenever one of these lead networks is noted in the schematic dia, it may be assumed that it is compensating for lags elsewhere in the cont. syst & is increasing the stab. of syst over the req'd freq range.
- <u>DISADVANTAGE</u>: of lead network: passes high f more readily than low freq's, & thus decreases the signal to noise ratio. This is becuz the noise freq's are usually in higher ranges, while signal freq's are in the lower range. For this reason, a lag network is @ times used for compensation in preference to a lead network.

The lag network:

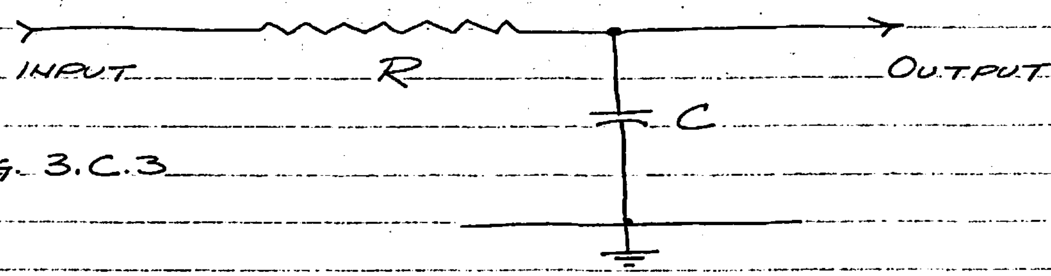
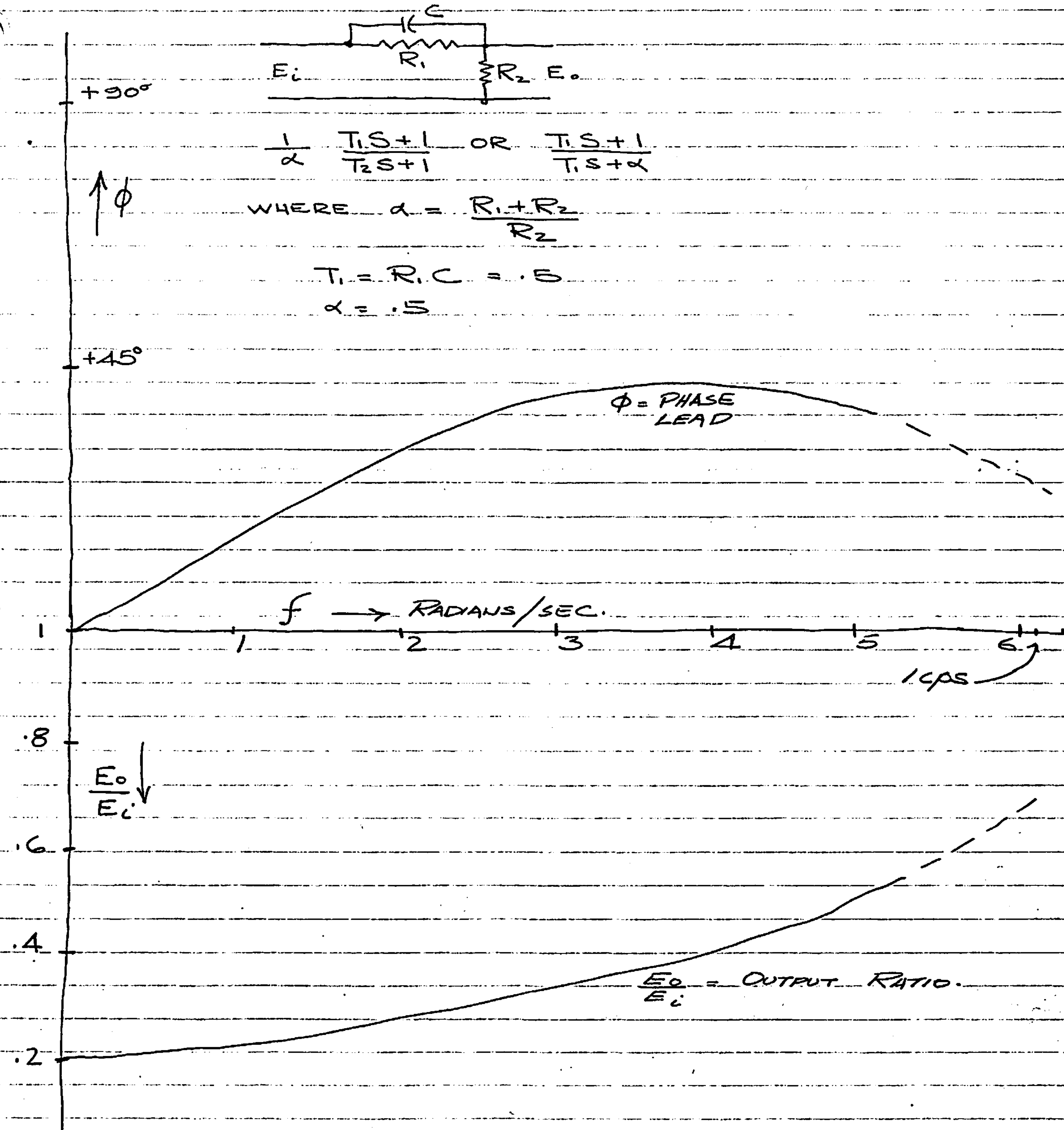


FIG. 3.C.3

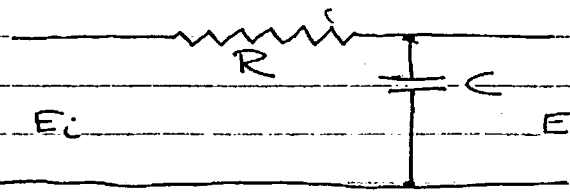
- Lags or delays the output wrt input.
- This may be deduced by the form of the above network. Output is taken from the voltage across the condenser. When an input is applied, it takes a certain time to charge the condenser thru the resistor R. This produces a time or phase lag in the output signal. Amp. is also affected.

- FIG. 3.C.4 sketch of amplitude & phase response @ various input f's. Solid line, indicating amplitude response, shows that @ 0 frequency (steady D.C.) the gain is 1. There is no loss in the network as the condenser acts as an open crct to D.C. voltage. As the freq increases, the amp of the output decreases as the condenser does not have time to completely charge or discharge during a cycle.
- Phase response curve (dashed line) shows that phase lag increases with frequency, at 3 rads/sec. (½ c.p.s.) the phase lag is 70°. As f increases, the amplitude of the output decreases rapidly and the phase lag increases, gradually approaching 90°. This sketch was drawn for an assumed time const of 1 (i.e., RC = 1). Increasing the value of this time constant will increase the phase lag at all frequencies.
- Although this is a lag network rather than a lead network, it can be used in some cases to compensate for system lags. Often the control system tends to be unstable



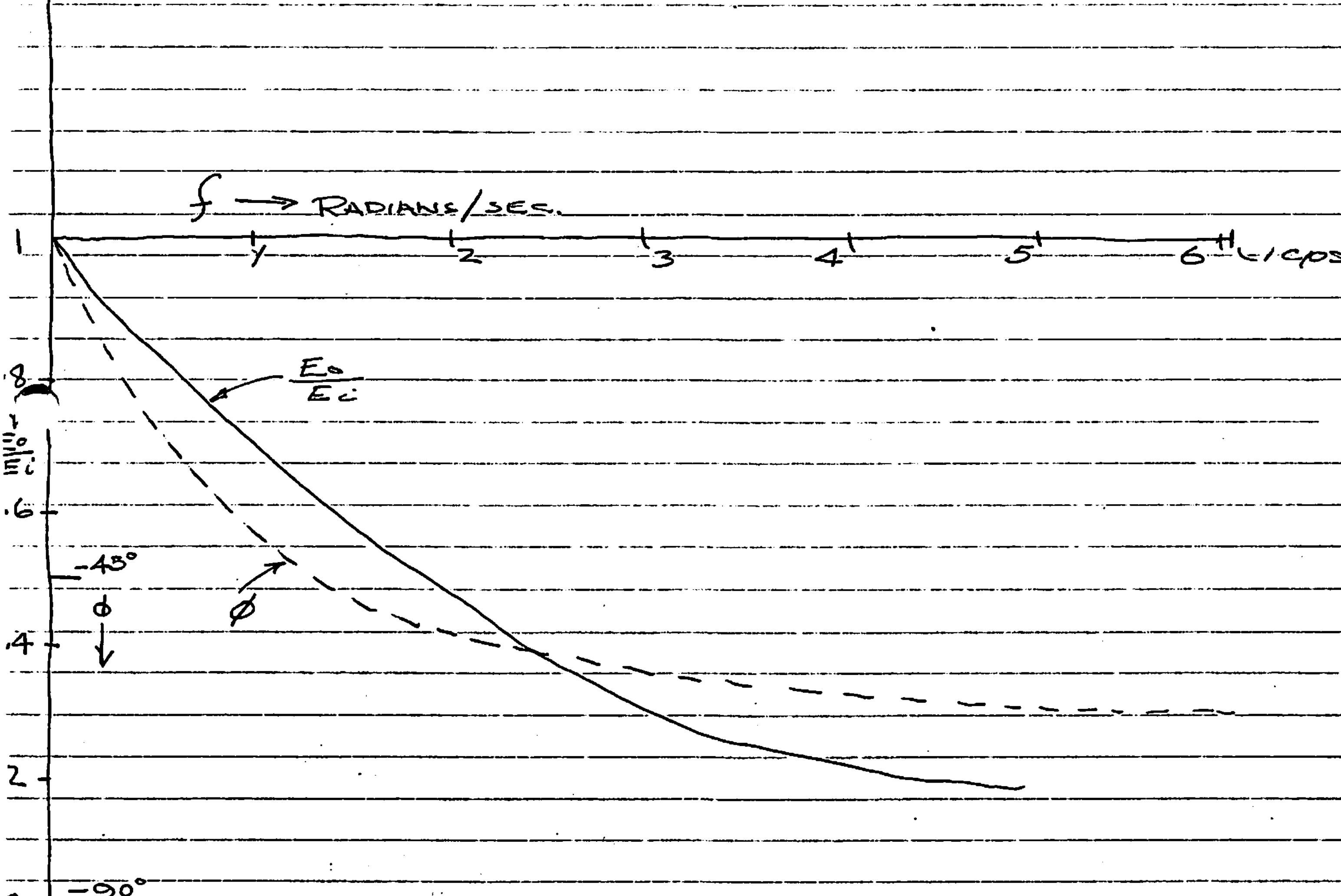
LEAD NETWORK

FIG. 3.C.2.



RC = 1

Increasing RC will increase phase lag at all frequencies.



LAG NETWORK
FIG. 3.C.4.

of A/P, where log networks on pitch rate & pitch displ't produce signals in phase with flt path rate & flt path, respectively.

HI-PASS NETWORK:

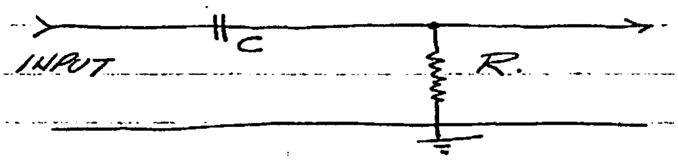


FIG. 3.C.5.

As its name indicates, hi-pass network is designed to pass higher f's & to attenuate lower frequencies. Specifically its principal application is in circuits where it is desired to block DC or steady state signals & yet allow any signal changes to go thru. The hi-pass network removes the steady state component from the input signal and the output is only the AC component of the input signal.

- On FIG. 3.6.6. → phase & amplitude response curves for hi-pass network. The curves are sketched for a time constant RC = 1. @ f = 0 (D.C.) the amp = 0, i.e., any D.C. component is completely blocked. @ a f of 3 rads/sec (1/2 cps) the amp. ratio is 0.95 and the phase lead about 16°. It is evident that f's of this order & higher are little affected by the network, but the very low f's are greatly attenuated.
- The notation for hi-pass network is $\frac{TS}{TS+1}$, where T = RC is the time constant.
- These three types of compensating networks are used quite xtensively in A/P. They can be used only if the signal pots are energized by D.C. supply voltage. Similar compensation circuits for a.c signal voltages are much more complex, and their proper operation requires an AC supply of constant frequency.

in the higher frequency range only. A lag network attenuates these higher f's & may reduce the overall system gain @ these high f's to the point where the system becomes stable. Since the error f's are in a lower range, their amp will be reduced a smaller amount. Some phase lag will be added @ the low f range too, but the system may be quite stable at low f & able to withstand a small amount of added phase lag.

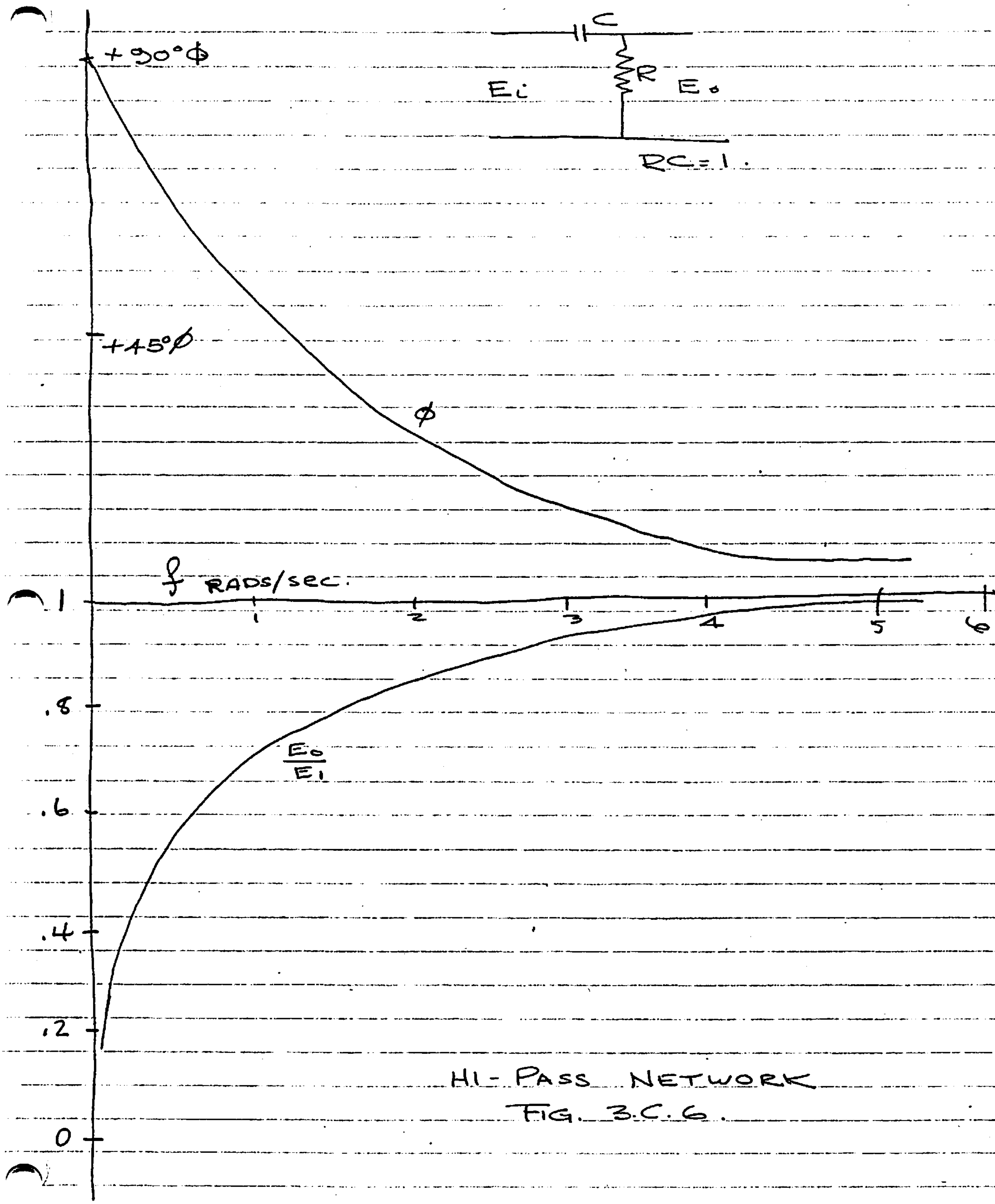
- Lag networks shown in Sect. I (A/P fcn) are identified on the block dia by notation $\frac{1}{TS+1}$, where T is the time const given by T=RC. Term S in the compensating network block diagram Xpression is simply a variable which is a fcn of time. The original, math'l Xpressions for these networks are quite complicated, involving diff'l equations in T time. This makes the Xpression hard to work with, so it is transformed into a new equation which has S as a variable by means of a mathematical transf'n known as a La Place transform. Any time it is desired, the Xpression can be transf'd back again in terms of T. For our purposes it is sufficient to remember that S is a fcn of T and that our lag network notation $\frac{1}{TS+1}$ simply shows what the output will be lagged @ any given time. A sudden step input will produce a gradually increasing output, an output whose value depends on the elapsed time since the step input was applied.
- In summary, lag networks are used where stability can be increased by attenuating the response of higher f's. Lag networks increase the signal to noise ratio, where lead networks decrease that ratio. Any situation that calls for attenuation of higher f's & emphasis of lower f's may find its solution in a lag network. Other applications will be noted in the section on stab op'n

D. AMPLIFIERS:

EG-66 Plug in single channel amp. (FIG. 3.D.1)

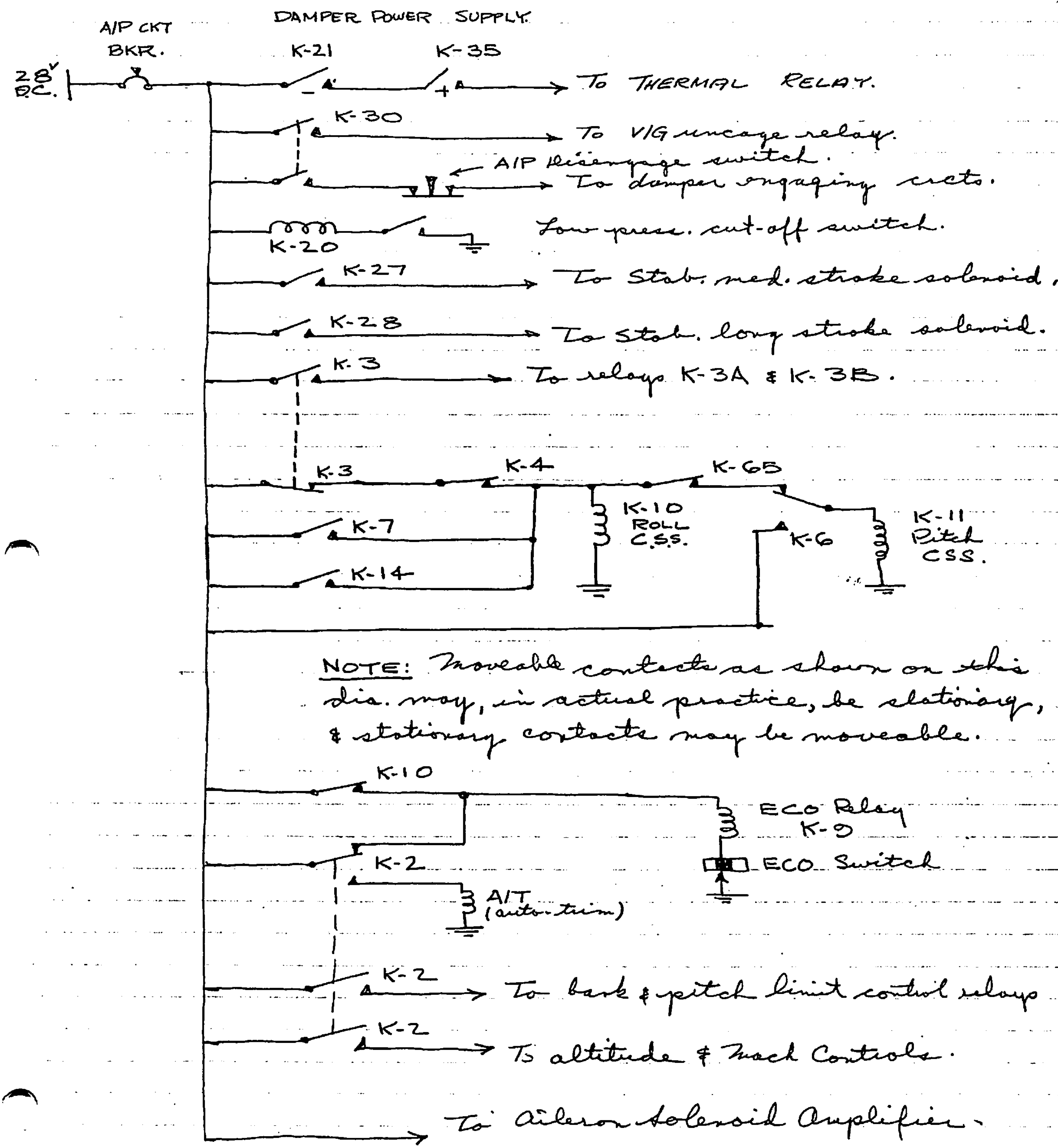
- Input signal to amplifier is a square wave, 400 ~ (sync-ed with the 400~ power source by the use of a 400 cycle chopper). This input is present at pin #1 & goes to the 1st grid (pin #2) of a 6112 dual triode.
- First stage of amplification has a 20 μμf condenser from plate to grid. This acts as -ve feedback, preventing this high gain stage from kicking into oscillation. All gain control voltages are fed into the cathode of this stage at pin #8 (tube #4).
- +ve feedback comes from the cathode of the 2nd stage, from amp pin #10 thru resistor "A" (FIG. 3.D.1) to the cathode of the first amp. stage. This feedback increases the over-all gain of the amp.
- -ve feedback comes from plate of second stage, from amp pin #4 thru resistor "B" (FIG. 3.D.1) to the cathode of the first stage. This feedback reduces the over-all gain of the amp.
- The over-all gain of 1st 2 stages of amplification of EG-66 can be varied from 100 to 1000 by the choices of feedback resistors.
- Output of 2nd stage of amp's is fed to the two grids of the discriminator. The 2 82K resistors in the grids of the discriminator are current limiting resistors to prevent drawing X cessive grid currents.
- The grids of the discriminators are biased to -14V DC, or -18V DC, or -50V DC depending on the application & fcn of the amp's. For more infor concerning these fcns, ref Sect. I.

- With -14ᵛDC on the grids of the discriminator, the output of the discriminator would be the greatest for a specified input signal. With -18ᵛDC on grids, the output would be something less than with -14ᵛDC. With -50ᵛDC on grids, the discriminator output = 0. ∴ the overall gain of the amplifier can be controlled by the bias on the grids of the discriminator.
- Another way to control the gain is to vary the amount of -ve feedback from the vel generator. Ref. FIG. 3-D·3.
- Ref FIG. 3.D.4 & 5, note that the plates of the discriminators have 212ᵛ of raw AC fed to them @ all times. As long as there is no signal to the grids of the discriminator the discriminator will not conduct. The bias on the grids prevent conduction. The AC voltages on the plates are 180° out of phase with each other. One of them is in phase with the 115ᵛ supply voltage. The other is 180° out of phase with the supply voltage.
- ~~Note~~ Now when a signal is present on the grids of the discriminator, only that 1/2 of the discriminator with the grid and plate of the same phase will conduct, and only while the grid & plate are +ve @ the same time. ∵ the grids are tied together & the plates are 180° out of phase, it is obvious that only 1/2 of the tube could ever conduct with a specified phase coming thru the amp's.
- The phase of the incoming signal, as it is applied to the discriminator grids, determines which 1/2 of the discriminator will conduct.
- FIG. 3.D.4, the discriminator is used to energize the Moog servo valve coils. If a current unbalance of 0.5 ma or more exists, the Moog valve will operate. ∴ it is quite important that the discriminator



HI-PASS NETWORK
FIG. 3.C.6.

currents be maintained balanced (equal) unless
Moog valve operation is desired.
- FIG. 3.D.5, the plate transformer is center-tapped and fed to a sync. motor. All the sync. motors are 2 ϕ induction type. To make these 2 ϕ induction motors run, the input voltage to the two field windings must be 90° out of phase.
- If the amp. phase is 90° leading the line phase, the motor will run one direction (say CW). If now amp phase is 90° lagging the line phase, motor will run in op. dir (CCW).
- Assume discriminator plate that is conducting is that one in phase with line voltage. ∴ the phase of the voltage feeding the amp phase winding of the motor must obviously be in phase with 115ᵛ, 400~ line.
- To make motor run, we stated we needed a 90° phase between the voltages in the 2 windings. To do this, we place a condenser in series with the voltage feeding the line phase winding of the motor. The size of this condenser is such that it forms a series resonant circuit with the motor winding. At resonance, the phase shift thru the condenser is 90°. ∴, the voltage in the line phase winding of the motor is now 90° phase shifted from the 115ᵛ, 400~ line. The voltage (as stated in the preceding paragraph) in the amp. phase winding is in phase with the 115ᵛ, 400~ line, ∴, motor will run.
- If amp. phase winding reverses (180°) the motor will reverse any 2 voltages switch from line phase lagging 90° to line phase leading 90° w.r.t amp. phase.



28V D.C.
A/P CKT BKR.
DAMPER POWER SUPPLY
K-21
K-35
To THERMAL RELAY.
K-30
To V/G uncage relay.
A/P disengage switch.
To damper engaging ccts.
K-20
Low press. cut-off switch.
K-27
To Stab. med. stroke solenoid.
K-28
To Stab. long stroke solenoid.
K-3
To relays K-3A & K-3B.
K-3
K-4
K-65
K-7
K-10 ROLL C.S.S.
K-6
K-11 Pitch CSS.
K-14
NOTE: Moveable contacts as shown on this dia. may, in actual practice, be stationary, & stationary contacts may be moveable.
K-10
ECO Relay K-9
K-2
ECO Switch
A/T (auto-trim)
K-2
To bank & pitch limit control relays
K-2
To altitude & Mach Controls.
To Aileron Solenoid Amplifier.

FIG. 2-1.

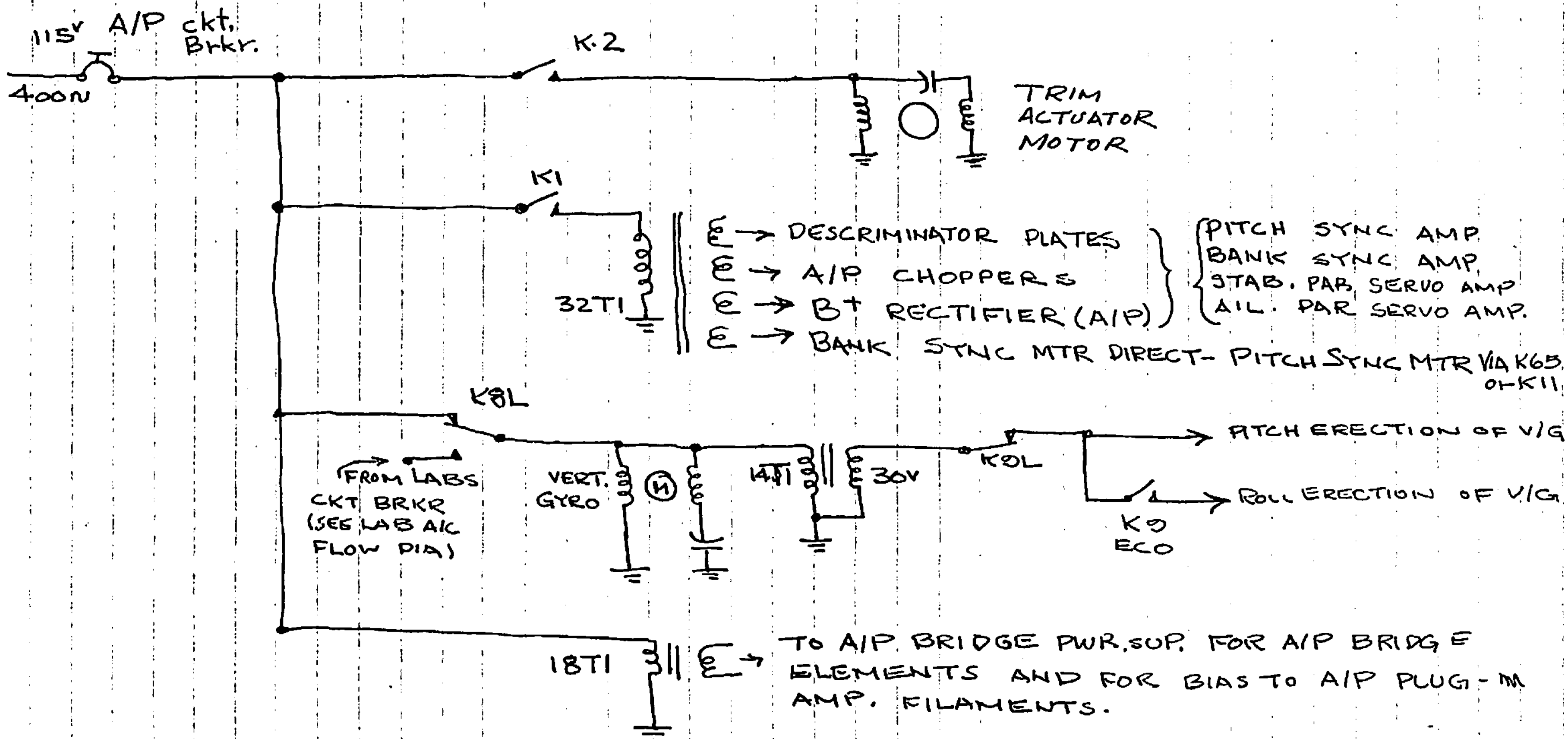
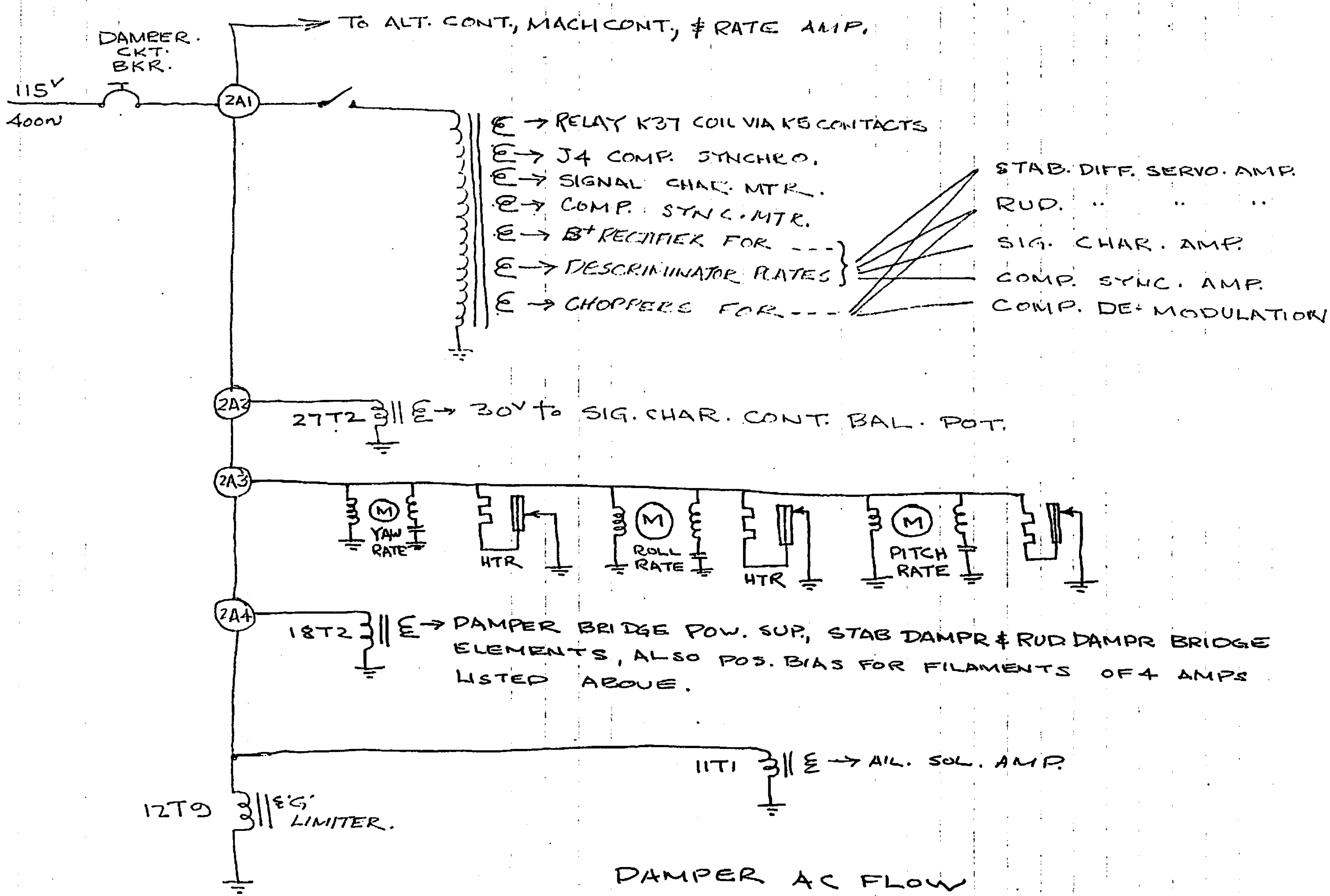


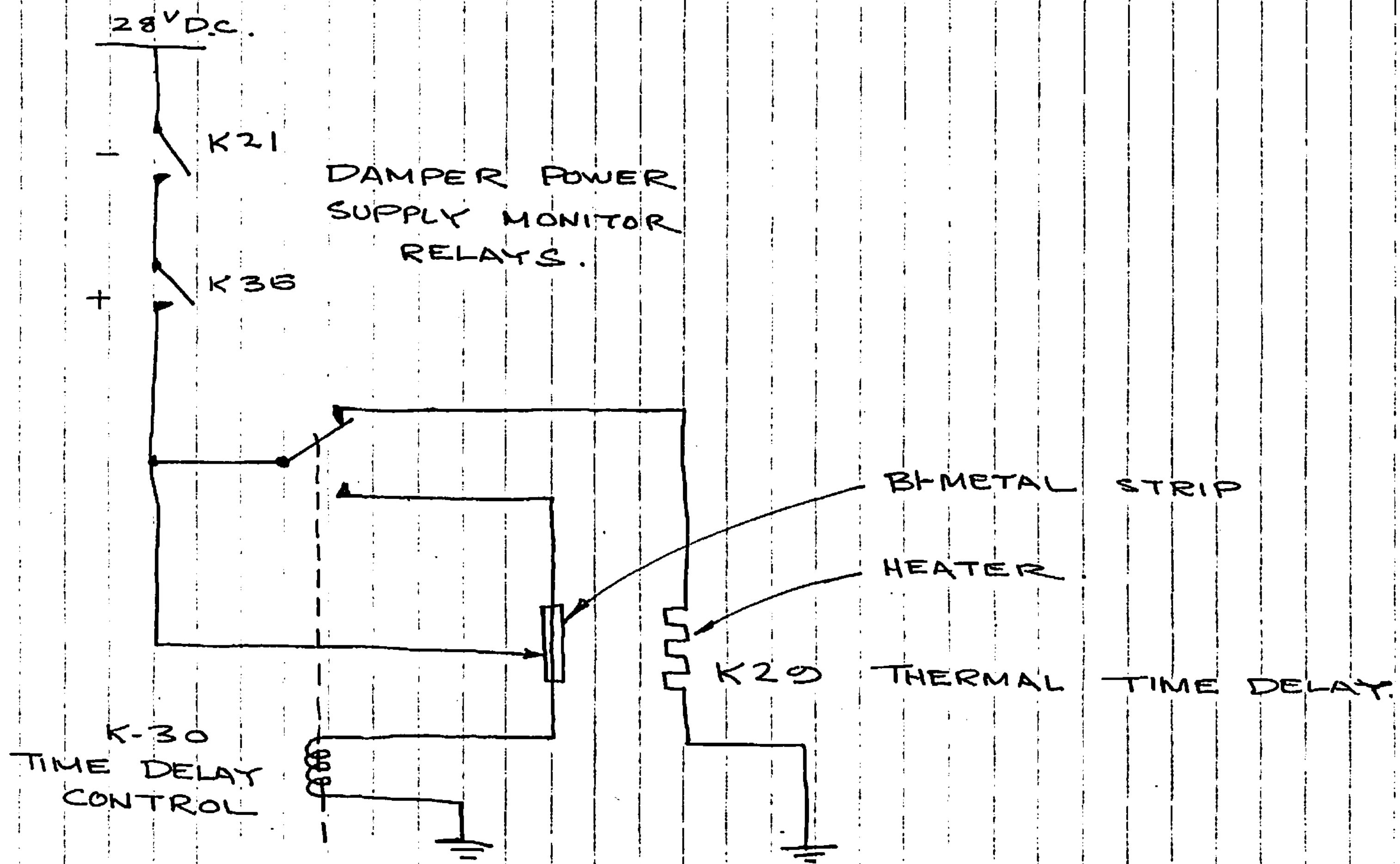
FIG. 2.2

AUTOPILOT A.C. FLOW.



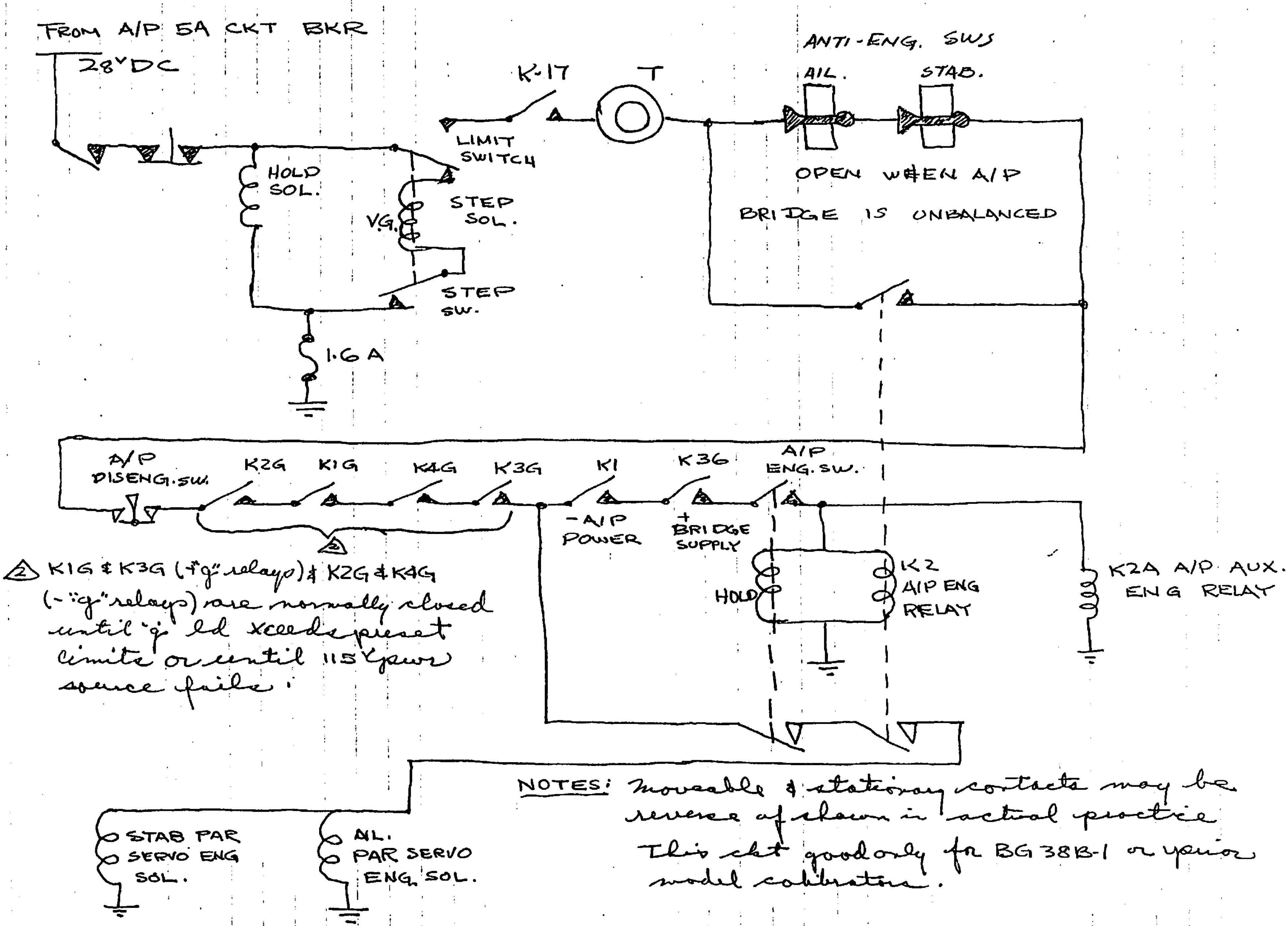
DAMPER AC FLOW

FIG 2.3.



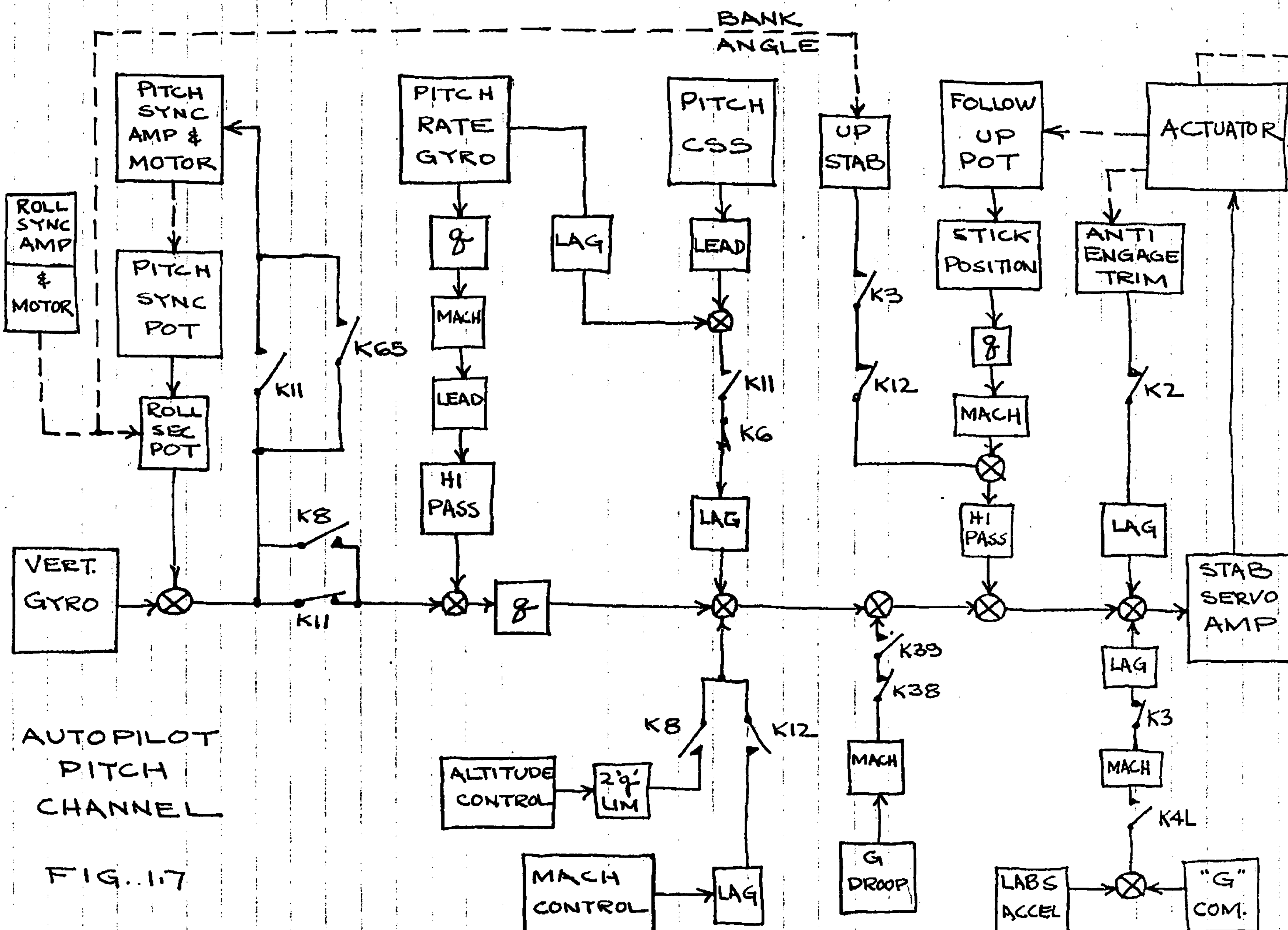
NOTE: Moveable contacts as shown on this dia may be stationary & vice versa.

FIG. 2.4.



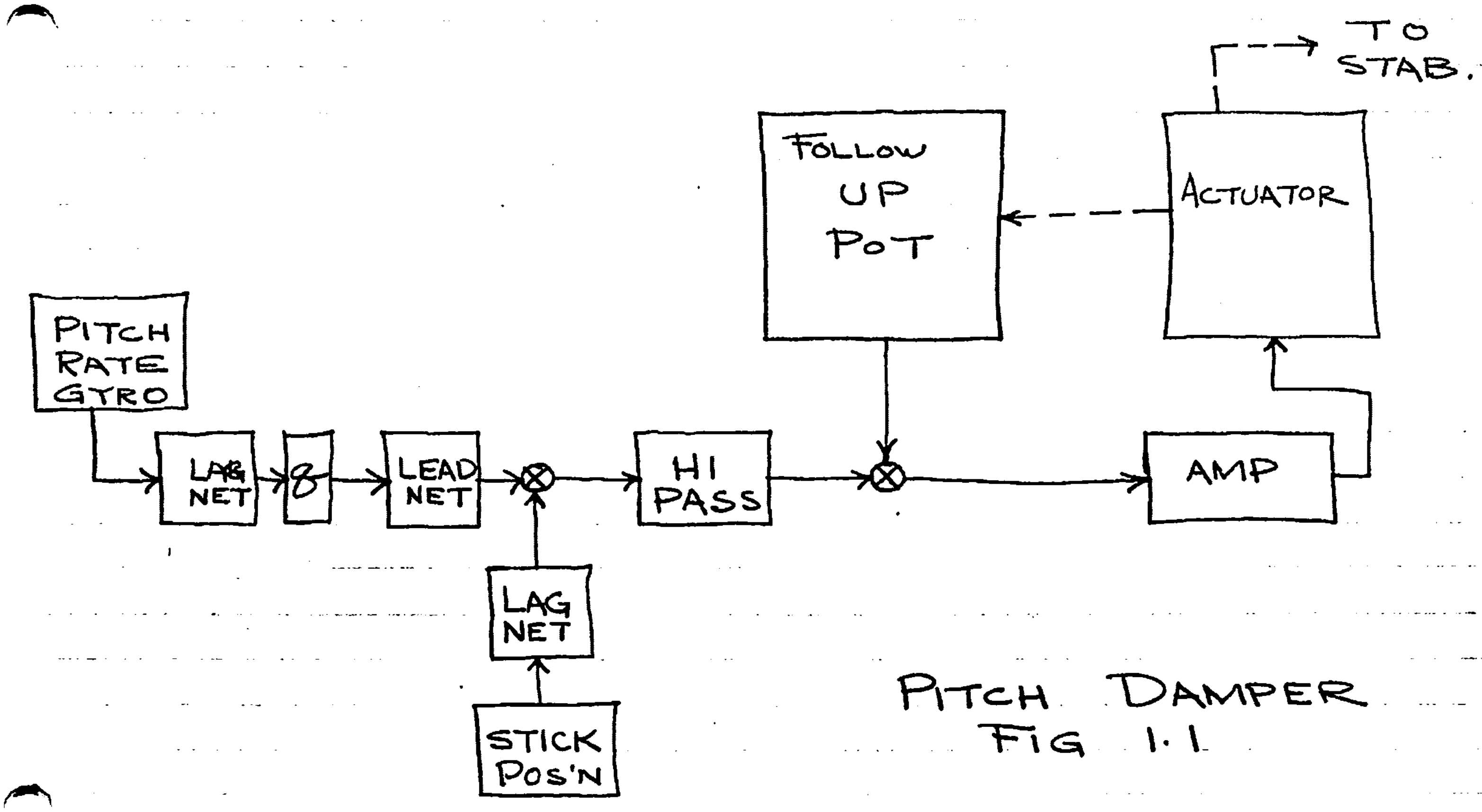
FROM A/P 5A CKT BKR
28V DC
K-17
T
ANTI-ENG. SWS
AIL.
STAB.
LIMIT SWITCH
HOLD SOL.
STEP SOL.
V.G.
STEP SW.
1.6 A
OPEN WHEN A/P BRIDGE IS UNBALANCED
A/P DISENG. SW.
K2G
K1G
K4G
K3G
K1
K36
A/P ENG. SW.
-A/P POWER
+ BRIDGE SUPPLY
HOLD
K2 A/P ENG RELAY
K2A A/P AUX. ENG RELAY
② K1G & K3G (+"g" relays) & K2G & K4G (-"g" relays) are normally closed until "g" ld xceeds preset limits or until 115V pwr source fails.
STAB PAR SERVO ENG SOL.
AIL. PAR SERVO ENG. SOL.
NOTES: moveable & stationary contacts may be reverse of shown in actual practice
This ckt good only for BG38B-1 or senior model calibrators.

FIG. 2-5.

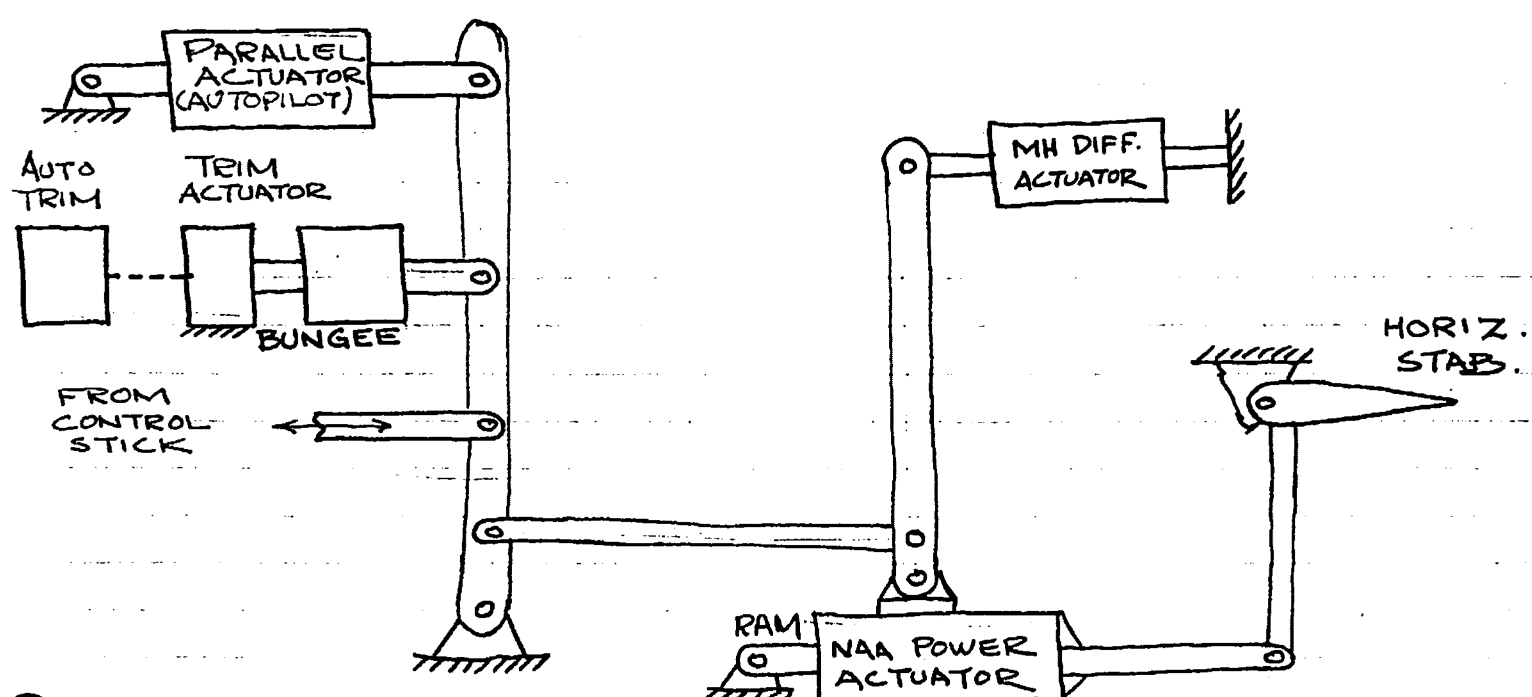


AUTOPILOT PITCH CHANNEL

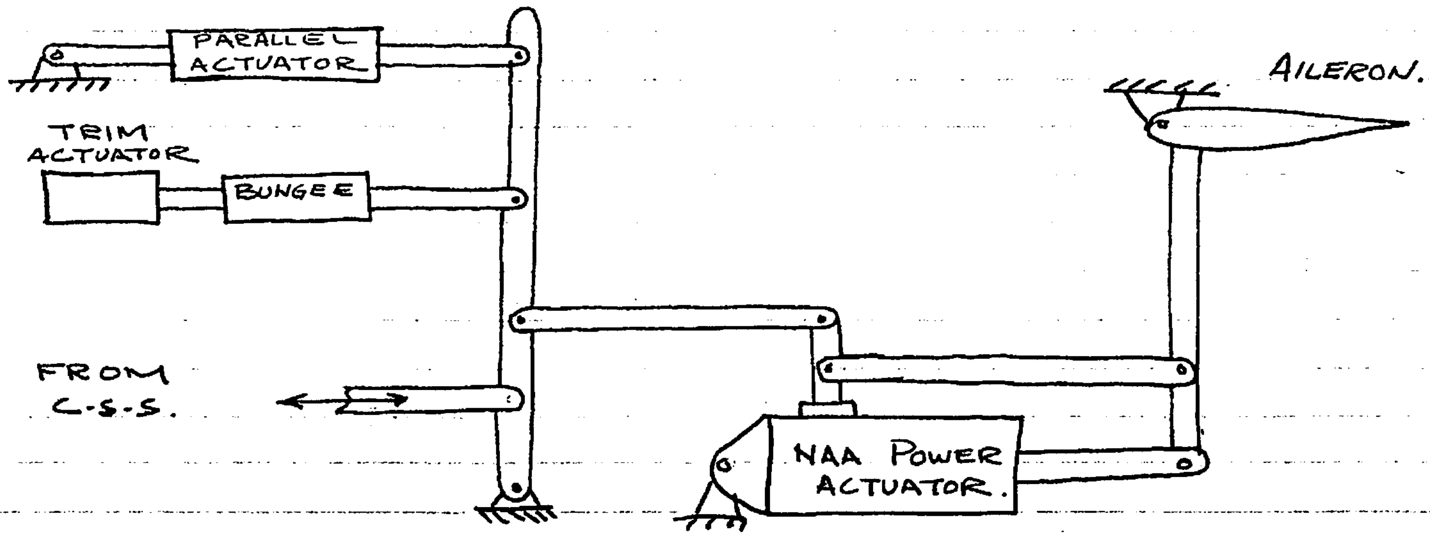
FIG. 17



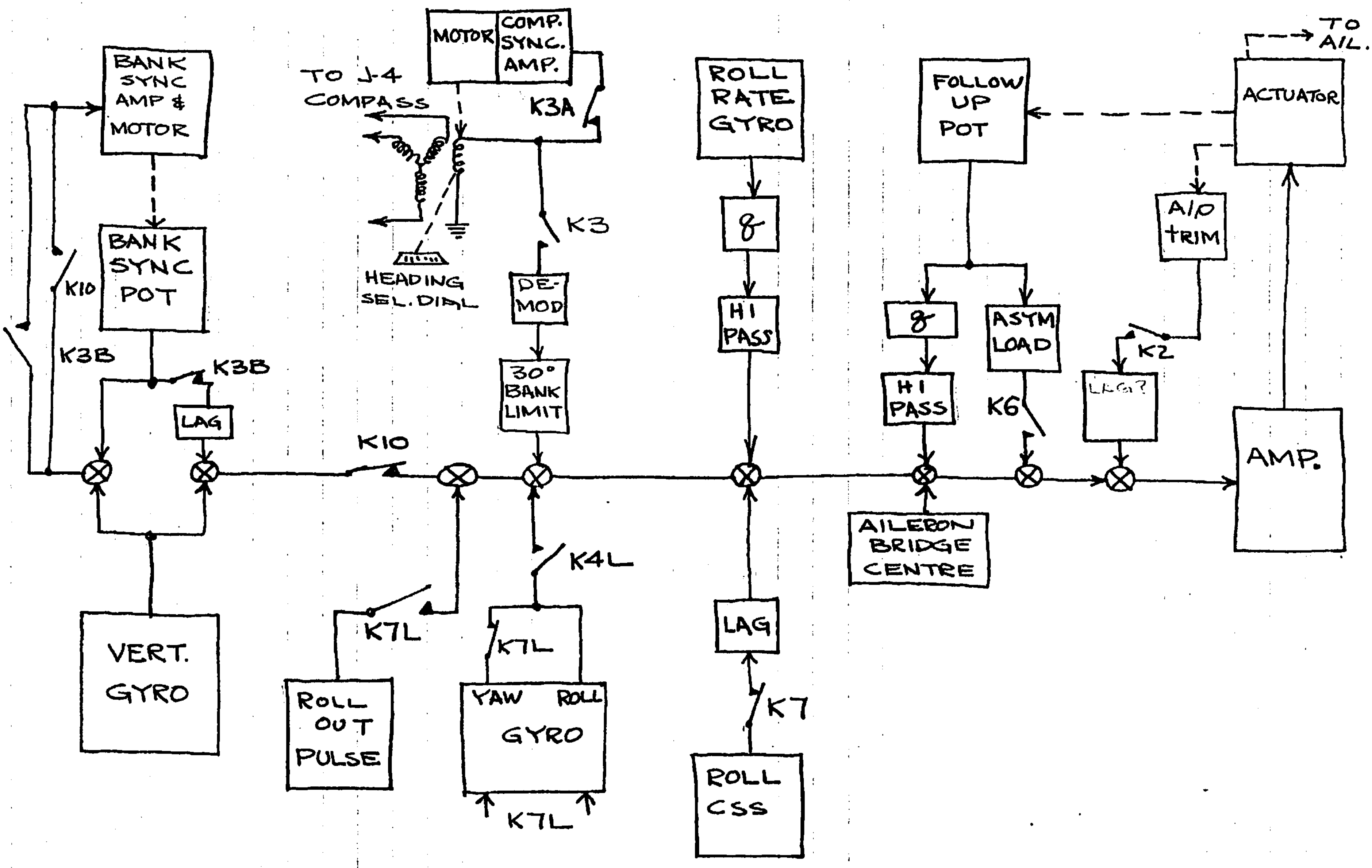
PITCH DAMPER
FIG 1.1



PITCH AXIS IRREVERSIBLE LINKAGE.
FIG. 1.2 & 1.8.

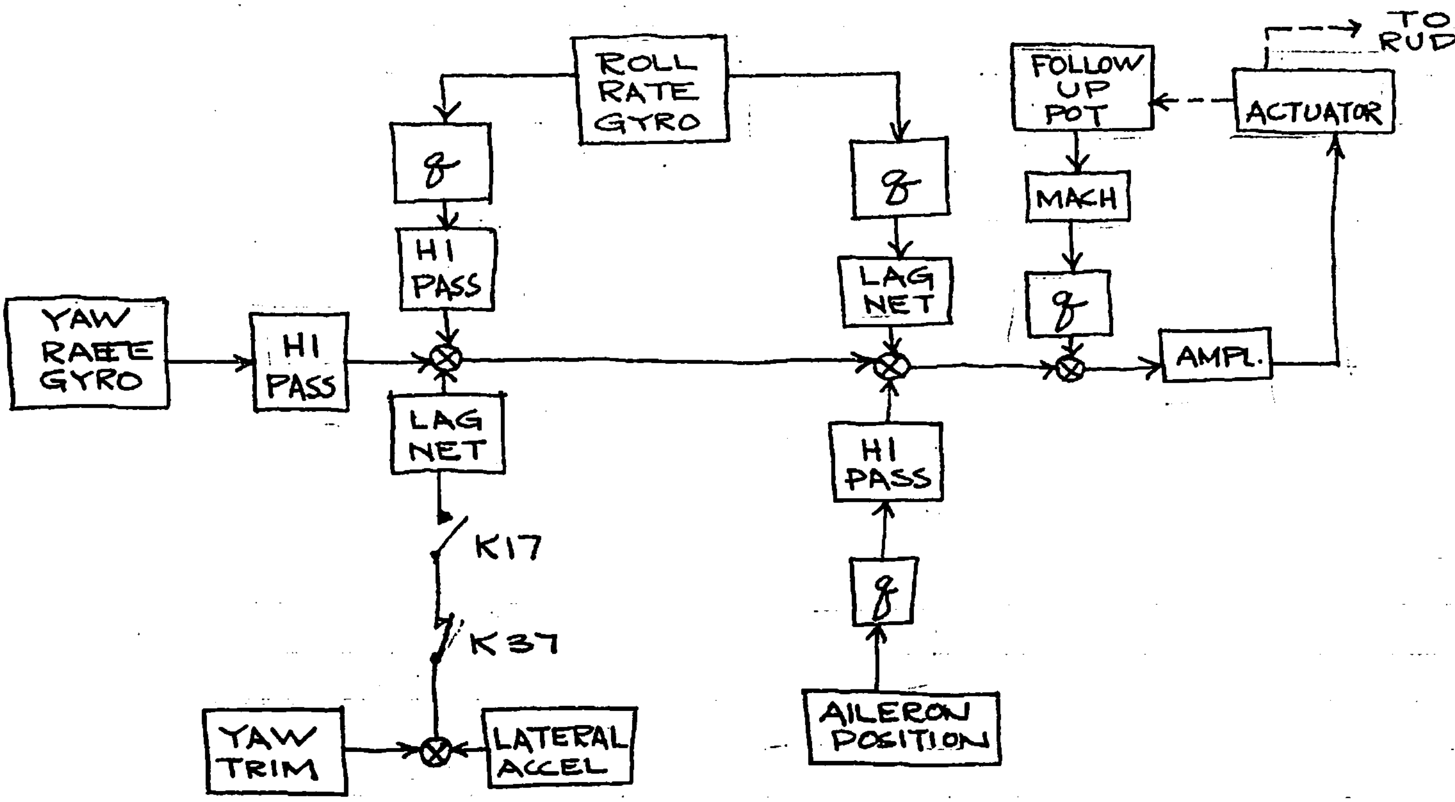


PARALLEL (AUTOPILOT) LINKAGE
ROLL AXIS
FIG. 1.6.

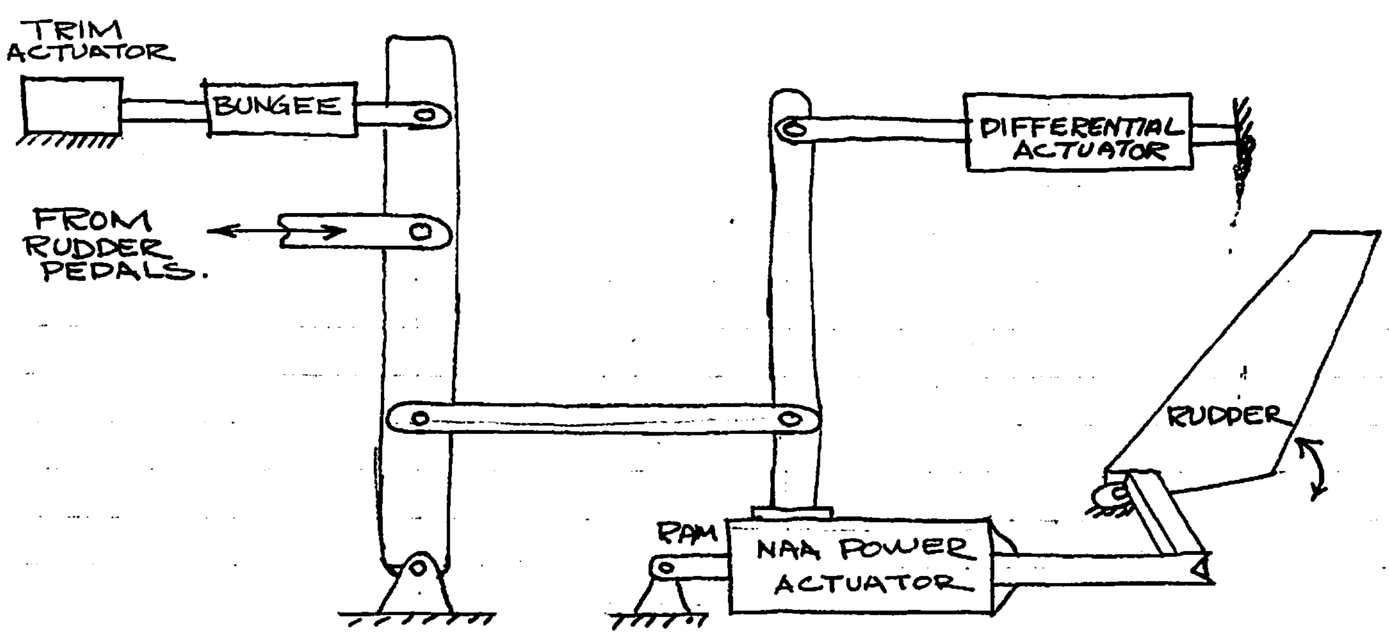


AUTO PILOT ROLL CHANNEL

FIG. 1.5



YAW DAMPER
FIG. 1·3



YAW DAMPER IRREVERSIBLE LINKAGE
FIG. 1-4.

TABLE 1.

AUTOPILOT OPERATIONAL DATA

AXIS	MANEUVERING LIMIT	OVERPOWER FORCE @ STICK	SERVO OUTPUT FORCE TOTAL	PARALLEL SERVO RAM PHASING (RAM FULL OUT)	SURFACE TRAVEL PRODUCED BY AUTOPILOT.
ROLL	360° IN ROLL WITH PILOT PROVIDING CO-ORD ABOVE ±60° BANK ∠'s AND/OR ±50° PITCH ∠'s.	PARALLEL APPROX. 22-27 LB.	PARALLEL 110-135 LB.	LEFT ROLL	AUTOPILOT ±15° MANUAL ±15°.
YAW	CO-ORD for ANY HEADING IF BANK ∠ IS LESS than ± 60°	DIFF. NONE	DIFF.	RIGHT RUDDER	DAMPER ±10° MANUAL ±20° LAT. ACCEL 150° RUDDER PER "G".
PITCH	360° IN PITCH WITH PILOT PROVIDING ATT. STABILIZATION IF PITCH ANGLE IS GREATER THAN ±50° OR IF ROLL ∠ IS GREATER THAN ±60°.	PARALLEL APPROX. 21-25 LB. DIFF. NONE	PARALLEL 105-135 LB. DIFF.	AUTOPILOT DOWN ELEVATOR DAMPER DOWN ELEVATOR	DAMPER* 5.135° above 36,000' 3.68° above 20,000' 2° below 20,000' AUTOPILOT +27° −4° TOTAL 31° MANUAL 31° TOTAL.

* 1" of ram travel produces approx 4.46° of surface deflection.

CONDITION	OPERATION	INPUT	AMPERES	WATTS.
STARTING	AUTOPILOT DISENG'D. & BRIDGE BALANCED.	115^{V}, 400~	3.05 a	350 ^{VA}
STARTING	AUTOPILOT DISENG.'D & BRIDGE BALANCED.	27.5^{V} DC.	5.1 a	140^{W}
RUNNING	AUTOPILOT ENGAGED & BRIDGE BALANCED.	115^{V} - 400~	2.13 a	245VA
RUNNING	AUTO PILOT ENGAGED & BRIDGE BALANCED.	27.5^{V} DC	4.18 A	115^{W}

TABLE II

POWER REQUIREMENTS.

FLYING CONTROL SYSTEMS:

Resumé of BROCHURE FC-1 (C-105):

1. INTRODUCTION:-

1.1 FULLY POWERED CONTROLS:
- large chord, highly loaded surfaces.
- eliminate mass balancing.
- take out cuz. supersonic airflow over rear of wings is unpredictable & variable.

1.2 RELIABILITY NECESSARY:
- minimum number of jacks
- fully duplicated power system.

1.3 HYDRAULIC POWER SYSTEM:
- reliability
- actuator compactness
- system response
- performance under extreme environmental press. & temp. cond's.

1.4 POWER (high demand)
- engine driven pumps
- 1/2 of each F/C Hyd. Syst. being driven from each engine.
- provides full control forces @ 1/2 max. rate during single engine oper'n.
- permits full control during adverse asymmetric thrust cond's.

1.5 THREE MODES OF CONTROL:

1.5.1) MANUAL MODE:
- uses signals from pilot input force transducers to control thru magnetic amplifier circuits, elevator & aileron command servos.

- these electro-hydraulic servos then operate the act. cyl. control valves thru short mechanical linkages.
- during the ~~m~~ command servo oper'n turn co-ordination is provided by the A/C damping system and the associated electronic coupling networks.
- pilot feel - as desireable to account for:
  - stick force / g.
  - dynamic press. on surface
  - stick position
  - stick rate, etc.

1.5.2 AUTOMATIC FLIGHT MODE:
- command signals from:
  - ground control guidance stations or
  - a/c fire control system

& fed by A.F.C.S. as signals to command servos, to be transformed as in 1.5.1 to surface movement.

1.5.3 EMERGENCY MODE:
- event of failure of primary stick force ~~tool~~ mode
- conventional cable & mechanical linkage syst to directly control actuator valves.
- FEEL:
  - stick forces - positional feel springs
    - elevator stick force/g bob wt.
  - rudder pedals - positional spring (spring constant variable with q_c)

1.6 NORMAL ARTIFICIAL DAMPING SYSTEM:
- provided @ all 3-axis by a rate-gyro syst'm
- feeding through a scheduling network to diff'l servos which supply signals to the actuator control valves by diff'l movement of the pilots input linkage during 1.5.1 & 1.5.2 only (& ∴ no feedback

to the stick to make pilot aware of the damping system operation).
- system failure - automatic & manual shut-off.

1.7 SPEED BRAKES (for subsonic use only)
- manual selector switch
- operated by 2 hydraulic jacks
- powered by Utility Hydraulic System (Ref. brochure H-2)

2. DESIGN OBJECTIVES:

2.1 GENERAL:

2.1.1 - provide a fully powered operated F.C.S. (elevator, aileron, rudder)

2.1.2 - etc for speed brakes.

2.1.3 - system to take advantage of the features of the automatic flt control syst to produce the most desirable pilot feel & response characteristics.
- sense input stick forces & transmit the signals via magnetic amplifier networks to the command servos, ∴ ensuring high response & permitting the simulation of the most elaborate feel reqts.

2.1.4 To provide a standby syst by conventional means & provide adequate stick force/unit stick displacement & stick force/g relationships.

2.1.5 Reliability achieved by duplication of hydraulic power system & of input syst (2.1.3 & 2.1.4).

2.1.6 Operating temps:
- soaked temp of 0°F.
limited perf. @ -20°F.

- rapidly warmed up from -65°F by operation of pilots input syst'm with pumps running.

2.1.7 Max. normal operating temp 250°F.
local hot spots 275°F.
- heat exchanger in hydraulic syst.

2.1.8 provide cable tension regulators

2.1.9 - F.C.S. capable of accepting command signals from:
- electronic fire control syst.
- other electronic navigation & flt control aids.

2.1.10 - F.C.S. capable of accepting signals from an electronic damping system in order to operate the surfaces differentially to the pilots & command input ~~signal~~ syst.

2.1.11 - standby rudder input system, a feel to prevent pilot from inadvertently applying large rudder deflections @ high equiv speeds.

2.1.12 - adequate control during asymmetric flying case - any engine failure within flt envelope.

2.1.13 - mech syst. of adequate stiffness, free from structural feedback, & effectively mass balanced, to preclude the possibility of spurious signals being transmitted to the control valves.

2.2 <u>ELEVATOR SYSTEM:</u>

2.2.1 movement 30° up
20° down
@ max rate of 40°/sec.
@ max hinge moment of 60,000 FT.LB /surface

2.2.2 el. pitch dampers movement authority of ± 6° for any position of the elevator.

2.3 AILERON SYSTEM:

2.3.1 movement 19° up
19° down
@ max rate of 35°/sec
@ max hinge moment 25,000 FT.LB./surface

2.2.2 aileron roll dampers movement authority of ± 7.5° for any position.

2.4 RUDDER SYSTEM:

2.4.1 movement ± 30°
@ max rate of 40°/sec.
@ max hinge moment of 12,000 FT.LB.

2.4.2 rudder movement yaw damper authority of ± 10° for any position.

2.4.3 achieve yaw damping of 2.4.2 by use of duplicated signalling & power syst., with automatic & instantaneous 'switch over' from normal to emergency syst.

2.5. SPEED BRAKES:

2.5.1. Extend, retract, or hold brakes @ any position by hyd. actuation @ airspeeds up to M = 1.0.

2.5.2 throttle mounted speed brake control:
- extends @ "speed brake extend" position until airloads balance hyd input force, or until selector is released
- hold in any position (S.B.E → HOLD) provided airloads on the brakes not increased.

2.5.3 - provide overspeed relief within speed brake selector valve → new pressure-airload equil'm @ "blow-in".

2.3 AILERON SYSTEM:

2.3.1 movement 19° up
19° down
@ max rate of 35°/sec.
@ max hinge moment 25,000 FT.LB / surface.

2.2.2 aileron roll dampers movement authority of ± 7.5° for any position.

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@ max rate of 40°/sec.
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2.5.3 - provide overspeed relief within speed brake selector valve → new pressure-airload equil'm @ "blow-in".

3. MODES OF CONTROL:-

3.1. MANUAL MODE (OR STICK FORCE MODE):-

3.1.1 GENERAL:-

- utilizes the same amplifiers as the automatic flight control system as a means of transmitting pilot input signals at stick to slide valves controlling the surface hyd. servo actuators
- allows for pilot "feel" and system response characteristics to be scheduled with alt., accel'n, & Mach. No. as desired.
- the irreversibility of the command (parallel) servos, which transmit the stick electrical signals as motion to the main control valves, force feed-back from the action of the diff'l servos of the artificial damping system is not transmitted to the stick (i.e., pilot is completely unaware of the op'n.)

3.1.2. OPERATION:-

- *Elevator System*:- principle of operation of this mode of signalling the control valves.
  - stick, moved by pilot, will be loaded through the cable system by the ‖'l servo, the hyd. resistance of which the pilot is attempting to overcome.
  - this force on the stick will induce deflections in the linkage, which are used to signal a sensitive electrical transducer.
  - transducer signals then transmitted to the appropriate command servo magnetic amplifiers, from which control signals are sent to the electro-hydraulic command (parallel) servos to energize them in a direction which will unload the forces in the pilots stick (i.e., reduce the error between input & output signals).

- In reducing this error to zero the ll'l servo's displace the main control actuator valves, thru' linkage system → surface movement.

- Within the damping system electronic circuits provision is made for generating signals which will result in pilot sensing constant force per 'g' independent of flight condition & most desireable stick position force for special cond'ns (e.g. take-off).
- During this mode of operation, to ensure that the mechanical standby input feel system is always in trim in the event of failure of the normal control system, the clutch of the trim brake of the spring feel system is energized to allow it to free-wheel, & thereby ensure that the springs are always unloaded within the trim range (ref 4.12). On failure of the normal system, the trim brake clutch is released & the pilots feel system is automatically trimmed as of the instant of failure.

- Aileron System: similar.

- Rudder System:
-fcn of rudder is turn coordination & is handled by the damper diff'l servos on signals from both A.E.C.S. & manual mode.
-Intentional Yaw: kick rudder to overcome a force switch, disengaging the turn co-ord'n circuit & allowing mech. input system to displace surface.

3.2. AUTOMATIC FLT MODE:

- command signals from ground & airborne navigation aids, or fire control system.
- transmitted to A.F.C.S., as before.
- pilot overide → overpower the relief setting of the parallel servo (ref. 4.13.)

3.3. EMERGENCY CONTROL MODE:

3.3.1. Mechanical manual control mode - standby against failure of electro-hydraulic normal mode (3.1)
- automatic reversion
- inferior to normal mode:
  - less elaborate feel system
  - emergency damping → restricted to yaw axis only.

3.3.2. Cables → mech. linkages → control surface actuator valves.

3.3.3. Indentical tension regulator quadrants for each control run:
- under cockpit floor.
- driven by control column & rudder pedal movement → to elevator & aileron quadrant in rear fuselage & to rudder quadrant in fin.

3.3.4. Elevator & aileron command (parallel) servos introduced @ rear quadrant (4.11).
- hence movement all mechanical & utilizes the appropriate automatic damping servo rod ends as fulcrum pts for final movement of servo control valves.

3.3.5. Rear fuselage elevator quadrant
- below surface of wing
- connected by push rods to the bell cranks @ elevator jack pivot pts
- other arm of each bell-crank (inside wing) connected to centre of main lever of el. jack follow-up mechanism & the valve is operated thru this mech'm (3.3.8).

3.3.6. Rear fuselage aileron quadrant:
- below bottom surface of wing
- connected by push rods to the inner wing tension regulator quadrant levers.
- movement from quadrant by cables → along rear face of rear spar → to quad. @ aileron jack pivot point.
- the quad @ aileron jack pivot point is also connected by push rod to the centre of the main lever of aileron jack follow-up mech'm (as elevator).

3.3.7. Rudder quadrant in fin:-
- connected by push rod to bell crank at rudder jack pivot point - other arm of bell-crank connected by push rod to centre of main lever of rudder jack follow-up mechanism (as el. & ail.).

3.3.8. Elevator, aileron, and rudder jacks follow up mechanism is similar and primary movement of main lever effected as mentioned above.
- main lever pivots about an inboard extension of the jack piston rod so that actuation of the jack induces the follow-up motion.
- other end of main lever connected by push rod to the valve operating lever which pivots about an end fitting on the diff'l servo piston rod and is connected @ its other end to the end of the valve spool.
- jack displaced ~~nt~~ until the follow up process induced by secondary movement of the main follow-up lever closes the valve again at the req'd control surface diffl̶ection.

- By pivoting the valve-operating lever on the end of the diff'l servo piston rod the valve position may be modified by diff'l movement from the damping servo during the electrical modes to achieve artificial damping.

3.3.9. Displacement →

- piston rod end → push rod & bell-cranks.

3.3.10 - spring-loaded feel units → artificial feel during emergency mode.

- aileron unit → @ quad under cockpit floor.
- elevator " → " rear fuselage quad.
- rudder " → in fin.
  - ↳ also supplies hinge moment limitation (ref 4.12 → artificial feel units.)

3.4. AUTO-STABILIZER:

3.4.1. all modes of control - affected by normal or emergency artificial damping syst.

3.4.2. signals → diff'l servos @ each jack.

- as the diff'l servo pistons act as the pivots for the levers connected to the actuator valves, (3.3.8), in response to these continuous damping signals the actuator valves, & consequently the actuators & control surfaces, are continuously adjusted to suit the a/c stability requirements.

4. DETAILED DESCRIPTION:

4.1 HYDRAULICS:

Normal operating press.	4,000 p.s.i.
Proof press.	6,000 p.s.i.
Burst pressure	10,000 p.s.i.
Normal Syst. Return press.	100 p.s.i.
Max Optg temp.	275°F.
Min " "	-65°F.

- two pumps / engine →
  - one for 'A' system, one for 'B' syst.
- actuators – tandem dual piston & cyl. type (each cyl supplied by indep syst.)
- single engine failure → press. @ $\frac{1}{2}$ req'd flow.
  - max C/S rate @ $\frac{1}{2}$ max hinge moment
    - a/c limited by available 'q' throughout flt envelope
- rudder → double diff'l servo → 2 integral units (one supplied by 'A' other by 'B'.) (A → emergency, B → normal operation).
- electrical & electronic signalling network duplicated cuz vital nature of yaw axis damping
- aileron & elevator diff'l servo units, actuate the jacks for damping purposes, supplied by 'B' only.
- Command (parallel) servos, actuate jack valves on receipt of signals from stick force syst or A.F.C.S. supplied by 'B' only.

4.2. CONTROL COLUMN: (STA. 155.26)
- operates quad's by lever system.

AT GRIP LINE		
C/S	MAX. TRAVEL.	PILOT LOAD.
ELEVATOR	11.0 IN.	200 LB.
AILERON	10.0 IN.	100 LB.

- Trim control – thumb button control on grip → changes earthing point of feel spring by means of el. actuator.

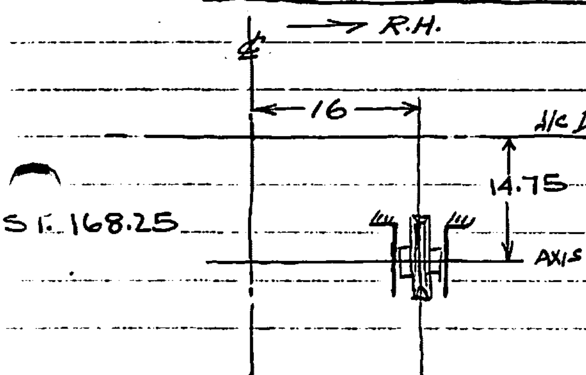
4.3. RUDDER PEDALS:
- overhead hinge point at STA. 134.25.
- connected by push rods to rudder bar which pivots @ torque tube passing thru cockpit floor.
- torque tube connected to rudder tension regulator quadrant.

PEDAL TRAVEL	6.65 IN.
PILOT LIMIT LOAD	300 LB.

4.4 TENSION REGULATORS (under cockpit floor).
- cables from here aft to R/F & Fin quadrants.

DIA.	12 IN.
RANGE of COMPENSATION	2.5 IN / CABLE
RIG LOAD VARIATION for FULL RANGE of COMPENSATION	40 LB. (MIN.) 60 LB. (MAX.)

ELEVATOR TENSION REGULATOR QUADRANT:

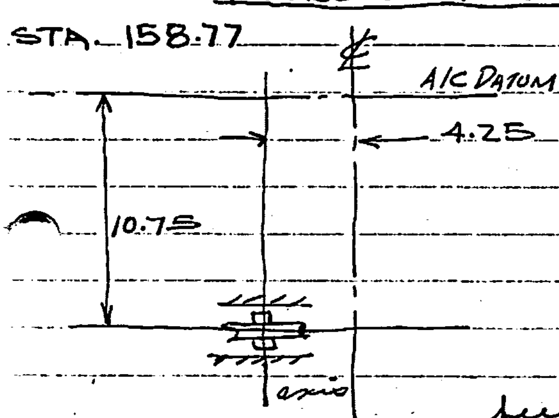


- 3.5 IN. lever mounted on inboard end of torque tube & connected by push rod to crank on control column. (also 3.7 LB bob wt on 7 IN. lever from torque tube).

- Elevator stick force transducer on torque tube between bob wt and quadrant. (Now on top, below handle)

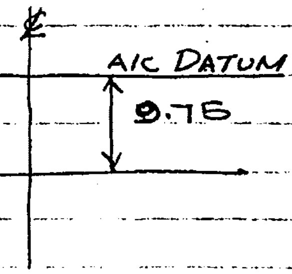
ANGULAR MOVEMENT	60° TOTAL
CABLE "	6.283 IN. TOTAL

AILERON TENSION REGULATOR QUADRANT:



- mtg integral with control column mtg.
- mt'd on lower end of torque shaft, thru cockpit floor.
- torque tube → 3.60 IN lever → push rod to control column (push rod travel 3.10 IN).
- 3.74 IN. lever on shaft → aileron spring feel unit, below a/c datum. | 23°39' | 4.953 IN. |

RUDDER TENSION REGULATOR QUADRANT: 7.



ANGULAR MOVEMENT	± 20°
CABLE MOVEMENT	4.189 IN.

AILERON TENSION REGULATOR ~ INNER WING:

STA. 692.79, 14.5 IN. O'T'D., total movent 3.26 IN.
- shaft through bottom of wing.
- lever & push rod to rear fuselage quad.

DIA.	5.65 IN.
RANGE of COMPENSATION	1.28 IN.
RIG LOAD VARIATION for FULL	40 LB (MIN.)
RANGE of COMPENSATION	60 LB (MAX.)

4.6 BOB WEIGHT:

- supplement to the feel springs to provide some natural feel proportional to 'g' in pitching plane. A/C normal accel'n → produces an opposing force at stick grip of 3 LB/'g' which is added to the positional feel of spring system.

4.7 ELEVATOR STICK FORCE TRANSDUCER:

- translate pilot input load at the stick into electrical signals for transmission, via the magnetic amplifier circuit, to the elevator command servo.
- transducer ~ differential transformer type
*- mounted on elevator quadrant torque tube.
  - senses resultant of pilot & bob-wt inputs.

4.8 AILERON STICK FORCE TRANSDUCER:

- as above.
*- located @ base of control column.
* now both handle mounted.

4.9 PEDAL FORCE SWITCH:

- cut out the electrical circuit providing turn co-ordination between rudder and aileron, allowing manual override (intentional slips).
- min. asym. rudder pedal load = 30LB → trip.

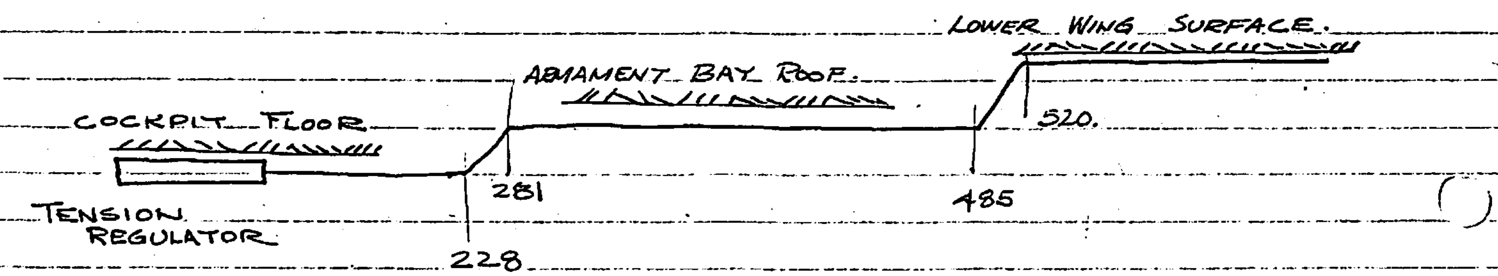
4.10 CABLE SYSTEM:

- connects ten. reg. quad's (under cockpit flr) to el. & ail. quads in rear fuselage & rudder quad & "feel" system in fin.
- wing run: from R/F. aileron quad by way of ten. reg. in wing → ailpak quad.
- 1/8 IN. dia (MIL-C-1511)
  alclad to .201" dia - to reduce elastic stretch; overall coefficient of exp ≈ that of airframe.

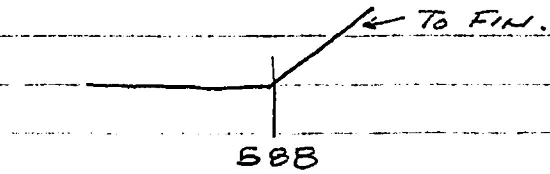
CABLE	TOTAL LENGTH (IN.)	% LENGTH		TOTAL CABLE MOVEMENT (IN.)	TOTAL TEN. REG. COMP. (IN.)
		BARE	CLAD		
ELEVATOR	1047.6	24.0	76.0	6.283	2.5
AILERON (F.)	1081.9	19.0	81.0	4.95	2.5
AILERON (W.)	828.24(2)	23.0	77.0	3.26	1.28
RUDDER	1301.2	16.5	83.5	4.189	2.5
OVERALL	4258.94	20%	80%		

- cable end fittings - swaged ball ends → sockets @ end of cable groove on quad's (cotter-pinned).
- length adjustment - turnbuckles in armament bay (sta. 285 - 485).
- run between quads → 32 pulleys.

FUSELAGE RUN:



RUDDER RUN:



→ ½" dia tubes to feel unit & hinge moment limitation quadrant.

WING RUN:

- 4 pulleys

4.11. REAR FUSELAGE QUADRANTS:

- transfer elevator & aileron cable movements from fuselage out to c/s act. system in wing.
- ELEVATOR R/F QUADRANTS:
  - hor. torque tube @ STA. 675.75, 19.58 above datum.
  - push rod → R.H. el. jack pivot pt. bell-crank
  - push rod → L.H. el. jack pivot pt. bell-crank with lever on opposite end of torque shaft.
  - quadrant at point where elevator command (parallel) servo (4.13.2) & el. feel unit (4.12.2) are introduced.

DIA. 10.70	MOV. 60°	CABLE MOVEMENT 6.283 IN.

- AILERON R/F QUADRANT.
  - on ℄ @ STA. 683.14, normal to wing surface.
  - push rods → between levers → quad with ail ten reg's in wing.
  - aileron command (parallel servo) is introduced here

DIA. 8.9	MOV. 60°	CABLE MOVEMENT 4.25 IN.

all cable movements quoted are less cable stretch.

4.12 FEEL & TRIM UNITS:

- positional springs of a suitable spring constant earthed to the fixed structure thru ~~an~~ an electrical trimming device.
- rudder system + mechanical system to vary bungee effective spring const with q_c - restrict pilot's input as a fcn of compressible dynamic press.
- el. & aileron trim selection → el actuator & brake op'g thru a gear train.

- during manual & automatic modes, trim unit automatically free wheels to follow ||'l servo.
- emergency mode - pilot controls trim actuator by means of thumb button on control column.

4.12.1 ELEVATOR FEEL & TRIM UNIT:
- connected to rear fuselage elevator quad & earthed near fuselage support yoke (697.3.8)
- positioned near to el. actuator control valves to minimise effect of cable elasticity & backlash on system response when operated on mechanical mode.
- feel spring is +ve break out type with a break out stick force adjustable from 0 to 10 LB.
- trim range - fwd 33% full fwd stick movemt.
  aft 60% " aft " "

4.12.2 AILERON FEEL & TRIM UNIT:
- connected to aileron tension regulator quadrant (under cockpit floor) & earthed to the bulkhead @ STA. 176.
- a compromise location (perf. & wt.)
* appears acceptable.
- +ve break out type feel spring unit, break out stick force 0-5 LB.
  40% trim range, sym. @ centre.

4.12.3 RUDDER FEEL UNIT & HINGE MOMENT LIMITATION SYSTEM:
- near rudder jack (ribs 4&5 & spars 7&10)
- cables → push rod connection between cable quadrant & bell crank lever @ jack pivot point → rudder jack valve linkage.
- feel & hinge moment limitation - power for driving mechanism supplied by elevator actuator acting on signals proportional to 'q_c'

QUAD DIA.	5.5 IN.
CABLE MOVENT	4.183 IN.
∠r MOVENT	± 30°

- feel & hinge moment limitation system near jack to ensure full movement of rudder over very small range available when subjected to max. hinge moment limitation conditions.
- displacement limited, but deflection max. deflection between feel unit & rudder pedals is catered for by unrestricted rudder pedal movement.

4.13 PARALLEL SERVOS:

4.13.1. GENERAL:

- electro-hydraulic actuator which performs fcn of moving a/c controls upon command from the stick force system or A.F.C.S.
- hydraulic ram, control valve, engage & disengage valve & solenoid, trim switches, force-limiting valves & overpower valves.
- powered by 'B' hyd. syst.
- control main elevators & aileron control valves thru mech. control linkage in parallel with pilot's mechanical syst'm
- may be overpowered by predetermined force on stick.
- can be disengaged automatically or manually by electric de-energizing the solenoids and upon disengagement of the spring feel system is automatically left in trim.

4.13.2 ELEVATOR PARALLEL SERVO:

- piston end to bottom port of rear fuselage elevator quadrant.
- pivot point mtd forward of quadrant on a bracket supported from the lower wing surface.

- force limited to 150 LB, @ arm 3 IN. exerts max. moment of 450 IN.LB on quadrant, which may be overpowered by 60 LB at stick grip.

4.13.2 AILERON PARALLEL SERVO:
- piston rod to a lever on rear fuselage quad.
- pivot point mtd aft of the quad on fuselage support yoke @ STA. 697.39.
- Servo force limitted to 90 LB, @ 3" → max. moment of 270 IN.LB. on quad, overpowered by 30 LB applied at stick grip.

4.14 DIFFERENTIAL SERVOS:
- high response el-hyd. actuator which performs the fcn of differentially actuating the main control valve to apply artificial damping control.
- hyd. ram & electrical torque motor type control valve, a solenoid disengage valve, and a shaft lock & self centering spring, as req'd.
- elevator & aileron units powered by 'B' hyd thru internal connections to main control valve on which they are mtd directly.
- critical rudder system, power by both 'A' & 'B' hydraulics, thru internal connections to its main control valve.
- non-duplicated elevator & aileron units spring self-centering on shut down of servos electrical or hydraulic supply.
- elevator & aileron units identical:
  - output 300 LB.
  - stroke ± 0.6 IN.
- rudder unit: output 300 LB, stroke ± 0.5 IN.
  - duplicated el & hyd syst., no shaft lock provision
  - standby el. system in continuous operation.
  - on failure of el. or hyd. syst., solenoid by-pass valve fluid to standby side (bypass normal side

4.15 ACTUATOR VALVES:

- double tandem type employing a common spool & two separate sets of press & return ports (for 'A' & 'B').
- mtd on actuators (connection with diff'l servos).
- interchangeability between valves, actuators & diff'l servos.

elevator spool travel	± .125	IN.
aileron spool travel	± .07	IN.
rudder spool travel	± .05	IN.

4.16 CONTROL SURFACE ACTUATORS:

- tandem dual piston & cylinder type, each piston supplied by a separate hydraulic system.
- semi-coiled steel line.
- flexible hose → elevator & aileron return lines only.

4.16.1 ELEVATOR JACK:

- pre-loaded self aligning bearing bolted to jack body.

static jack load	(4000 p.s.i.)	71,000 LB.
cylinder bore	(max.)	4.19 IN.
piston rod O/D	(max.)	2.50 IN.
working area	(2 x 8.88)	17.76 IN^2
normal operating stroke		10.0 IN.
total stroke		10.2 IN.

4.16.2 AILERON JACK:

- 4 needle brgs - universal jt bolted to jack body.

static jack load	42,100 LB.
cylinder bore (max.)	3.125 IN.
piston rod O/D (max.)	1.75 IN.
working area (2 x 5.26)	10.5 IN^2
normal operating stroke	5.56 IN.
total stroke	5.76 IN.

4.16.3 RUDDER JACK:

- pre-loaded self aligning brg:

static jack load	30,000 LB.
cylinder bore (max)	2.75 IN.
piston rod O/D (max.)	1.625 IN.
working area (2 x 3.865)	7.73 IN.^{2}
normal operating stroke	5.0 IN.
total stroke	6.10 IN.

4.18 CONTROL SURFACES:

CONSTRUCTION:

- light alloy ribs & skin, extruded light alloy front spar with piano hinge on top.

4.18.1 ELEVATOR:

area (2)	106.75 FT.^{2}
span (each)	10'-2"
chord (const.)	5'-3"
movement	30° up.
	20° down.

4.18.2 AILERON:

area (2)	66.5 FT.^{2}
span (each)	10'
chord	5'-3" root
	1'-4.8" tip
movement	10° up
	10° down

4.18.3 RUDDER:

area	38.85 FT.^{2}
height	10'-0.5"
chord	5'-5.14" root
	2'-3.7" tip
movement	± 30°

4.18.4 SPEED BRAKES:

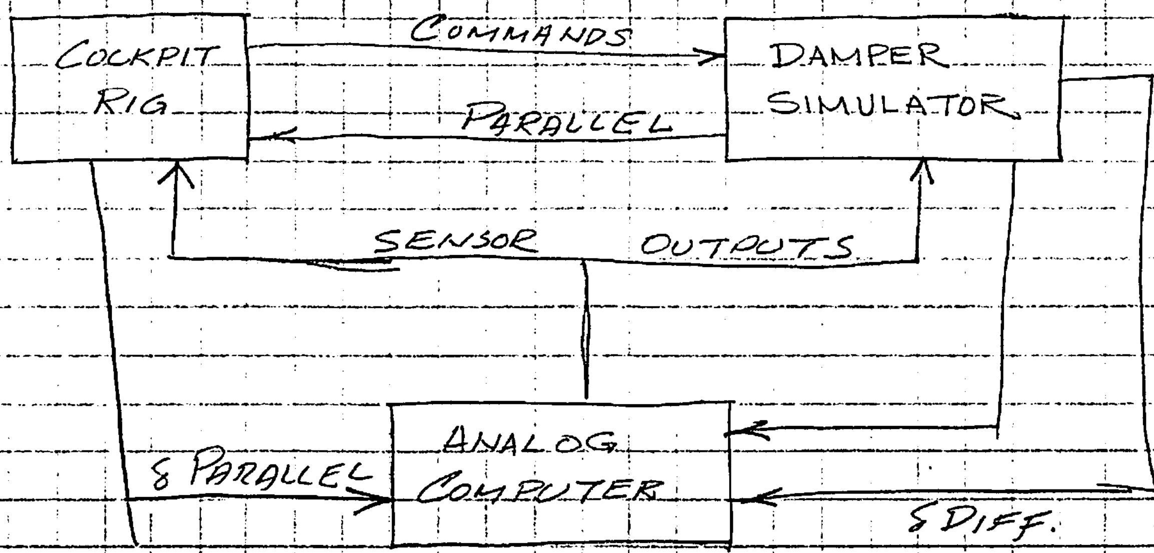
- throttle lever mounted thumb button, which opens or closes the elevator (~~solenoid~~) circuit to a solenoid operated hydraulic control valve.
- single cylinder & piston jack, swivel couplings

static jack load	22,500 LB.
cylinder bore (max.)	2.875 IN.
piston rod O/D (max.)	1.00 IN.
working area (tension load)	5.70 $IN.^2$
stroke	12.50 IN.

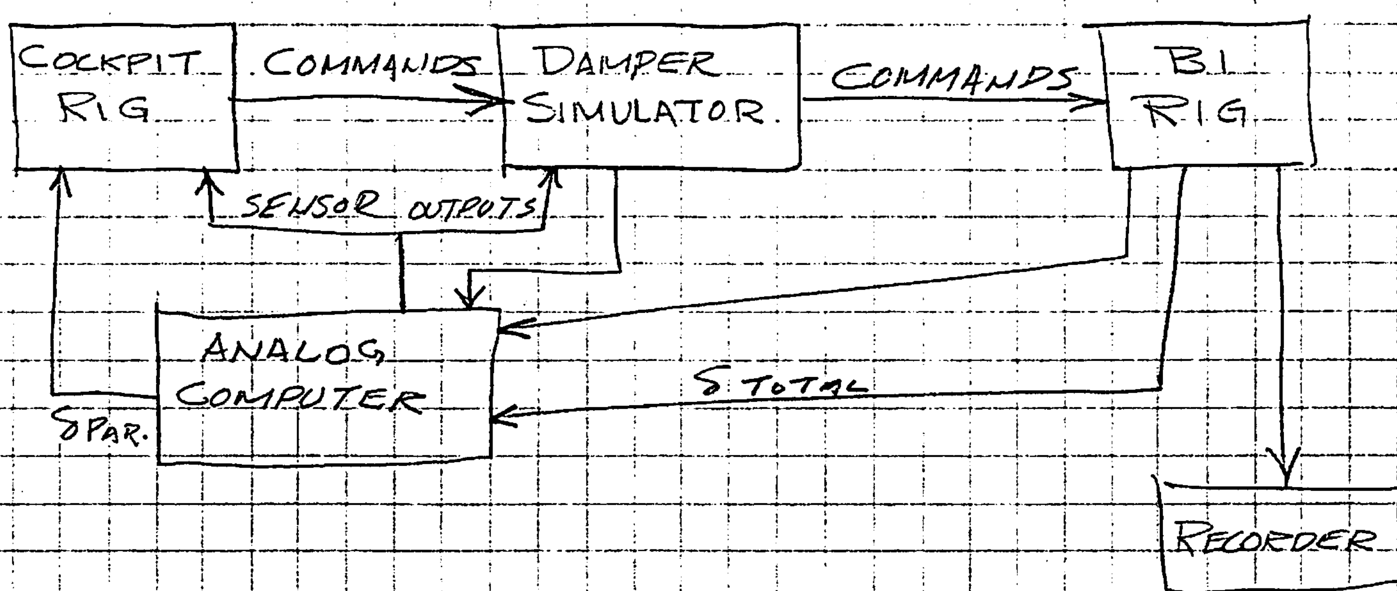
4.18.5 air brake construction

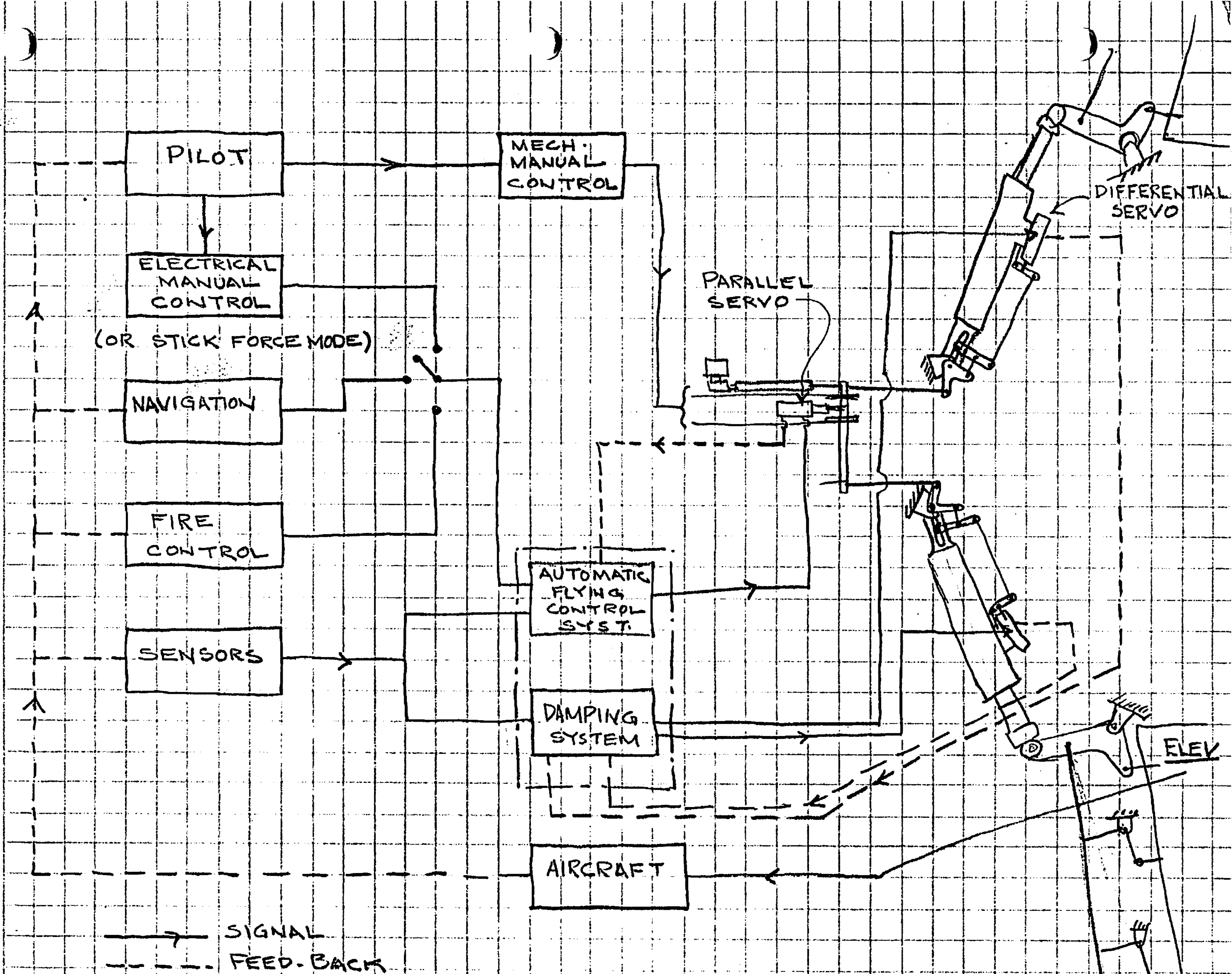
width (each)	2'-2"
length	3'-3.5"
area (total)	14.3 $FT.^2$

DAMPER SIMULATOR & COCKPIT RIG TESTS:



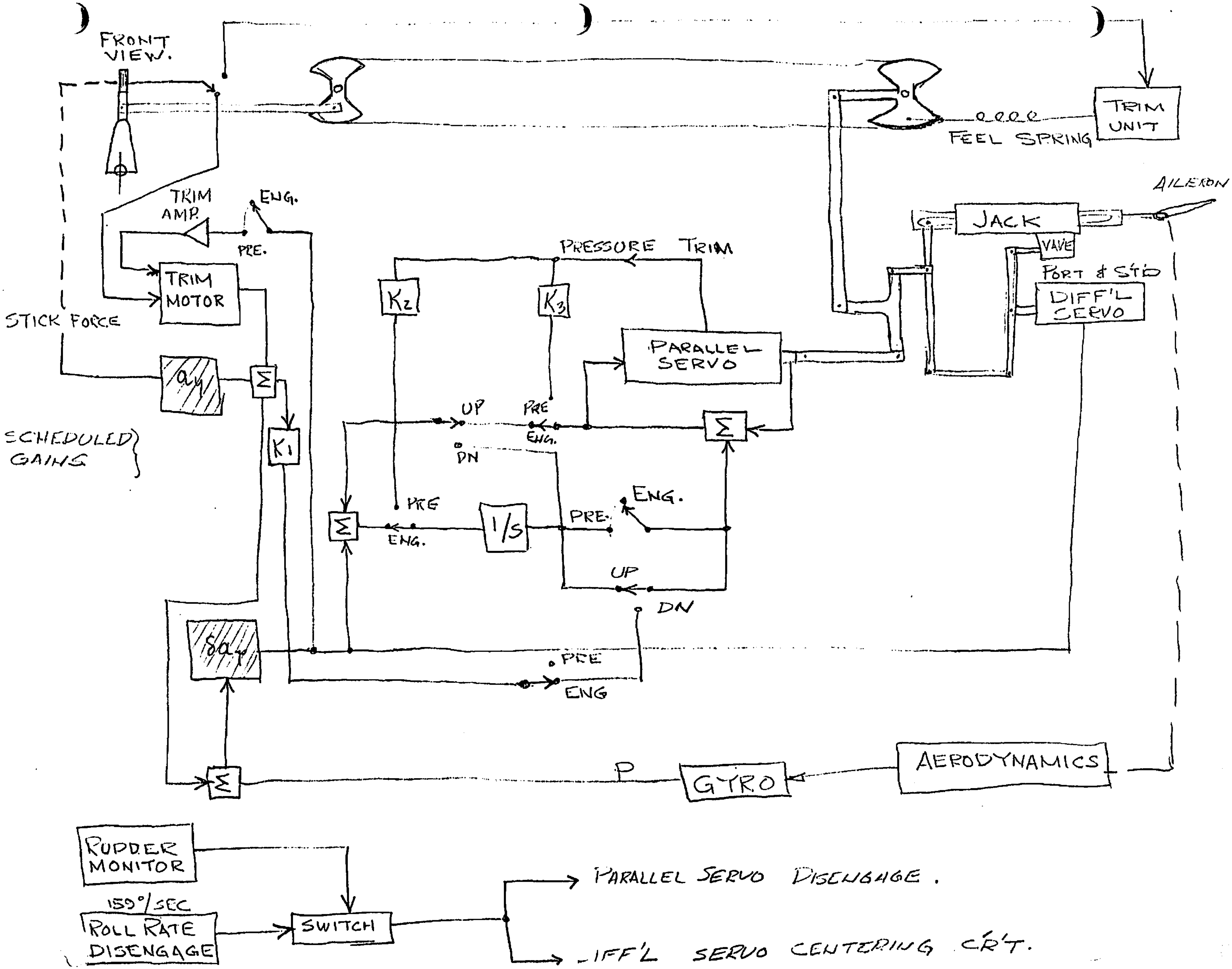
B-1 RIG, COCKPIT RIG & DAMPER SIMULATOR TEST



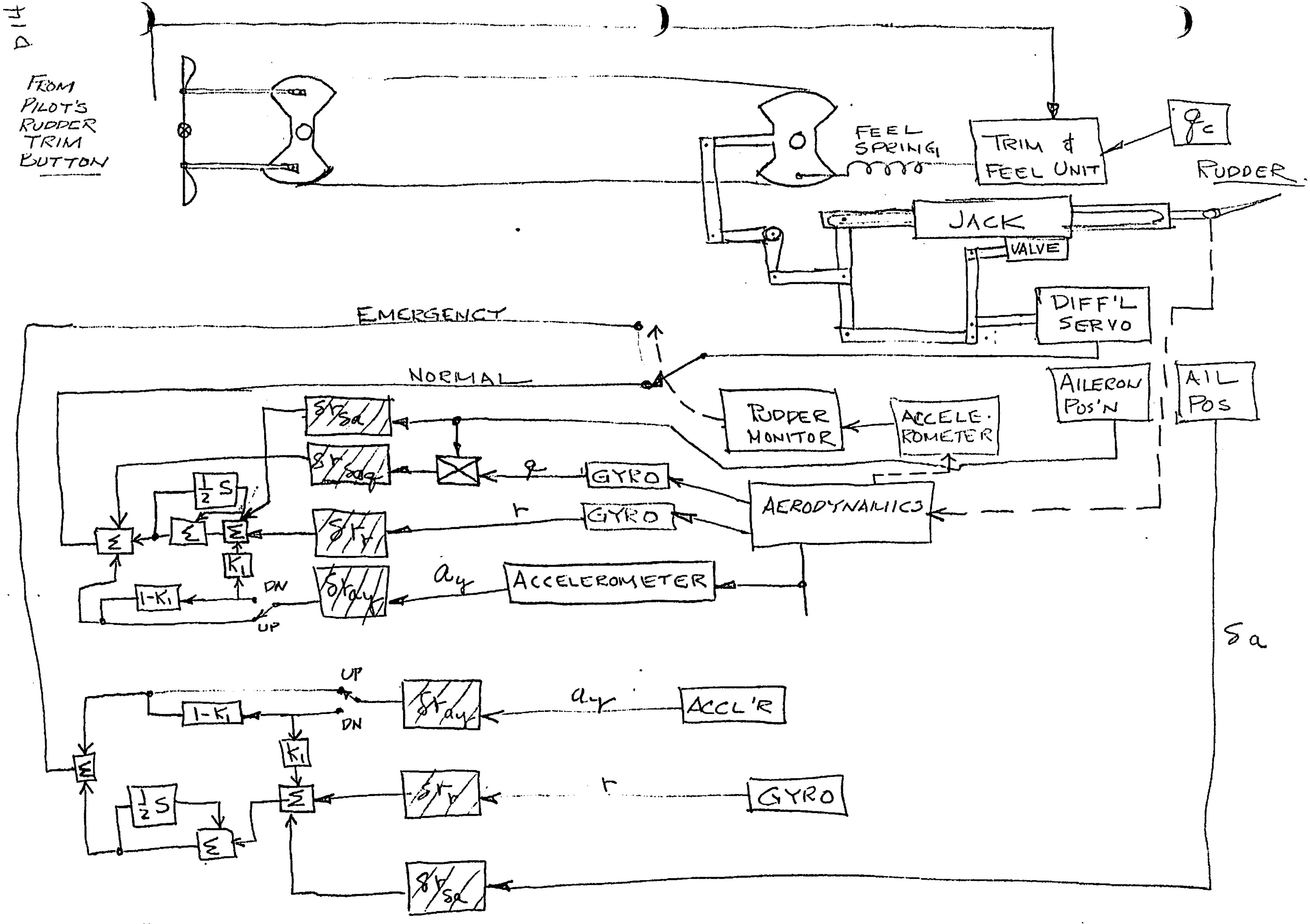


F EVATOR BLOCK DIA.

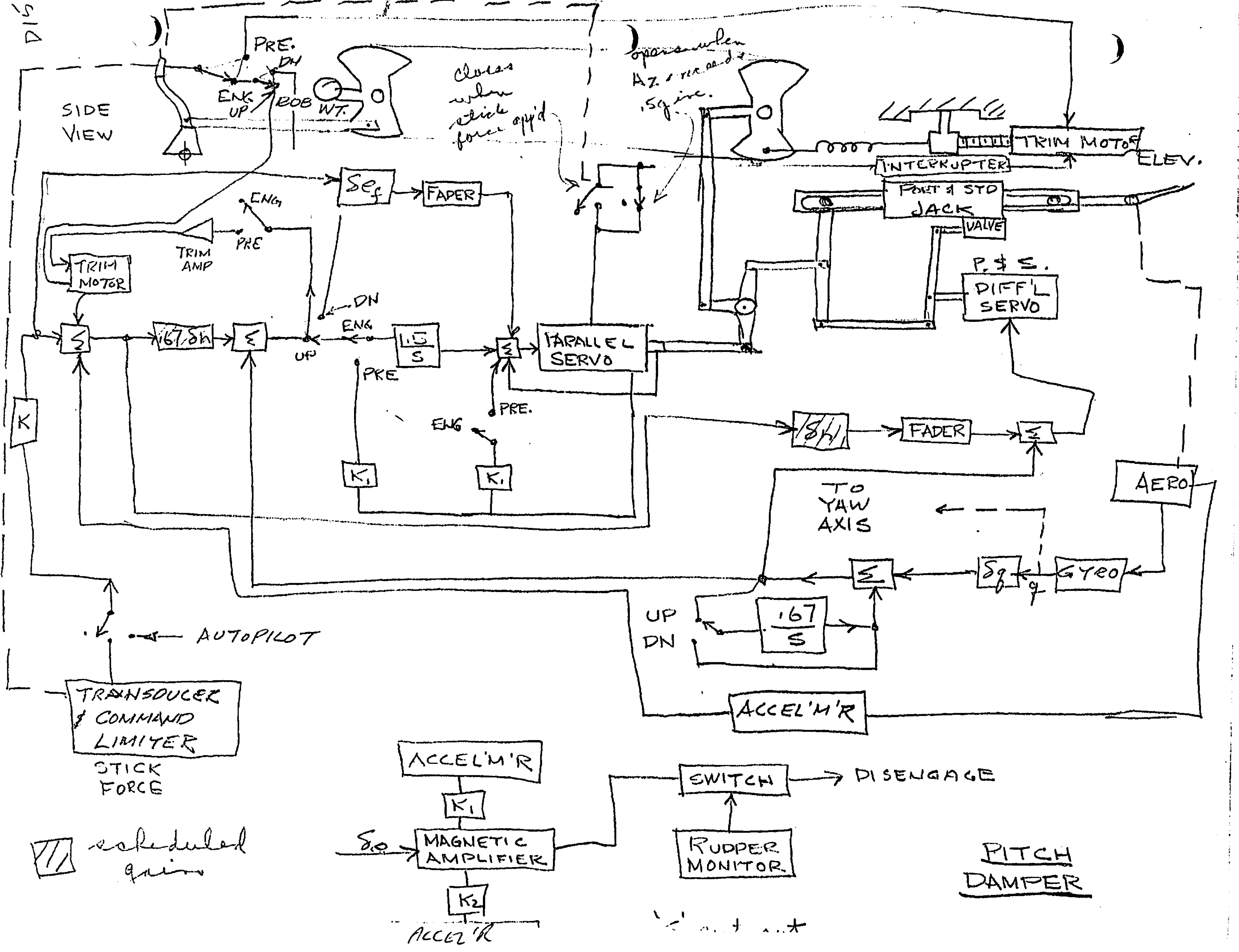
ROLL DAMPER



FRONT VIEW.
TRIM UNIT
FEEL SPRING
AILERON
JACK
VAVE
PORT & STB
DIFF'L SERVO
TRIM AMP.
ENG.
PRE.
TRIM MOTOR
STICK FORCE
PRESSURE TRIM
K2
K3
PARALLEL SERVO
a_y
Σ
K1
UP
PRE
ENG.
DN
SCHEDULED GAINS
PRE
1/S
PRE.
ENG.
UP
DN
δa_y
PRE
ENG
P
GYRO
AERODYNAMICS
RUDDER MONITOR
159°/SEC
ROLL RATE DISENGAGE
SWITCH
PARALLEL SERVO DISENGAGE.
DIFF'L SERVO CENTERING CR'T.


FROM PILOT'S RUDDER TRIM BUTTON
FEEL SPRING
TRIM & FEEL UNIT
RUDDER
JACK
VALVE
DIFF'L SERVO
EMERGENCY
NORMAL
RUDDER MONITOR
ACCELE-ROMETER
AILERON POS'N
AIL POS
GYRO
GYRO
AERODYNAMICS
ACCELEROMETER
DN
UP
δa
UP
DN
ACCL'R
GYRO
SCHED'D GAINS.

YAW DAMPER.



PITCH DAMPER

DAMPING SYSTEM DEVELOPMENT.

1. GENERAL REQ'TS:

1.1 to damp short period oscillations about all three axes.

1.2 to damp longitudinal long period oscillations

1.3 provide spiral stability, rate of divergence is less than double amplitude in 20 secs.

1.4 provide stability augmentation in yaw - 80% fin limit load not exceeded.

1.5 provide manual emergency control compatible with normal system (flt commands from electrical control stick or automatic modes).

1.6. response to commands compatable with req'ts of fire control.

1.7. provide acceptable feel characteristics resulting in stick force per 'g' and stick force per unit rate of roll essentially constant within the speed and altitude range, with exception of low speed.

1.8- provide positional feel in all three axes in landing & take-off configuration.

1.9 - provide acceptable trimming characteristics.

1.10- safeguard a/c against manoeuvres resulting in prohibitive load factors (normal acceleration, transverse accel'n, rate of roll).

1.11- minimise sideslip in manoeuvres (turn co-ordination).

1.12- provide for unco-ordinated manoeuvres at low speed (i.e., landing with sideslip)

1.13- provide satisfactory feel characteristics in yaw axis during sideslips at low speeds.

2. EMERGENCY MODE REQUIREMENTS:

2.1 complete duplication of the part of normal system providing stability augmentation in yaw.

2.2 provide 1.4, 1.10, 1.11, & 1.12.

2.3 switching.

2.4 switching from one mode to another should not result in sudden changes in level of control forces in any axis.

2.5 automatic changeover in case of failure of any component causing dangerous build-up of load factors.

3. FUNCTIONAL DESCRIPTION:- NORMAL DAMPER:

3.1 PITCH AXIS:-

3.1.1. three basic inputs in pitch axis:
- stick force (el. output of stick force transducer)
- normal acceleration (accel'r 22' fwd of C.G.)
- pitch rate (pitch rate gyro.)

- operation: stick force compared with normal acceleration and error signal drives parallel servos.
  - results in essentially constant stick force / 'g'.
  - pitch rate → short period damping and normal accel'n phugoid damping.
  - suitable trimming units, switches, and faders for low speed operation are provided. (also a 'g' limiter).

3.1.2 PITCH RATE:

- gain schedule based on compressible dynamic pressure (q_c) - fed into differential servos thru a high pass filter while effective proportional signal is fed into parallel servo.
- avoids differential servo sat'n under high steady state normal load factors

(damping assured under all cond's.).

3.1.3 NORMAL ACCELERATION & STICK FORCE ERROR SIGNAL:

- error signal fed thru a q_c gain schedule to diff'l servo and also thru another gain schedule (q_c and altitude) to the integrator in front of the parallel servo.
- minimizes undesirable stick shaking in gusty air associated with normal feed back, while providing phugoid damping.

3.1.4. TRIMMING - MANUAL:-

- with this arrangement, no trimming is necessary for level flt (apart from minor corrections due to interference, stray voltages, etc.)
- to trim into a manoeuvre pilot's button operates a motor which introduces a signal into the comparator, trimming to any desired load factor.

3.1.5. TRIMMING - AUTOMATIC:-

- to provide desirable feel effects in cases of failure of the normal damper the automatic trim is added.

3.1.5.1 With pilot exerting force at the stick:

- trim motor is actuated by the pressure pick-up in the parallel servos in such a manner that servo load is transmitted fully to the feel spring.
- on disengagement of the parallel servo there is no change in stick force level.
- if stick force is released, a/c will be out of trim and has to be retrimmed manually.
- advantage in that servo operates

with small loads, thus permitting optimum performance & also in case of main control valve tending to jam the trimmer spring helps to overpower the increased forces.

- interrupter is provided in the trimmer motor crct to adapt it for continuous operations.

3.1.5.2 <u>With no force on the stick</u>:

- as above, but returns to within ±0.5 'g' of level flt.
- separate accelerometer is utilized.

3.1.6. <u>PRESSURE TRIM</u>:

- provided in parallel servos to avoid engagem't when pressures in servo are not equalized.
- assures smooth engagement free of undesireable stick movements.

3.1.7. <u>COMMAND LIMITS</u>:

- output of stick force transducer limited to 4-6 'g'.
- fixed on prodcn a/c.
- also can vary stick force/'g' for development purposes.

3.1.8. <u>"G" LIMITER</u>:

- to disengage the system in case of malfunction of any of the components.
- operates from two accelerometers (1 fwd, 1 aft of C.G.) & two servo position pick-offs (parallel & diff'l).
- signals combined in amplifier thru filtering networks to obtain enough anticipation and assure proper functioning of limiter under all flt cond's.

- separate pick-off on each diff'l servo.
- parallel servo pick-off protects against servo runaway.

- 'g'-limiter automatically disengage normal pitch axis at such level of normal acceleration that resulting overload will not exceed structural limits under all flt conditions.
  - rudder monitor signal connected to 'g'-limiter to disengage the normal mode whenever rudder axis fails.
- disengagement-contact on parallel servo which releases the pressure and another contact which recenters the diff'l servo. Diff'l servo will recenter immediately <u>only if</u> this action is going to reduce the resulting load factor, otherwise the diff'l servo is centered by normal damper action and then disengaged.
- when disengagement is completed, a/c will be in emergency mode of control and then pilot is responsible for not exceeding structural limit of airframe.

3.1.9. <u>LOW SPEED OPERATION:</u>

- undesireable to maintain constant stick force/'g' at low speed - over sensitive control.
- require proportional feel.
- switches & faders which operate automatically with undercarriage selector switch (U/C down).
- <u>Operation</u>: normal acceleration input into the diff'l servo is faded out and pitch rate proportional signal introduced thus bypassing the high-pass filter. This provides good short period damping

normal inputs into the parallel servo are cut-off & the proportional signal introduced into the junction box of the parallel servo by running up the fader in the line.

- Trimmer button is connected directly to the integrator.

3.1.1.0. PRE-ENGAGE SWITCHES:

- to energise components & assure smooth engagement.

3.2. ROLL AXIS:

3.2.1 - Two basic inputs:

- stick force (stick force transducer)
- roll rate (gyro output).
- stick force and roll rate error signal drives servos.
- result → essentially constant stick force per unit rate of roll.
- suitable trimming units and switches for low speed operation and rate of roll limiter.
- command limiter scheduled on traverse accel'n is included (for safety)

3.2.2. ROLL RATE & STICK FORCE ERROR SIGNAL:-

- error signal fed thru a q_c gain schedule into both parallel & diff'l servos.
- result → optimum conditions from point of view of response to command signals & damping of the "dutch roll" mode.

3.2.3. TRIMMING - MANUAL:-

- electrical input to comparator, thru a motor operated by pilot's button.
- automatic trim not included.

3.2.4. PRESSURE TRIM:-

- provided (as in 3.1.6).

3.2.5. COMMAND LIMITS:

- command limiter is provided in the stick force transducer @ 120°/sec of roll rate.

- also, a limiter scheduled with transverse acceleration.

- this limits the command at some conditions to a value (below 120°/sec.) → not give excessive fin loads.

- applies at high dynamic pressures and @ low supersonic speeds @ high alt's.

- latter cond's → action noticed in rolls exceeding ± 180° of roll angle, while up to this angle max rates of roll can be realised.

- stick force per unit rate of roll is essentially constant so that max. rate of roll (120°/sec.) corresponds to full aileron force (20LB.).

3.2.6. ROLL RATE LIMITER:-

- protection against system function.

- operates from wing tip mounted accel'rs, has an input from rudder monitor to disengage normal mode when a failure occurs. Disengagement → by disconnecting parallel servo & recentring of diff'l servos.

3.2.7. LOW SPEED OPERATION:-

→ proportional fuel @ low speed → switches op'g automatically with U/C selector switch (U/C down).

-operation- a proportional signal with constant gain K, is introduced into parallel servo & the integrator is disconnected. Error signal remains in diff'l servos providing damping of "dutch roll" mode.

3.2.8. PROVISION FOR SYMMETRICAL DEFLECTION of AILERONS:

- symm. defl'n of ailerons (above 45,000' & M>1) → reduction in trim drag.
- achievment - splitting quadrant thru which commands are delivered to each aileron.
  - relationships of two halves to the command system are then governed by a jack controlled by an altitude switch - chges neutral setting by desired amount.

3.3. YAW AXIS:

3.3.1 Four basic inputs:
- transverse accel'n (accel's ≈ 13' fwd of C.G.)
- yaw rate (gyro output)
- aileron position (ail. pos'n pick-off.)
- prdct of pitch rate & aileron position.
- transverse acceleration provides stability augmentation
- yaw rate assists in damping of "dutch roll"
- high-passed aileron position controls side-slip in rolls entered from level flt.
- product of pitch rate and aileron position offsets inertial cross-coupling effects in rolling pull-outs.
- unco-ordinated manoeuvres are almost impossible.
  - switch added to provide for intentional sideslipping @ low speeds.
  - rudder monitor - automatic switch over to emergency loop in case of malfunction.

3.3.2. YAW RATE:-
- q_c gain schedule & fed into diff'l servo thru a high pass filter.
- contributes to damping, esp'y @ high altitudes by causing the rudder to oppose yaw rates.

3.3.3 AILERON POSITION:-

- q_c schedule & is fed into diff'l servo thru some high pass filter, thus steady state aileron will not produce a signal in this channel.
- steady state aileron may be req'd in level flt to balance asymmetric moments.

3.3.4. TRANSVERSE ACCELERATION:-

- q_c schedule & is fed directly into the summing point in front of differential servo.
- effect - similar to that of a sideslip angle feedback in that it will tend to minimise sideslip under all cond's.
- (since accelerometer registers total aerodynamic force acting on the airframe rather than acceleration. Main component of force is sideforce due to sideslip angle. ∴ sideslip minimisation will be provided also under steady state cond's where transverse accel'n of airframe is present.)

3.3.5. PRODUCT of PITCH RATE & AILERON POSITION:-

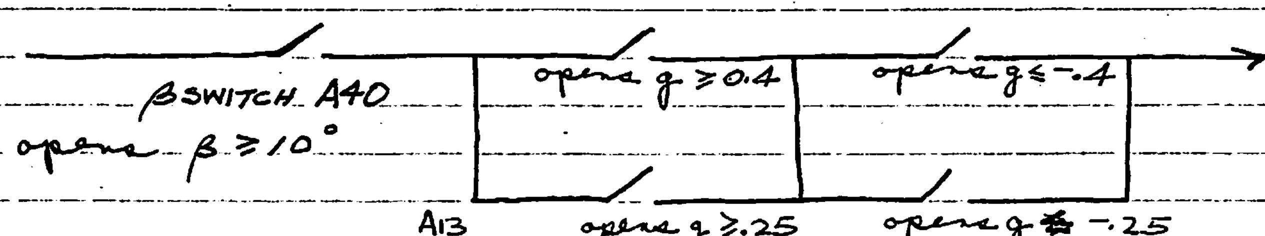
- obtained in damper & fed thru a q_c schedule into the rudder diff'l servo.
- inertia cross-coupling effects on low aspect ratio a/c ⇒ weathercock stability in yaw effectively reduced in proportion to the product of pitch & roll rates causing excessive buildup of sideslip in rolling pull-outs.
- to offset this effect, prdct of pitch rate & aileron ∠ was introduced.
- aileron ∠ used instead of roll rate ∵ more anticipation is obtained in this manner & it is more convenient for scheduling.

3.3.6. TRIMMING:-

- no parallel servo ∴ el. trimming not req'd.
- conventional trim provisions incorporated within rudder feel unit.

3.3.7. RUDDER MONITOR:-

- provides protection against malfunction of system by switching over to emergency whenever transverse acceleration or sideslip approaches structural integrity limits.
- switching mechanism operates on all 3 ones.
- rudder monitor operation based on 2 transverse accelerations & a sideslip switch
- accelerometers 13' fwd of c.g. & 40' fwd set to open @ 0.25 'g' & 0.40 'g' resp'y.



- switching → when both accel'ns ≥ values shown & both in same direction.
- such combination of accel's is possible only in rudder runaway, co-ord rolling → opp's signs.
- A13 detects direction of sideslip
  A40 " indication of yawing accel'n.
- if yawing accel'n helps reduce sideslip, cut-out will occur @ relatively large values of accel'n (≃ 0.6-0.7 g @ c.g.) opposite sense (≃ 0.2-.3 g @ c.g.).
- this complicated monitor results from cross-coupling.
- co-ordinated man's relatively large values of transverse & yawing accel's needed & system must be able to

pass these & cut out only when failure occurs.
- accel's alone will not produce desired fcns @ low speeds ∴ small accel's → high slip ∠. ∴ a/c has undesireable characteristics ∠ > 12°-12° additional switch provided. (>10°).

3.3.8. LOW SPEED OPERATION:-
- switch (from U/C down) to allow intentional slip.
- achieved by high-passing most of transverse accel'n signal while a small part is fed directly.
- results in well damped "dutch roll" mode while rudder moves in natural direction @ high sideslip ∠'s @ low speed.
- clean configuration → tendency for small or opposite rudder angles req'd for landing in high X-wind (unnatural feel for pilot)
- so limitation on landing speed
- above syst → acceptable characteristics of rudder to sideslip ∠ ratio @ low speeds.

4. FUNCTIONAL DESCRIPTION:-
EMERGENCY MODE:-

4.1. PITCH AXIS:-
- all servos & stick force transducer disconnected
- no electrical signals (except trim unit)
- mechanical connections to main control valves.
- proportional feel provided together with conventional trim unit.

- command & 'g' limiters inoperative
  - responsibility of not exceeding structural limits rests with pilot.
  (some cases protected by hinge moment & elevator deflection limiters).

4.2 ROLL AXIS:
- all servos & stick force transducers disconnected.
- mechanical connections to control valves.
- proportional feel & conventional trim unit provided
- limiters inoperative, pilot must not exceed structural limits.
- transverse acceleration feedback not operating ∴ pilot must restrict roll rate commands, especially in rolls entered @ high normal accelerations.

4.3 YAW AXIS:-
- three inputs:
  - transverse acceleration
  - yaw rate
  - aileron position
- emergency mode inputs → same principle as normal; reliability → separate sensors used.
- RUDDER FEEL & TRIM UNIT:
  - pedal force / unit rudder deflection scheduled $\propto q_c$ to restrict rudder application by pilot.
  - high pedal forces → small deflections at high speed.
  - pilot force (150LB); $\frac{1}{5} \rightarrow \frac{1}{3}$ total jack travel @ high speeds, full rudder deflection @ low speeds.

- trim authority, proportional to & somewhat higher than pilot's authority @ high speeds, while full rudder can be trimmed @ low speeds
- permits un-coordination of sideslip to a limited extent @ high speeds & sufficient to escape with asymmetric power & other moments throughout speed range.

- Low speed operation identical with normal mode.

5. TEST PROGRAMMES:-

5.1. COCKPIT RIG:-
- Purpose:
  - solve prob's connected with feel & handling characteristics
  - familiarize pilots
  - establish flyability regions (emergency cond's).
  - develop instrumentation (for prdn a/c)

5.2. DAMPING SYSTEM SIMULATOR (from M.H.)
- non flt worthy damper
- in conjunction with analog computer, cockpit rig, & B-1 rig.
- assessment of electrical hardware of damping system.
- performance of individual eq't, & effect on system.
- with other rigs, functionally prove behaviour of damping system (servos, control surfaces, etc.)
(time delay in system ⇒ insufficient no. of demodulation channels!)

5.3. B-1 RIG:-

- req'd for tests on damping system (+ other tests)
- separate axis development
- combined (3) axes runs.

5.4. FLIGHT TEST:-

DEVELOPMENT OF AUTOMATIC FLIGHT CONTROL SUB-SYSTEM FOR ARROW A/C.

3.2 FUNCTIONS:

3.2.1. The A.F.C.S. in conjunction with the other sub-systems enable the interceptor to perform the following functions:

a.) Automatic Attack
b.) Automatic Navigation
c.) Automatic approach for Landing
d.) Pilot assist Fcns Consisting of:
  i) Heading Hold
  ii) Bank Hold
  iii) Altitude Hold
  iv) Mach Hold
  v) Pitch Hold
  vi) Manual Control by A/C Control Stick.

3.3 SUB-SYSTEM INPUTS:

3.3.1 COMMAND INPUTS:

3.3.1.2 AUTOMATIC ATTACK:
- Command signals from computer sub-system
- to fly correct firing course during attack
- breakaway by stick (force preselection
- STUDY - automatic breakaway

3.3.1.3 AUTOMATIC NAVIGATION AND INTERCEPTION:
- close control-signals from data link receive
- automatic broadcast control-signals from navigation computer
- Dead Reckoning Navigation - from navigational computer & directional gyro

3.3.1.4. AUTOMATIC APPROACH FOR LANDING:
- AGCA through data link receiver in A/C
- STUDY - automatic landing

3.3.1.5 - PILOT ASSIST:
- select req'd functions
- provide command signals to perform assist fcns.

3.3.2. OTHER INPUTS:

a.) Heading
b.) Attitude angles
c.) Attitude rates
d.) Acceleration data
e.) Mach No.
f.) Pitot pressure 'q'.

3.6.2. MODES OF OPERATION:

3.6.2.2. PILOT ASSIST MODE:

a.) AFCS maintain a/c according to further selection by pilot of subsidiary functions described below.
The only commands are those inserted by pilot.

b.) Function Selections:

i.) HEADING HOLD:
- normally engaged during pilot assist mode.
- no selection switch provided.
- auto-disengage - small stick force.
- re-engage when bank is 3° to 5°.
- maintain a/c heading within ± 1°.

ii.) BANK HOLD:
- AFCS hold A/C bank angle selected by pilot by normal control.
- no selection switch
- threshold for bank holding 3°-5°; override by light stick force.

iii.) ALTITUDE HOLD:
- switch selected & holds pressure altitude (±10 ft. or 0.1% whichever is greater)

iv.) MACH HOLD:
- switch selected

v.) PITCH HOLD:
- selection is central position on altitude / Mach Hold switch.

vi.) MANUAL MODE:
- Pilot commands manoeuvres through control stick; force sensing pick-offs shall provide the command signals.
- Light break-out forces to produce disengagement of hold functions and cause switching from AFCS to damping mode for duration of commands.
- Upon completion of command manoeuvres and return to zero stick force, the appropriate attitude hold shall be automatically engaged.

3.6.2.3. NAVIGATION MODE:
a.) AUTOMATIC DEAD RECKONING MODE OF NAVIGATION:
- AFCS steers a/c in azimuth to destination computed by navigation computer and heading hold from directional gyro.
b.) BROADCAST CONTROL MODE OF INTERCEPTION AND RETURN TO BASE:
- AFCS steers a/c.
- signals from navigation computer or stick force
- Mach Hold may be used.

3.6.2.4. CLOSE CONTROL MODE:
- AFCS - signals from Data Link
- function: interception, return to base, and approach for landing.

3.6.2.5. ATTACK MODE:
1. Requirements:
a.) Noise component of steering command signals shall be adequately smoothed in relation to range and flight parameters so as to minimize:

i.) miss due to noise
ii.) random control surface movement
iii.) roughness of ride for crew

b.) Rapid response to minimize initial heading errors and miss due to target manoeuvre.

c.) Adequate dynamic stability shall be provided in all degrees of freedom of a/c and system.

d.) Static bias shall be as small as possible.

2.) Auto steering in azimuth and elevation provided for lead collision and lead pursuit attacks.

3.) Optical attacks: in either of pilot assist or damping modes.

3.6.2.6. DAMPING MODE:
- AFCS disconnected from control loop.
- Control directly by pilot, damping system fully operative.

3.6.2.7. EMERGENCY MODE:
- AFCS disconnected
- Control by pilot, emergency damping system operative.

3.6.3. COMMAND SIGNAL LIMITING:
- When computer demands a manoeuvre approaching value of normal acceleration which would cause a/c to enter the buffet zone or to approach structural 'g' limit the AFCS shall limit the executive signal to avoid either of these effects.

- Demanded manoeuvre is continued at limited rate until the demand is satisfied.
- Command Signal Limiter shall operate in all modes except Emergency Mode.

3.6.4. Rates of Response:
- up to max. allowable by crew or 'g' limiter.

<u>3.6.1.4.</u> Acceleration Range:
a.) Normal acceleration of +6 'g' in pull-outs, +4 'g' in turns, and −2 'g'.
b.) lateral acceleration ± 0.2 'g'
c.) fore-&-aft acceleration + 1.5 'g' to −1.0 'g'.

<u>3.6.1.1.</u>
c.) Equivalent Air Speed: 700 knots max. (720 ?).

Oct. 10/56.

✓ NACA. 664. - flaps.
also report by Young.
determine air loads by pitching moments.

- Also do a comparison with pneumatics.

* { - Normal Force on flaps & controls R.Ae.S. data sheets.
@ ⅓ flap chord. FLAPS. 05. 01. 01

✓ - - Aerodyn. Drag. - Hoerner. 533.6.013.12
also legs (drag on). p. 133.

✓ John H. Meyer - McDonnell A/C.
Aero Eng. Review March 1948.
- The Design of Secondary power systs ... A/C.

✓ - - Aero. Eng. Review. Vol. 7. 1948.

~~Pneumatic systems for A/C. 629.13.064.~~

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Patterson Product Eng. Vol. 25 April 1954
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(Brady, Paul L.)
- Pneu. for ~~use~~ ancillary power in A/C
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(Hearle. H.R.)
- Pneumatic units for A/C.
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Taylor pp. 574-578.
(Webb. S.R.)

Pod Wilson & K Bateman

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Notes on Applied Science. No. 12.
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Paul Greebler. pp. 374-378.
Jet Propulsion, Nov-Dec. 1954.

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& A.S.M.E.

Resumé of Meeting with Mr. Spillman
Sept. 1956.

It was agreed that the best methods of approach re Thermal Insulation was:

i.) Review heat transmission theory.

ii.) Dismantle & re-assemble rig in order to become completely familiar with the unit.

iii.) Upon re-assembly, colour code and chart complete system.

iv.) Complete a test run upon the rig to ascertain whether end effects are influencial.

v.) If end effects are large, rig must be altered as soon as possible.

vi.) If effects are not large, carry out standardization test on sheet.

vii.) The existing theory should be checked by the end of the first term. Rigs must be devised for further tests. One example being a vacuum plate. Others must be devised.

ITEMS to be checked During TESTING:-

i.) When standardising the heating surface, test section in both hor. & vert. plane as air will circulate in granular solid.

ii.) Layers of aluminium foil look much more attractive than asbestos (fibre glass not given.) both re. ρ. & k.

iii.) Has it ever been shown which part of A/C receives greatest degree of kinetic heating? Presumably all leading edges surfaces. Could be shown on a model made of a mat'l which sublimes just above room temperature.

YES IT HAS.

The stagnation pts.

RECORD:-

OCT. 12/56
Wired test specimen up & with the help of George Flavel. - insulation thickness = 1.5 inches -

OCT. 13/56 Completed wiring two test thermocouples and did a calibration test of copper-constantan thermocouples using freezing & b.pts of water. These checked to within ½ of 1% of std figures (Ref Tables for Thermocouples N.B.S. 561).
See other side of page.

OCT. 14/56. Completed low temp. test on section. Model was sitting on table. The temperatures stabilised after about 5 hrs. running.
Temperature loss at edges is low.

OCT. 17/56 Completed higher temp. test on box in 5 hrs c.f. 15 hrs. of Sopers. Sindanyo reinforcing cracked. Temp (heat flow) around end seems low - temps still to converted & confirmed!
Attempts will be made with cracked sindanyo - effects will be known when checked with theory.
Mr. Borthwick started the large refrigerator and had shelves installed for convenience.
Discussed with Mr. Borthwick the running of the calibration sheet.

OCT. 16/56 Discussion with Mr. Spillman on the evacuation of boxes. It was felt better to use an evacuated box rather than the evac. chamber. (chamber is large heat sink.)

Oct. 17/56.

Discussed the zero drift of the Cambridge box with Mr. Trotman. It was felt that the drift was due to 2 causes:-

1.) room temperature increase.
2.) the current in the ~~box~~ wiring slowly heated the ~~wiring~~ box up.

Oct. 13/56.

The determination of the temp of boiling water was difficult to measure. 2 conclusions were drawn.

1.) the ~~vapour~~ temperature of the vapour immediately above the surface was the only reliable point to read the temp.
2.) sufficient length of the thermocouple wire must be ∥'l with the water surface (i.e. @ same temp.) in order to prevent heat conduction & radiation effects from the wires. (Ref. § 15. p. 203 thermocouple experiments of H. Reiher)

Also it was decided with Mr. Trotman that we should not take the box apart as the thermocouples were to difficult to assemble in the first assembly.

OCT. 23/56.

Readings were taken up to this date.

OCT. 24/56.

Mr. Flavel & myself wired the thermocouples wires of the guard-plate rig onto the switch. Arrangements were made with Mr. Fratman & Mr. Borthwick to obtain a water drain system and electrical equipment - Variacs, A/C ammeters & voltmeters, and a power-factor meter (or watt meter.)

OCT. 25/56.

By this time it was obvious that the gaurd plate had been constructed inncorrectly but decided to take several readings in order to see the type of values obtainable.

Points which are wrong are:-

1.) The heat flow should not be measured by the water flow, but electrically.

2.) The water paths in the guard plate were not chosen correctly.

3.) Hence the gaurd element top thermocouples were not added.

4.) No provision was made for adding guard plates above the gaurd element. (The gaurd elements are entirely to narrow.)

It appears obvious at this date that the main rig suffers from the same type of troubles - poor design. Commence design on new rig - circular.

→ - It has come to mind that the cold junctions of the thermocouples have not been judisciously chosen. It is proposed to take these all to a propper cold junction of ice. (32°F.)

- provide for at least 50 wires.

REVIEW of HEAT TRANSMISSION.

REF. HEAT TRANSMISSION
WILLIAM H. McADAMS.
McGRAW-HILL.

CH. I. INTRODUCTION:

i.) CONDUCTION:

the instantaneous rate of heat transfer dq is proportional to the area dA through which heat flows at right angles & to the temp. grad. $-dt/dx$

$$dq = -k\, dA \frac{dt}{dx}$$

proportionality factor k - "thermal conductivity" (range of ten thousandfold)

ii.) THERMAL RADIATION:

$$dq = \sigma \epsilon\, dA\, T^4$$

dimensionless factor ϵ "emissivity" (range $0 \to 1$)
proportionality factor σ "dimensional constant" = units

iii.) CONDUCTION & CONVECTION:

heat transfer from the surface of a solid @ temp t_s to a fluid having bulk temp t flowing past it is complex → NEWTON'S LAW OF COOLING.

$$dq = h\, dA\, (t_s - t)$$

dq = local rate of heat transfer through surface element dA.

h = coeff. of heat transfer
≃ units employed & certain physical properties of the fluid, dimensions of apparatus, vel. of fluid past surface, & whether or not the fluid is changing phase. (range 100 thousandfold)

Ref. Table I. p. 4.

CH. 1. CONDUCTION:- (Nomenclature p. 5-6.)

Thermal conduction through a Single Homogeneous Solid:-

i.) — Basic Equation:-

Fourier's Law:-

$$\frac{dQ}{d\theta} = -kA\frac{dt}{dx}$$

- two conditions:
  - a.) dt changes with time $d\theta$ -- unsteady state
  - b.) dt is steady :-- steady state cond's.

ii.) Basic Equation for Thermal Conduction in the Steady State.

As $-dt/dx$ & $dQ/d\theta$ are independent of time,

$\therefore dQ/d\theta = Q/\theta = q$

& $q = -kA\frac{dt}{dx}$ ... $k \; \frac{BTU}{(hr)(ft)(°F)}$ (ref. p379) ----- (2).

iii.) Thermal Conductivities of Solids:-

k ∝ temp - nearly linear over a wide range.

$\therefore k = k_o(1 + a.t)$

--- a = temp. coeff. (+ve for most insulators).
(-ve for good conductors).

N.B. aluminum is +ve.

- For non-homogeneous solids, thermal cond. is fn of the apparent or bulk density.

eg. @ 32°F, for asbestos wool, k = .052 for ρ = 249
k = .111 for ρ = 43.6 lb/cu.ft.

N.B. Griffiths: apparent thermal conductivity of granular solids:
- air circulates within the mass of granular solid. (e.g. charcoal grains, k = 9% > when test sect. vert as comp. to horiz.

If radiation is important, the plot of apparent k (ord.) & temp. should be concave up @ T^4

Aluminum fibre sheet is good re. ρ & k.
cuz: small air space & low emissivity of mat'l.

- for porous solid, when cond. conv & rad are present → results as conductances not k. (ref. P. 25.)

Tables and Plots of Thermal Conductivities of various solids, liquids, & gases ... p. 380–392.

In order to integrate (2), variation of k w.r.t. t & A w.r.t. x (?)

usually $k = k_0(1 + at)$ – – – (3).

then, $-k\,dt = -k_0(1+at)\,dt = q\,dx/A$ – – – (4).

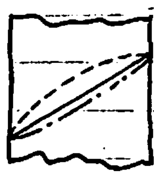
$$-\int_{t_1}^{t_2} k\,dt = (t_1 - t_2)(k_0)\left[1 + a\frac{(t_1 + t_2)}{2}\right] = q\int_1^2 \frac{dx}{A}$$

for linear k, $k_a(t_1 - t_2) = q\int_1^2 dx/A$

or $k_m = \frac{1}{(t_1 - t_2)}\int_{t_1}^{t_2} k\,dt$ for k non-linear.

CASE I. Conduction of Heat through a Solid of Constant Cross Section.

$$q = \frac{k_m A(t_1 - t_2)}{x_2 - x_1} = \frac{k_m A\,\Delta t}{x} \quad ——— (6)$$



Temp. grads in flat walls:–

- – – k decr. with temp.
- —— k ind. with temp.
- –·– k incr. as temp incr.

CASE II. Cross Section of Path Proportional to Linear Dimension (Lagged Pipes):–

For changing areas, use average value: $q = k_m A_m \Delta t / x$

For pipe, (5) → $\int dx/A = k_m(\Delta t)/q$

$$\int_1^2 \frac{dx}{x} = \frac{k_m \Delta t\, 2\pi L}{q} \quad \text{as } A = 2\pi x L. \quad —— (8)$$

$$q = \frac{k_m\, 2\pi L(\Delta t)}{\ln(x_2/x_1)} \quad ——— (9)$$

equating (9) & (7)

$$q = \frac{k_m 2\pi L \Delta t}{\ln(x_2/x_1)} = k_m A_m \frac{\Delta t}{x_2 - x_1} \quad – – – (10)$$

$$\therefore A_m = \frac{2\pi x_2 L - 2\pi x_1 L}{\ln(2\pi x_2 L / 2\pi x_1 L)} \quad – – – (11)$$

$$= \frac{A_2 - A_1}{\ln(A_2/A_1)} = \frac{A_2 - A_1}{2.3 \log(A_2/A_1)} \quad – – – (12)$$

this is called the logarithmic mean.

i.e. rate of heat conduction / unit length ∝ id & od & Δt.

when $A_2/A_1 < 2$, $A_a = (A_1 + A_2)/2 \doteq A_m$ within 4%.

Case III. Cross Section of Path Proportional to Square of Linear Dimension:-

The case of a hollow sphere:

$A = 4\pi x^2$.

Int. (5) $\rightarrow$ $\frac{q}{4\pi}\left(\frac{1}{x_1} - \frac{1}{x_2}\right) = k_m \Delta t$ — — (13)

$q = \frac{4\pi k_m x_1 x_2 (\Delta t)}{x_2 - x_1}$ — — (13 a)

eqt. (7) & (13a) $\rightarrow$ $A_m = 4\pi x_1 x_2 = \sqrt{A_1 A_2}$ ← geometric mean. — — (14).

(N.B. log. & geom. means are <u>lower</u> than arithmetic means

Case IV. Rectangular Bodies Having Walls at Least One-half as Thick as the Shortest Inside Dimension

Ref. p. 14. (This may occur in our model.).

iv.) Steady Flow from an Insulated Heat Source:-

Rudenberg: $q = (t_1 - t_\infty)/R$

R = resistance factor. Ref. Table II. p. 15.

v.) Graphical Solutions for Complex Cases.

plates with ribs, etc. p. 16.

vi.) Two-Dimensional Heat Flow: Fig 3. p. 16.

Awbery & Schofield problem: plate & web:

a.) Subdivide $\int_1^2 k\,dt$ into N equal parts $k\Delta t_x$.

b.) Conduction per lane = $q_L = k A_m \Delta t_x / x$

$= k (Ly)(\Delta t_x)/x$.

Now, $k\Delta t_x$/isotherm is equal & q_L & L are const, then $\frac{y}{x}$ = const.

Total heat flow is $q = N_L \, k L (t_1 - t_2)/N$. — N_L = no. of lanes

vii.) Three-Dimensional Heat Flow:-

$dq = -k\,dy\,dL \frac{dt}{dx}$.

viii.) Thermal Conduction In Fluids :-

- k becomes very small.
- cannot eliminate convection effects.

a.) Thermal Conductivity of Liquids :-

Bridgman : $k = 2 R_G V_a / z_c^2$

R_G = gas const.,
V_a = acoustic vel. in the liquid.
z_c = mean distance of separation of centers of mol's.

$z_c = (M'/\rho)^{1/3}$

M' = wt. in grams of one molecule.

also; $k = .00266 + 1.56(C - 0.45)^3 + 0.3(\rho'/M)^{1/3} + .0242(\mu'/\rho')^{1/2}$

& $k \sinh(100 b_1) = k_1 \sinh(x_{w_1} b_1) + k_2 \sinh(x_{w_2} b_1)$ ...

ref. p. 20.

b.) Thermal Conductivity of Gases :-

- Maxwell .. $k = a_1 \mu C_v$

μ = absolute viscosity of gas.
C_v = specific heat at const. vol.
a_1 = const, consistent units being employed.
= 2.5 monatomic gases, 1.90 diatomic, 1.72 triatomic.

Eucken: $a_1 = 0.25(9K - 5)$

K = ratio of sp. hts = C_p/C_v.

Then $\frac{C_p \mu}{k} = \frac{4}{9 - \frac{5}{K}}$ important for convection p. 243.

Tables pp. 391-392 (may be in error 10-20 %).

Sutherland: $k = k_{492} \left(\frac{492 + C_s}{T + C_s}\right)\left(\frac{T}{492}\right)^{3/2}$

T = temp. in °F abs.
C_s = Sutherland Const. (same is used to find μ).

- if mean free path of gas molecule small compared with thickness of conducting layer, k ind. of p.

Experimentally, if p suff. low, effect is predicted by kinetic theory. p. 22.

ix.) Conduction Through Several Bodies in Series: Resistance Concept.

a.) For the steady state:- rate of heat flow calculated

a.) dividing the temp. drop through any individual resistance by the resistance of the body, $R = x/k_m A_m$

or b.) dividing the total temp. drop by the sum of the individual resistances.

Eq. 7.) → $$q = \frac{\Delta t}{x/(k_m)(A_m)} = \frac{\Delta t}{R}. \quad (26.)$$

For 3 solids,

26.) → to each solid:- $$q = \frac{t_0 - t_1}{R_a} = \frac{t_1 - t_2}{R_b} = \frac{t_2 - t_2}{R_c} \quad (26.a)$$

$$\text{or } q = \frac{t_0 - t_2}{R_a + R_b} = \frac{t_0 - t_3}{R_a + R_b + R_c} \quad (26.b)$$

$$q = \frac{\Sigma(\Delta t)}{R_T} = \frac{(\Delta t)_a + (\Delta t)_b + (\Delta t)_c}{R_a + R_b + R_c} \quad (26.c)$$

$$= \frac{\Sigma(\Delta t)}{\frac{x_a}{k_a A_a} + \frac{x_b}{k_b A_b} + \frac{x_c}{k_c A_c}}. \quad (26.d.)$$

h = surface coeff. of heat loss

$$= \frac{q}{A_0 (\Delta t)}$$

b.) Contact Resistance:-

A very high temp. drop may exist at contact surfaces due to poor contact, air intrusion, oxide coatings, etc.

Take average k for all layers - heat meter.

c.) Conductance: when heat is transferred by more than one mechanism,

$$C = \Sigma q / \Delta t$$

$$C' = C/A = \Sigma q / A \Delta t = \text{unit conductance}.$$

For conduction only, $q = k_m A_m (\Delta t)/x$

then $C = k_m A_m / x$

& $R = x / k_m A_m$ (reciprocals)

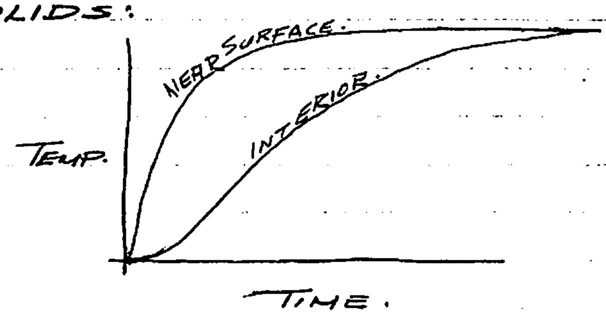
c.) Other Applications of the Basic Conduction Equation:- ref. p. 25.

CH. II.

HEATING & COOLING OF SOLIDS:

i.) INTRODUCTION:-

- unsteady state.
  - temp. gradient.



- ∝ thermal conductivity, density, specific heat of body, its shape & size, external cond's including the temp of surroundings & coeff. of heat transf between surroundings & surface.

ii.) THEORY:-

a.) Simple limiting case of unsteady - heat conduction with slab, vol = V, area = A., thickness $2r_m$ @ temp t. in warm air @ t'. @ time θ, quant. of ht transf = dQ in time dθ, is:

$$\frac{dQ}{d\theta} = h\,A\,(t' - t_s) \quad \text{——— (1).}$$

where h = coeff of ht transf from surroundings to surface. h small, $\frac{dQ}{A\,d\theta}$ small, k large, $t = t_s$ = uniform.

ρ = density of metal, C_p = sp. ht.

$$dQ = hA(t' - t)\,d\theta = V\rho\,C_p\,dt \quad \text{—— (2).}$$

If $\frac{hA}{V\rho C_p}$ = const, int. from $t = t_b \to t$ & $\theta = 0 \to \theta$,

$$\ln\left(\frac{t' - t_b}{t' - t}\right) = \frac{hA\theta}{V\rho\,C_p} \quad \text{——— (3).}$$

- h = const, plot $\ln(t' - t)$ vs θ → st. line, -ve slope = $\frac{hA}{V\rho C_p}$

Could get from $\frac{Q}{\theta} = hA(t' - t)_m = \frac{V\rho C_p(t - t_b)}{\theta}$

using logarithmic mean temp. diff.

b.) Derivation of Differential Eq'n for Unsteady-state Condition:
Consider element of vol. dy dz (area) & t = dx.
heat leaving along x-axis is:

$$(dy\,dz)\left[k_x \frac{\partial t}{\partial x} + \frac{\partial}{\partial x}\left(k_x \frac{\partial t}{\partial x}\right) dx\right] d\theta$$

& ht entering $-k_x (dy\,dz)(\partial t/\partial x)(d\theta)$.

Diff. = that stored in element:-

$$dx\,dy\,dz\left[\frac{\partial}{\partial x}\left(k_x \frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial t}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial t}{\partial z}\right)\right] d\theta$$

$$= (dx\,dy\,dz)\left(\rho C_p \frac{\partial t}{\partial \theta}\right) d\theta \quad \text{--- (5.)}$$

Then gen. diff. eq'n for unsteady-state ht cond'n (rect. co-ords.)

$$\frac{1}{\rho C_p}\left[\frac{\partial}{\partial x}\left(k_x \frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial t}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial t}{\partial z}\right)\right] = \frac{\partial t}{\partial \theta}$$

--- (5.A).

Neglecting variation in k with temp, & assuming substance to be homogeneous & isotropic, then

$\alpha = k/\rho C_p$ = thermal diffusivity.

For a very large plate, unidirectional flow,

$$(5) \rightarrow \quad \frac{k}{\rho C_p}\left(\frac{\partial^2 t}{\partial x^2}\right) = \frac{\partial t}{\partial \theta} \quad \text{--- (5.b).}$$

For a plate thickness $2r_m$ & neg. surface resistance $h = \infty$ value., surface temp immediately changes.
then $t = t'$ @ $x = 0$ & $x = 2r_m$; $t = t_b$ @ $\theta = 0$, & $t = t'$ @ $\theta = \infty$
solution is rapidly converging series:-

$$\frac{t' - t}{t' - t_b} = \frac{4}{\pi}\left(e^{-a_1 X} \sin\frac{\pi x}{2r_m} + \frac{1}{3} e^{-9a_1 X} \sin\frac{3\pi x}{2r_m} + \frac{1}{5} e^{-25a_1 X} \sin\frac{5\pi x}{2r_m} \ldots\right)$$

--- (6)

where $a_1 = (\frac{\pi}{2})^2$,
X = dimensionless ratio $\alpha\theta/r_m^2$.

Heat absorbed up to any time θ, evaluate int. of $(t' - t_b)\rho C A\,dx$ from 0 to $2r_m$

$$\frac{Q}{2r_m A \rho C (t' - t_b)} = 1 - \frac{8}{\pi^2}\left(e^{-a_1 X} + \frac{1}{9} e^{-9a_1 X} + \frac{1}{25} e^{-25a_1 X} + \ldots\right) \quad \text{--- (7.)}$$

slab. - thickness $2r_m$ <u>finite</u> surface resistance h=const.
boundary conditions :-

$$k\left(\frac{\partial t}{\partial x}\right)_{x=0} = h(t_s - t')$$

$$k\left(\frac{\partial t}{\partial x}\right)_{x=2r_m} = -h(t_s - t').$$

$t = t_b$ @ $\theta = 0$, $t = t'$ @ $\theta = \infty$. .... Integrate 56.
(Use of relaxation method).

iii.) <u>APPLICATIONS:-</u>

ref. p. 31 for nomenclature for unsteady-state conditions.
t' = surrounding medium temp.
t_s = surface temp.
$2r_m$ = thickness of slab = L.

Method of plots of dimensionless ratios.
Figs 7-14 give plots of Y & X
where $Y \equiv \dfrac{t' - t}{t' - t_b}$ & $X = \dfrac{k\theta}{\rho C_p r_m^2} = \dfrac{\alpha\theta}{r_m^2}$.

<u>conc's:-</u>
a.) it would take 4 times as long to heat a 2ft thick and of the same mat'l & density as a slab 1ft thick. ($\theta \propto r_m^2$)
Example pp. 34-35.

(3) → $$-\ln Y = \left(\frac{A r_m}{V}\right)\left(\frac{1}{m}\right)(X) \qquad (8).$$

Dimensionless ratio $Ar_m/V = 1$ for slab (ref p. 38)

iv.) LIMITATIONS:-
t' & h have been assumed const., but may vary.
Hence plot log Y & X.

RANKINE, FAHRENHEIT Abs = 460 + °F.
KELVIN, CENT. Abs. = 273 + °F.

CH. III:

RADIANT HEAT TRANSMISSION:

major cont'ors @ low t
- @ low temp – transfer chiefly conduction (from molecule layer to mol. layer.)
- convection – fluid – (transfer of energy by mass motion).

dominat @ high t.
- radiant energy – (molecules or atoms excited by temp – energy emitted – determined by temp level.)

- convection & conduction – affected by temp diff.
- radiation – " " " level.
- conv & cond = rad; ∝ emissivity or conv. coeff.

pp. 46-47. Nomenclature.

i.) NATURE OF THERMAL RADIATION:-

- body htd, radiant energy is emitted at a rate, and of a quality, dependent on the temp of body.
- below 1000 °F, radiation is not perceived by human eye.
- when quality & quantity of radiant energy emitted / unit time ∝ on temp of body the radiation is called → "THERMAL RADIATION."

- certain mat'ls, → electric discharge, bombardment, etc → emit a characteristic radiation.
- certain mat'ls → fluorescence or phosphorescence.
- exciting wave length is usually shorter than the visible one

- Two bodies A_1 & A_2 in enclosure (evacuated). emit radiation at rates A_1W_1 & A_2W_2 where W = total emissive power.
  intensity of energy impinging on bodies due to radiation from enclosure is I. & absorptivities α (fraction of I absorbed)

energy balance:-

$$IA_1\alpha_1 = A_1W_1 \quad \& \quad IA_2\alpha_2 = A_2W_2 \quad \text{hence } \frac{W_1}{\alpha_1} = \frac{W_2}{\alpha_2} = \frac{W_x}{\alpha_x}$$

V.) Graphical Methods: exs. p. 32.

or "at thermal equilibrium the ratio of the emissive power of a surface to its absorptivity is the same for all bodies" — "KIRCHHOFF'S LAW."

$\alpha = 1$ @ upper limit, W upper limit = W_B
- perfect radiator (zero reflectivity) or BLACK BODY.

EMISSIVITY ϵ = ratio of the emissive power of an actual surface to that of a black body.
KIRCHHOFF'S LAW restated → "at thermal equilibrium the emissivity and absorptivity of a body are the same."

Emissive power of a black body $\propto$ temp:
From Second Law of Thermo, emissive power $\propto T_{abs}^4$:

i.e., $W_B = \sigma T^4$ — — — — (1).

STEFAN - BOLTZMANN LAW:
σ = Stefan - Boltzmann constant (ref. p. 49.)

- Two surfaces A_B & A (one black, one grey) close together & space evacuated.
  - both @ same temp.
    black surface emits W_B.
  of this, grey surface absorbs $W_B \alpha$
    & reflects $W_B(1-\alpha)$
    & emits $W_B \epsilon$.
    black surface absorbs all incident radiation $(W_B)(1-\alpha) + W_B\epsilon$.
    & emits W_B.
    $\therefore W_B(1-\alpha) + W_B\epsilon = W_B$. & hence $\epsilon = \alpha$ as above

Other prop's of black body:-
If $W_{B,\lambda}$ = "monochromatic emissive power" @ wave length λ such that
$W_{B,\lambda} \cdot d\lambda$ = energy emitted from a surface/unit A/θ in wave length interval $\lambda \to \lambda + d\lambda$

PLANCK'S LAW:→ $$W_{B,\lambda} = \frac{C_1 \lambda^{-5}}{e^{\frac{C_2}{\lambda T}} - 1} \quad — — — (2)$$

where $C_1 = 3.27\,(10^{-12})$ etc. } ref. p. 50.
$C_2 = 2.58$ .... "

- the monochromatic emissive power @ any Temp varies from 0 @ $\lambda = 0 \rightarrow$ max. $\rightarrow$ 0 @ $\lambda = \infty$.
- max. value shifts to shorter wave lengths as T ↑.

- WIEN'S DISPLACEMENT LAW → position of max is inversely prop'l to abs. temp.
- Total emissive power (given T.) is area under curve:

$$W_B = \int_0^\infty W_{B\lambda}\, d\lambda \quad \text{--- --- ---} \quad (2a.)$$

- Emissivity ϵ ∝ temp, degree of roughness, degree of oxidation. TABLE XIII (p. 393).
  - a well polished surface may be 15–20% higher.

- Generalizations concerning emissivity :-
  1.) ϵ of highly polished metals are very low: fn of $\rho_e T$
      where ρ_e = specific electrical resistance
      T = abs. temp.
      poorly polished specimens → several times theor. min ϵ
  2.) ϵ of nearly all substances incr. with Temp.
  3.) low-temp ϵ of most non-metals > 0.8.
  4.) Iron-steel. (fn of roughness & oxidation).

	high temp	low temp
clean	.4 – .7	.06 – .45
ox, or rough	.9 – .95	.6 – .95

- Absorptivity α fn of above & on quality of incident radiation
  $\alpha_{a,b}$ -- a → temp of receiver, b temp of incident radiation.
  α_λ increases towards short λ.
  & $\alpha_{1,2}$, increases as T_2 increases.

- if α_λ is const. dep. on λ, surface is called grey.
  & its ~~total~~ absorptivity α ~~dep~~ is indep. of spect. energy of rad.
  then $\alpha_{1,2} = \alpha_{1,1} = \epsilon_1$ i.e., $\epsilon = \alpha$ even if $T_{rad} \neq T_{receiver}$ (p. 51)

Review of
Elements of Heat Transfer & Insulation.
— Max Jakob & George A. Hawkins.
John Wiley & Sons, Inc.

Ch. 1. Introduction.

a.) <u>Conduction</u> :- $q_k = kA \cdot \frac{\Delta_x t}{\Delta x}$. steady state.

Rate of ht stored . $q_{ST.} = \rho\, C_p\, (A \cdot \Delta x)\, \frac{\Delta_\tau t}{\Delta \tau}$ {unsteady state.
τ = time .
in the small vol. $(\rho\, C_p\, (A \cdot \Delta x) \Delta_\tau t.)$ ≡ ht energy stored in vol $A \cdot \Delta x$ in $\Delta \tau$.

b.) <u>Convection</u> :-

$$q_h = hA \cdot \Delta t.$$

h ≡ film coefficient of ht transfer.

c.) <u>Radiation</u> :-

$$q_r = \epsilon \sigma A T^4$$

$\epsilon \propto$ kind of surface & on temp.
$\sigma \propto$ const. of nature, ind. of surface & temp.
$\epsilon = 1$ for black surface.
Stefan - Boltzmann's law --- when $\epsilon = 1$.

γ ≡ specific wts ---- $\gamma = \rho \cdot g$.

CH. II. THERMAL CONDUCTIVITY:-

a.) Factors which influence conductivity:
- depend on: a.) chemical composition
  b.) physical state & texture.
  c.) temperature & pressure.

Molecular physics → thermal conduction is considered as a transportation of heat energy due to molecular motion, whereas heat transmission connected with the ordinary flow of a fluid belongs to thermal convection.

b.) Gases & Vapours:-

k.	32°F.	212°F.
air	.0130	.0180
water vapour	---	.013

Press. has no influence in this range.

Properties of dry air - Table II-2 p. 10.

c.) Liquids:-

Properties of Saturated Water: Table II-3 p. 12.

d.) Insulating Materials:-

Factors to take into account during selection:-
a.) efficiency
b.) resistance against temp.
c.) shock
d.) corrosive chemical fumes
e.) cost
f.) reuse value

e.) Fibrous insulation:-

conductivity decreases & then increases when the fibers are packed more densely.
due to: - combined influences of convection & radiation which depend in a diff way upon
- size & no. of air spaces in the mat'l, temperature, & temp. difference.
- also the arrangement of fibres.

f.) Metals & alloys. p. 25.

Influence of Through Metal on Heat Transfer Through A/C-Structural-Sandwich Panels.

J.R. Woolf. & L.R. Scott.

(Session of Heat Transfer & Aviation Divisions @ A.S.M.E. Semi-annual Meeting Cleveland June 17–21, 1956.)
Paper No. 56 - SA - 23.

Abstract.

Analytical inspection of a sandwich-type structural panel indicates that the fin effect of the inner & outer skins and the through metal is of great importance in determining the heat transfer characteristics. An analytical derivation is presented for the over-all conductance of a sandwich panel having internal through metal slugs with metal skins of the same thickness on both sides. The derivation is for a basic configuration and the final equations must be modified for application to different configurations. Theory is extended to include a specific panel & results are obtained for a test specimen in which the effect of special splice slugs between two adjoining sections is considered.

Nomenclature:

A - area
C_1 - conductance of core filler.
C_1' - defined in text.
C_2 - conductance of spacer slug.
C_2' - defined in text.
C_3 - " " FIG. 14.
C_4 " " " "
C_5 " " " "
C_6 " " " "
C_7. " " " "
h - outer (hot) convective-film coefficient
h' - inner (cold) " "
k - thermal conductivity of skin material.
l - half-width of spacer or splice slugs.
L - " - distance between slugs (fin-width)
$m = (h/k\delta)^{1/2}$
$m' = (h'/k\delta)^{1/2}$
$n = [(C_1' + h)/k\delta]^{1/2}$

q - heat flux.

$r = (h/h')^{1/2}$
t = temp of outer surface @ $x > 0$.
t' - " " inner " @ $x > 0$.
t_a - defined in text.
t_c - temperature of inner (cold) fluid.
t_h - " " outer (hot) "
t_m - mean temp. of outer surface over L.
t_m' - " " " inner " " L.
Δt_m - mean temp difference $(t_m - t_m')$
t_o - temp of outer surface over l.
t_o' - temp of inner surface over l.
U - through metal coefficient (fluid-to-fluid)
U_o - specimen coefficient (fluid-to-fluid).
x - distance along fin-width L.
$\beta = C_1 \Delta t_m / h$.
$\beta' = C_1 \Delta t_m / h'$.
δ = thickness of inner & outer skins
Δ = " " " honeycomb core fillers

Sandwich panels

$\theta = (t_h - t)$
$\theta' = (t' - t_c)$
$\theta_m = (t_h - t_m$
$\theta_o = (t_h - t_o)$
$\theta_o' = (t_o' - t_c)$
$\ell = \tanh mL.$
$\ell' = \tanh m'L.$
$\sigma = c_2\, l/k\, \delta m$
$\phi = \Delta t_m / (t_h - t_c)$
$\psi = (t_h - t_o)/(t_h - t_c).$

Subscripts:
A, B - splice plug A, splice slug B.
S - spacer slug
T - total
I, II, III - Area I, area II, area III.

Introduction:

A type of structural configuration which has been receiving attention lately for a/c is the sandwich panel. The 2-D representation shown in FIG. 1. consists of metal skins which are filled with materials such as fiberglas or metal honeycomb, balsa wood, and foamed-in-place plastics. It is usually necessary to have slugs of through-metal in these sandwiches to improve the strength and to form a base for attachment of internal spars, webs, and stringers. The rate of heat transfer through these panels is of great interest for three reasons:

(a) to determine fuel temperature in fuel tank areas,

(b) to determine temp dist n in the structure, and

(c) to determine heating or cooling loads in crew & equipment compartments. The problem of fuel heating has received attention lately because aerodynamic heating at flt spds now being considered can cause appreciable loss thru boiling.

Previous work.

The probs of thin-metal skins was treated by V. Paschkis & M.P. Heisler[1] for a 2-D case under the following cond's:

1.) The thickness of the through slug, l, is twice the skin wall thickness, δ.
2.) The convective film coefficient on one side is infinite (or the surface temp on that side is uniform & constant).

Paschkis & Heisler solved, by el. analogy, for factors which would enable one to calculate the heat loss. H.G. Elrod, in discussion of the foregoing paper, presented an eq'n derived for condition 2, assuming that lateral conduction in the filler could be neglected. The latter assumption seems satisfactory when the filler is a fairly good insulator & the thin metal & surfaces are good conductors. Elrod points out that this equation can also be used for the case where the film coefficient is the same on both sides, since the symmetry causes a uniform temperature dist'n about the center layer.

Present Analysis

Assumptions:

The case at hand is one in which the film coefficients on either side may be quite different, such as with a high-speed airstream on one side & fuel, fuel vapour, or relatively still compartment air on the other side. An analytical solution is made for the following

1. "The Influence of the Metal on the Heat Loss from Insulated Walls" by V. Paschkis & M.P. Heisler, Trans. ASME, vol. 66, 1944, pp 653-663.

Sandwich Panels.

assumed conditions.

1.) Skin thickness are the same on each side.

2.) Uniform and const fluid temp & film coeff't on either side ($h \neq h'$).

3.) Homogeneous & isotropic materials, the conductivity of which is independent of temperature.

4.) Radiation effects are absent.

5.) No lateral conduction in the core filler or through metal.

6.) Heat transfer from 1 metal skin thru the insulation to the other skin is approx'd by use of a const. Δt mean.

Analytical Derivation:

The solution is derived as follows:
a heat balance on an element of the outer skin in Fig. 1 gives[4]

$$q_a + q_b - q_c - q_d = 0 \qquad (1.)$$

which is written as

$$h\,dx(t_h - t) - KS\frac{dt}{dx} + KS\left(\frac{dt}{dx} + \frac{d^2t}{dx^2}dx\right) - C_1\Delta t_m\,dx = 0 \qquad (2.)$$

Substituting $\theta = (t_h - t)$, $\beta = C_1\Delta t_m/h$, and $m = (h/kS)^{1/2}$; and noting the boundary conditions

$$\theta = \theta_0 \text{ at } x = 0 \text{ and } \frac{dt}{dx} = 0 = \frac{d\theta}{dx} \text{ at } x = L$$

the outer surface temp. in the interval $0 \leq x \leq L$ is

$$(\theta - \beta) = (\theta_0 - \beta)\frac{\cosh m(L-x)}{\cosh mL} \qquad (3.)$$

The solution for the inner surface, noting that θ' has a somewhat different algebraic meaning than θ, becomes

$$(\theta' - \beta') = (\theta_0' - \beta')\frac{\cosh m'(L-x)}{\cosh m'L} \qquad (4.)$$

Assuming the surface temperature is uniform over the slug half-width l, the total heat transfer per unit depth is

$$q = hl\theta_0 + \int_{x=0}^{x=L} h\theta\,dx \qquad (5.)$$

$$= h l \theta_0 + K \delta m (\theta_0 - \beta) \tanh mL + h L \beta \qquad (6.)$$

These three terms are, respectively, the heat convection directly into the slug face, the fin-effect conduction into the slug, & the conduction thru the insulation.

An over-all heat-transfer coeff't U, is defined

$$U = \frac{q}{(l+L)(t_h - t_c)} \qquad (7.)$$

hence,

$$U = \frac{h l \theta_0}{(l+L)(t_h - t_c)} + \frac{K\delta m}{(l+L)}\left[\frac{\theta_0}{(t_h - t_c)} - \frac{\beta}{(t_h - t_c)}\right] \tanh mL + \frac{h L \beta}{(l+L)(t_h - t_c)} \qquad (8.)$$

Substituting, for simplicity, dimensionless temp. ratio $\psi = \theta_0/(t_h - t_c)$ and $\phi = \Delta t_m/(t_h - t_c)$ gives

$$U = \frac{hl}{(l+L)}\psi + \frac{K\delta m}{(l+L)}\left(\psi - \frac{c_1}{h}\phi\right)\tanh mL + \frac{c_1 L}{(l+L)}\phi \qquad (9.)$$

The heat-transfer coeff't is now expressed in terms of the geometry & surface conditions.

Relations for the dimensionless temp. ratios will now be derived from the basic eq's below. The temp. drop through the slug is not neglected & its conductivity is not assumed the same as that of the skin. A heat balance for the slug shown in Fig. 1 allows:

$$c_2 l (t_0 - t_0') = -K\delta\left(\frac{dt}{dx}\right)_{x=0} + h l (t_h - t_0)$$

$$= +K\delta\left(\frac{dt'}{dx}\right)_{x=0} + h' l (t_0' - t_c) \qquad (10.)$$

The linear average temp's of the surfaces are

$$t_m = \frac{1}{L}\int_{x=0}^{x=L} t\,dx \quad \& \quad t_m' = \frac{1}{L}\int_{x=0}^{x=L} t'\,dx \qquad (11)$$

Sandwich Panels.

Noting that $(t_m - t_m') = \Delta t_m$; solving the above equations for ϕ & ψ gives, in symbols,

$$\phi = \frac{1 - \frac{\varphi' r}{mL} + \frac{\left[\frac{\varphi' r}{mL}\left(\frac{\varphi}{\sigma} + \frac{ml}{\sigma} + 1\right) - \frac{\varphi}{mL}\right]}{\left[1 + \left(\frac{\varphi + ml}{\varphi' + ml/r}\right)\left(r + \frac{\varphi'}{\sigma} + \frac{ml}{\sigma r}\right)\right]} - \varphi' r^2}{1 + \frac{c_1}{h}\left\{1 + r^2 + \frac{\varphi' r}{mL}\left(r^2 - \frac{\varphi}{\sigma}\right) - \frac{\varphi}{mL} - \frac{\left[\frac{\varphi' r}{mL}\left(\frac{\varphi}{\sigma} + \frac{ml}{\sigma} + 1\right) - \frac{\varphi}{mL}\right]\left[\varphi\left(r + \frac{\varphi'}{\sigma} + \frac{ml}{\sigma r}\right)\right]}{\left[\varphi' + \frac{ml}{r} + (\varphi + ml)\left(r + \frac{\varphi'}{\sigma} + \frac{ml}{\sigma r}\right)\right]}\right\}} \qquad (12.)$$

$$\psi = \frac{1 + \frac{c_1}{h}\left(\frac{\phi}{\varphi' + \frac{ml}{r}}\right)\left[\varphi\left(r + \frac{\varphi'}{\sigma} + \frac{ml}{\sigma r}\right) - \varphi' r^2\right]}{\left[1 + \left(\frac{\varphi + ml}{\varphi' + \frac{ml}{r}}\right)\left(r + \frac{\varphi'}{\sigma} + \frac{ml}{\sigma r}\right)\right]} \qquad (13.)$$

φ, φ', σ, and r being introduced to shorten the equations.

The equations for ϕ and ψ are rather complex. For certain cases these can be simplified considerably. For instance, if the slug material is the same as the skin material and there are no contact resistances, the conductance of the slug, c_2, can be replaced by $k/\Delta s$, where Δs is the slug thickness. Also, the temperature drop through the slug may be omitted ~~omitted~~ in most cases. With an additional complexity in the relations for ϕ and ψ, the case of different skin thickness on either side could be handled.

Range of Calculations:

ϕ, ψ, and U were evaluated for several cond's of particular interest, namely

1.) $l = 0.5, 1.05, \& 1.8$ in.
$L = 5.0, 4.45, \& 3.7$ in.

2.) $\delta \rightarrow$ 0.051, 0.032, & 0.020 in.
3.) h = 6, 9, 12, 15, 18, & 25 BTU/hr. sq. ft deg. F.
h' = 2, 10, 25, & 50 BTU/hr sq ft deg F.
4.) C_1 = 1.9 BTU/hr sq. ft. deg F.
C_2 = 625 BTU/hr sq. ft. deg. F.
k = 70.1 BTU/hr ft deg (75-ST.)
ϕ and ψ for δ = 0.051 in are plotted in curve form in FIGS. 2 → 7. Corresponding U-values are in Figs 8 → 10.

Modification of Elrod Solution:

For comparison purposes, an Elrod-type sol'n is made not neglecting the surface convection over the slug, & taking into account the conductivity of the thin-metal is not necessarily the same as that of the skin material. The latter permits an allowance for surface contact resistance between the skin & the thin metal slug.

Utilizing the same nomenclature as before, assigning the temp. ta to the inner surface in the case of h' = ∞ (which corresponds to the center-line temperature when h = h'), and noting that the conductances C_1' and C_2' are between the outer surface & the surface section for which t = ta; a heat balance on an element of the outer skin gives –

$$h\,dx(t_h - t) - K\delta\frac{dt}{dx} + K\delta\left(\frac{dt}{dx} + \frac{d^2t}{dx^2}dx\right) - C_1'(t - t_a)\,dx = 0 \qquad (14)$$

Substituting $\theta = (t_h - t)$ & $n^2 = (C_1' + h)/K\delta$, and accounting for the boundary conditions

$\theta = \theta_0$ @ $x = 0$ & $\frac{d\theta}{dx} = 0$ at $x = L$

the solution for the temp dist'n is

$$\theta = \frac{C_1'}{n^2 K\delta}(t_h - t_a) + \left[\theta_0 - \frac{C_1'}{n^2 K\delta}(t_h - t_a)\right]\frac{\cosh n(L-x)}{\cosh nL} \qquad (15)$$

Sandwich Panel

Assuming the temp over the slug-half-width l is constant at t_0, the total heat flow is

$$q = h l \theta_0 + \frac{C_1' l L}{n^2 K \delta}(t_h - t_a) + \frac{h}{n}\left[\theta_0 - \frac{C_1'}{n^2 K \delta}(t_h - t_a)\right] \tanh nL \quad \text{—(16.)}$$

Making a heat balance for flow through the slug gives:

$$h l \theta_0 - K\delta \frac{d\theta}{dx} = C_2' l (t_h - t_a - \theta_0) \quad \text{—(17.)}$$

and a solution for θ_0 is obtained as

$$\frac{\theta_0}{(t_h - t_a)} = \frac{1 + \frac{C_1'}{C_2' l n} \tanh nL}{1 + \frac{h}{C_2'} + \frac{K\delta n}{C_2' l} \tanh nL} \quad \text{—(18.)}$$

The overall ht transfer coeff't for the case of $h = \infty$ is:

$$u = \frac{q}{(l+L)(t_h - t_a)} \quad \text{—(19)}$$

which allows

$$u = \frac{h l \theta_0}{(l+L)(t_h - t_a)} + \frac{h L C_1'}{(l+L) n^2 K \delta} + \frac{h}{(l+L) n}\left[\frac{\theta_0}{(t_h - t_a)} - \frac{C_1'}{n^2 K \delta}\right] \tanh nL \quad \text{—(20).}$$

where $\theta_0/(t_h - t_a)$ is evaluated as in the foregoing.

For the case of $h = h'$, evaluate $\theta_0/(t_h - t_a)$ and U using $C_1' = 2C_1$ and $C_2' = 2C_2$ according to equations (18) & (20). The overall U is then 1/2 of the value calculated.

Numerical Comparison of Various Theories.

A comparison is now made of several methods of solving a symmetrical film-coff't case for a configuration with the following values.

$l = 0.5$ in. $k = 70.1$ BTU/hr ft deg
$L = 5.0$ in. $\delta = .081$ in.
$C_1 = 1.9$ BTU/hr. sq ft deg F. $h = h' = 10$ BTU/hr sq ft deg F
$C_2 = 625$ BTU/hr sq. ft deg F.
From Figs 2 & 5, the following values are taken
$\phi = .493$ $\psi = .488$.
Calculating U according to Eq. (97) gives
$U = 2.75$ Btu/hr sq. ft deg F.
Using the symm. eq (120), one obtains
$U = 2.79$ Btu/hr sq. ft deg F.
A relaxation analysis, accounting for 2-d flow in the filler, resulted in
$U = 2.82$ BTU/hr sq. ft deg F.
A 1-D analysis, assuming no lateral heat flow yields
$U = 1.61$ BTU/hr sq ft deg F.
A plot of the calculated temp dist'n in the metal surfaces is given in FIG. 11, showing little difference in the first 3 methods, but, as expected, no semblance of accuracy for the 1-D method.

Experimental Program

An experimental program was initiated to determine the conductance thru sandwich panels. When the program was begun it was designed to yield experimental values for a certain type panel. However, as the theoretical considerations progressed, it became apparent that it would be impossible to test all of the configurations which would be used in a/c — different skins, thicknesses, and materials, different fillers, and different geometrical spacing. The experimental program then became a check for the theoretical program. The test rig is a quasi-steady-state apparatus shown schematically in FIG. 12.

Sandwich Panels -

Electrically heated, thermostatically controlled air was re-circulated beneath the panel. The heat flow was measured by the temp rise of a known weight of water contained in an insulated tank above the specimen. Uniform water temp was maintained by stirrers and the energy addition from the stirrers was accounted for by calibration. A limited control of air-side film coeff't was available through blower speed control. The air vel. was measured by means of a pitot tube which enabled cal'n of the air-side film coeff't. Tests were run on a panel ~~to in order to determine~~ filled with fiberglass honeycomb, 0.5 in thick, with no internal slugs in order to determine the conductance of the core ~~fibre~~ filler. The results of this test along with a description of the honeycomb are shown in FIG. 13. The structural panel tested was not 2-D in geometry, but, to represent splice sections, was of the configuration shown in Fig 14.

Modification of Theory For Test Specimen.

Regarding Fig. 14, there are three values of the slug-half-width l, and fin-width L. The conditions are accounted for by use of area ratios. The over-all conductance for the panel is then

$$u_0 = C_3 u_{(I,III)} + C_4 u_{II} \qquad (21.)$$

where C_3 & C_4 are defined in FIG. 14.

Noting that there are 3 spacers & one splice in both areas I & III, the conductance for the combined areas is written as:

$$u_{(I,III)} = \frac{3u_3 + u_5}{4} \qquad (22.)$$

where U_S & U_B refer to conductance as determined from eq (9) for the spacer & splice B, resp'y.

The conductance for area II cannot be determined in this manner, but must include:

(a). The effect of conduction thru the honeycomb core,

(b) the effect of conduction in the spacers and splices,

& (c) the fin-effect resulting from the skins, spacers, and splices. Calculations indicate that the foregoing effects may be evaluated @ splice A conditions for area II. Items (a) & (b), the direct conduction effects, become

a) $C_1 C_5 \phi_A$.

b) $C_6 h \psi_A$

the ratios C_5 & C_6 being defined in Fig 14. Items (c), the fin effect, is from eq. (6)

(c) $\frac{C_7}{L_A} K \delta m \left(\psi_A - \frac{C_1}{h} \phi_A\right) \varphi_A$

where C_7 results because of the increase in fin-effect due to overlap in the corners. The conductance for are II becomes

$$U_{II} = C_1 C_5 \phi_A + C_6 h \psi_A + \frac{C_7}{L_A} K \delta m \left(\psi_A - \frac{C_1}{h} \phi_A\right) \varphi_A \quad (23)$$

Application of Eq's (21), (22), & (23) allows the over-all panel conductance to be written in its final form as

$$U_0 = C_3 \left(\frac{3U_S + U_B}{4}\right)^{?} + C_4 \left[C_1 C_5 \phi_A + C_6 h \psi_A + \frac{C_7}{L_A} K \delta m \left(\psi_A - \frac{C_1}{h} \phi_A\right) \varphi_A\right] \quad (24).$$

Discussion of Results.

Fig. 15 shows the theoretical results for the test panel as cal'd from eq (24). Fig. 16 indicates the agreement between experiment & theory with the scale enlarged for better comparison. The experimental cold-side film gain as the same panel with no thru metal slugs.

Conclusions.

A method for determining heat flow thru sandwich panels has been derived and tested over a limited, but useful, range of variables. The assumption of treating the heat transfer thru the core filler with a const. Δt and omitting lateral conduction is satisfactory for fair insulators. The method could be extended to other geometric configurations.

Sandwich Panels.

coeff., h, was estimated @ 50 Btu/hr sq ft deg. The resulting difference between experiment & theory for U_o is 7.8% average with a max deviation of 10.6% over the experimental range. Unfortunately, no provision for measuring the cold side film coeff was made when the apparatus was designed. The average difference between experiment & theory for a cold-side film coeff of 35 Btu/hr sq ft deg F is only .6% with a max dev. of 4.5%. Of course the cold side (water) film coeff't varied slightly from test to test.

For the range of conditions investigated, the primary variables are the slug-half-width l, and skin thickness, δ. Cross plotting of the data indicates that changing the slug width has a greater effect on U_o than changing skin thickness. Doubling the slug width results in an increase in U_o roughly 2 times that obtained by doubling the skin thickness. The main contributor in all cases is the fin effect caused by the skins & through metal; this being in the order of 50% of the total heat gain through the panel.

With a hot-side coeff't of 10 BTU/hr sq. ft. deg F & a cold-side coeff of 25 BTU/hr sq ft. deg. F, which might simulate alt. supersonic flight, Fig 15 indicates an over-all coeff. of 4.34 BTU/hr sq ft deg F for the test panel. Comp. of this fig. with the 7.14 BTU/hr sq ft deg F. allowed by a conventional skin reveals that the test panel permits a ht transfer rate about 40% less than that thru a solid skin. However, the test panel allows nearly 3 times the heat

8

CALIBRATION of THERMOCOUPLES.

~~CH. III~~
~~HEATING - RA3~~

Cu. Const.

AT. 32°F.

	Read with 1	2	3	4	5
32°F = .000 33°F = .021	.0476°	.0952°			.238.°

AT. 660°F.

	034 .001. .0294°.	0588°			.005. .147.°
660°F = 17.754 661°F = 17.788					

Chromel Alumel:-

AT. 32°F:-
32°F = 0.00
33°F = 0.02

Hence accuracy: 0.5°F

AT. 660°F:-
660°F. = 14.25
661°F. = 14.27

→ 0.5°F

Accuracy to which readings are taken should not be greater than ½ °F. for chromel-alumel thermocouples. Hence there is no sense taking the cu. const. thermo readings to any greater significant figures.

TEST. 1. Cu. Const. OCT. 12/56.

a.) Readings when not measuring H_2O vapour.

m.V. →	3.315	3.320	3.316	$\overline{°F}$ = 174.4; 212.0 − 174.4 = 37.6° ; % error = 37.6/180 = 20.9%
°F →	174.3	174.5	174.4	

b.) Readings of

m.V →	4.151	4.160	$\overline{°F}$ = 207.3°F; 212.0 − 207.3 = 4.7° ; % error = 4.7/180 = 2.61%
°F →	207.1	207.5	

c.) Reading of Vapour with line ‖ to surface :-

m.V.	4.26~~7~~	4268	4270	°F → 211.~~6~~ ‖ % Error = .~~6~~/180 = ~~.334~~% .222%
°F	211.6	211.~~6~~	211.~~6~~	

TEST. 2. Chromel-Alumel thermocouples :-

	~~480~~	~~.482~~	% ERROR :-
m.V.	4.086	4.088	.5/180 = .278%.
°F.	211.5	211.5	

These results suffer a double ~~loss~~ error in that the cold point used was Room temperature. Hence both the freezing point and boiling point of ~~of~~ water had to be read, which gives ~~to~~ the errors due to two readings.

Also, the room pressure of the vapour was assumed to ~~be~~ 14.696 (standard) which gives the vapour temp. as 212°F. It should be noted that a 1°F temp diff would be caused by approx .295 psi press. diff from 14.696 psi in this region.

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The transient Heating of an Insulated Slab

DRAFT

Summary

There are several contradictions in the basic assumptions leading to the standard Fourier series solution to the heat diffusion equation, and in addition the information given by this solution is far from complete.

In the present report, a reappraisal of the whole problem has been carried out, and it has been determined that the problem of the transient heating of an insulated slab is not capable of being solved by a Fourier series, since it does not, strictly speaking, completely fulfill the requirements of Fouriers theorem.

The present analysis results in a solution by an ordinary trigonometric series, for which it is no longer necessary to assume the contradictory boundary conditions usually assumed, and which, in the light of recent literature on the diffusion type of equation, is mathematically more sound.

A much more satisfactory and informative result is obtained, and while completely acceptable from the standpoint of physics, is nevertheless, fundamentally different from the result indicated by the classical solution.

The present solution indicates, unlike the standard solution, that a finite time elapses between the time that heating is initiated in a slab of uniform temperature, and the time that maximum gradient is reached at all points within the slab, including the surface. The maximum value that the temperature gradient reaches in any particular problem is consequently smaller, and in the case of insulating slabs, considerably smaller than that calculated from the so called Fourier series solution. The new solution further makes it possible to calculate the time it takes the material in question to reach its condition of maximum temperature gradient.

In general, the new solution, by showing that the heat transfer co-efficient in the case of aerodynamic heating is a function of the thermal properties of the material being heated, as well as of the air, reveals a method of reducing the heat transfer problem to a completely general case, for simple shapes, at least.

Specifically, it shows that the heat transfer co-efficient, when an insulating material is being considered is far less than is ordinarily supposed, and the effectiveness of insulators in transient heating conditions for greater than has been realized.

The solution has immediate usefulness in determining the temperature distribution without recourse to cumbersome numerical methods or computor programs and makes it possible to calculate maximum stress conditions without calculating complete temperature histories.

Because of the interdependence of the temperature and velocity gradients in the boundary layer, the present solution also indicates that the skin friction and hence the drag, may be, in some cases, below the usual estimate.

Introduction

A close look at Newton's equation of cooling indicates that it applies only when the temperature difference between the fluid and solid surface, and the gradient in the solid at the surface, are decreasing.

$$h(T - T_E) = -k\left(\frac{\partial T}{\partial x}\right)_l$$

Yet physical reasoning requires that, if a solid is suddenly subjected to a heating or cooling environment, there must be a period, initially when the gradient at the surface must be increasing while the temperature difference decreases. There is no physical reason for believing that the time during which this phenomena occurs is infinitely short. It should, in fact, depend on the thermal properties of the slab.

Nevertheless, the classical solution to this problem implies that the temperature gradient assumes a value

$$\left(\frac{\partial T}{\partial x}\right)_l = -\frac{h}{k}\left(T_l - T_E\right)$$

instantaneously at the surface, thus causing a discontinuity in the second derivative at the surface and contradicting Newton's equation in its differentiated form

$$\left(\frac{\partial^2 T}{\partial x^2}\right)_l = -\frac{h}{k}\left(\frac{\partial T}{\partial x}\right)_l$$

There are other discrepancies in the usual solution to the heat diffusion equation. For this reason, and also because the usual solution has never seemed complete or satisfactory, this problem is investigated again here, attempting to make only those assumptions which may be rigorously proven to be true or which at least seem physically reasonable.

Analysis

The differential equation for heat conduction in a solid is given by

$$\frac{\partial T}{\partial t} = K\frac{\partial^2 T}{\partial x^2}$$

K is the thermal diffusivity and may vary by a factor of over a hundred for different materials. A possible solution is

$$T - T_x = (a_1 \sin\alpha x + b_1 \cos\alpha x)\, e^{-K\alpha^2 t}$$

$$\text{or } = (a_1 \sinh\alpha x + b_1 \cosh\alpha x)\, e^{K\alpha_1^2 t}$$

That these equations satisfy the basic differential equation may be confirmed by carrying out the differentiations. An investigation also shows that these solutions are identical, with real in the first instance, and imaginary in the second. Thus, it is only necessary to consider one form, and for convenience, the present analysis is restricted to the first equation, using circular functions and a real value for

It appears that the solution contains three arbitrary constants, which must be determined by three independent initial or boundary conditions, which, when applied to the general form of the equation given above, causes it to be a solution to the particular problem defined by the boundary conditions. This is, however, not quite true. Only two of the constants may be regarded as arbitrary; the third is specified when the other two are specified.

The heat conduction equation, or diffusion equation, belongs to a family of differential equations generally defined as parabolic, which all exhibit some rather peculiar properties. The result is that a unique stable solution is obtainable for positive values of only, and only when the boundary is left open i.e. "the boundary goes to infinity and no boundary conditions are imposed along the part at infinity." (Ref. 1) In addition, either the value or the slope of the function may be specified, but not both independently. Otherwise the solution becomes overspecified.

Considering a slab of material, insulated on one side and exposed to a heating or cooling flow on the other, we may stipulate that the temperature gradient is zero at x=zero for all t, as one boundary condition.

$$\left(\frac{\partial T}{\partial x}\right)_{x=0} = 0 \quad \text{all } t$$

$$\left(\frac{\partial T}{\partial x}\right)_{x=0} = -(\alpha_n a \cos\alpha_n x - b\alpha_n \sin\alpha_n x)\, e^{-K\alpha_n^2 t} = 0$$

$$\therefore \; a = 0$$

and the solution reduces to

$$T - T_E = b_n \cos\alpha_n x\, e^{-K\alpha_n^2 t}$$

We may write, therefore

$$T_l - T_E = b_n \cos\alpha_n l\, e^{-K\alpha_n^2 t}$$

$$\left(\frac{\partial T}{\partial x}\right)_l = -b_n \alpha_n \sin\alpha_n l\, e^{-K\alpha_n^2 t}$$

$$\left(\frac{\partial^2 T}{\partial x^2}\right)_l = -b_n \alpha_n^2 \cos\alpha_n l\, e^{-K\alpha_n^2 t}$$

Now, at a particular value of t, these parameters, the temperature and first and second derivatives with respect to x, must have a certain fixed relationship with each other, given by a function of t. Expressed arithmetically in non dimensional form

$$\frac{l\left(\frac{\partial T}{\partial x}\right)_l}{T_l - T_E} = -f_1(t)$$

$$\frac{\left(\frac{\partial T}{\partial x}\right)_l}{l\frac{\partial^2 T}{\partial x^2}} = f_2(t)$$

$$\frac{l^2\left(\frac{\partial^2 T}{\partial x^2}\right)_l}{T_l - T_E} = -f_3(t)$$

These functions may contain thermal constants relating to the material, in addition to t, but in any one problem, these will be invariable.

From and we may write

$$\frac{l\left(\frac{\partial T}{\partial x}\right)_l}{T_l - T_E} = -\alpha_n l \tan\alpha_n l = -f_1(t)$$

$$\frac{\frac{\partial T}{\partial x}}{l\left(\frac{\partial^2 T}{\partial x^2}\right)_l} = \frac{\tan\alpha_n l}{\alpha_n l} = f_2(t)$$

$$\frac{l^2\left(\frac{\partial^2 T}{\partial x^2}\right)_l}{T_l - T_E} = -(\alpha_n l)^2 = -f_3(t)$$

From

$$l\left(\frac{\partial T}{\partial x}\right)_l = -f_1(t)(T_l - T_E)$$

we have, by differentiation w.r.t x

$$l\left(\frac{\partial^2 T}{\partial x^2}\right)_l = -f_1(t)\left(\frac{\partial T}{\partial x}\right)_l$$
$$= \left[\frac{f_1(t)}{l}\right]^2 (T_l - T_E)$$

from which we get $f_1(t) = -\frac{1}{f_2(t)}$

and $f_3(t) = [f_1(t)]^2$

The above result is rather surprising, since it implies that α_n is a function of t. The nature of the solution demands that α_n be independent of t, and this can only be true if f_1 f_2 and f_3 are constants.

Since

$$\alpha l \tan \alpha l = f_1$$
$$\frac{\tan \alpha l}{\alpha l} = \frac{1}{f_1}$$
$$\alpha l = \pm f_1$$

we have

$$\tan \alpha l = \pm 1$$

as the condition which must be met if the equation

$$T - T_E = b \cos \alpha x \, e^{-K\alpha^2 t}$$

is to be a solution of the problem.

There are an infinite number of roots to this equation, and hence the solution is the sum of all solutions and may be represented by an infinite series of trigonometric functions

$$T - T_E = \sum b_n \cos \alpha_n x \, e^{-K\alpha_n^2 t}$$

It should be noted that this series is not necessarily a Fourier series. A Fourier series is an infinite series of trigonometric functions with certain characteristics, which are lacking in this case. These characteristics simplify the process of solving for the constants, in the case of Fourier series. In other words, a series of the latter type apply only to problems in which the boundary conditions are of a certain type. In cases where they are not, an ordinary trigonometric series may be made to represent the function, providing the constants may be determined. In these cases, there is not a specified way of determining the constants. All that can be said is that, if the constants when determined give a solution which satisfies the boundary conditions and the original differential equation, the solution is the correct one. (Ref)

It should also be noted that the constant α has been solved for without specifying any particular value to the temperature or temperature gradient at the boundary x = l. Only one constant remains to be determined b_n and to find this we are free to specify either the temperature or the gradient at the surface for a specific time.

Writing $$T_e - T_E = 2\sum b_n \cos\alpha_n l \, e^{-K\alpha_n^2 t}$$

$$\frac{T_e - T_E}{l\left(\frac{\partial T}{\partial x}\right)_l} = \frac{2\sum b_n \cos\alpha_n l \, e^{-K\alpha_n^2 t}}{2\sum b_n \alpha_n l \sin\alpha_n l \, e^{-K\alpha_n^2 t}}$$

Since the term on the left hand side is constant, we may cross multiply and equate corresponding terms in the resulting series, giving, finally

$$\frac{T_e - T_E}{l\left(\frac{\partial T}{\partial x}\right)_l} = \pm\sum \frac{1}{\alpha_n l}$$

$$= \pm\sum \frac{4}{\pi}\left(1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} \cdots\cdots\right) = \pm 1$$

Then $$\left(\frac{\partial T}{\partial x}\right)_l \Big/ l\left(\frac{\partial^2 T}{\partial x^2}\right)_l = \mp 1 \quad \text{and} \quad \frac{l^2(\partial^2 T/\partial x^2)_l}{T - T_E} = \pm 1$$

Now a difficulty arises physically and the difficulty is reflected in the mathematics. If a slab, such as the one referred to in this problem is suddenly subjected to strong heating or cooling, there exists a short but finite time initially, when the above solution does not apply. This is because the heat travels at a finite velocity, and hence must, in the beginning be distributed in the slab as if the slab were of infinite depth. Strictly speaking then, the solution for a semi-infinite slab should be applied at t = o, and the initial conditions for the present solution should be those which exist in the slab at the moment the heat reaches the insulated side.

Fortunately, we now know that the solution is completely specified if we know either the temperature or the gradient at any time t; it is not necessary to know both.

At $t = 0$ $$T - T_E = 2\sum b_n \cos\alpha_n x = 2\cos\alpha_n x \sum(-1)^{n+1} b_n$$

Put $x = 0$ $\cos\alpha_n x = 1$

$$T_0 - T_E = 2\sum(-1)^{n+1} b_n$$

Put $$b_n = \frac{T_0 - T_E}{2}\,\frac{1}{\alpha_n l}$$

This may seem rather arbitrary and in fact it is. What we are really doing is assigning a value to b_n and then studying the resulting series to determine what boundary condition it refers to. As far as the equations themselves are concerned, any value could be ascribed to b_n providing

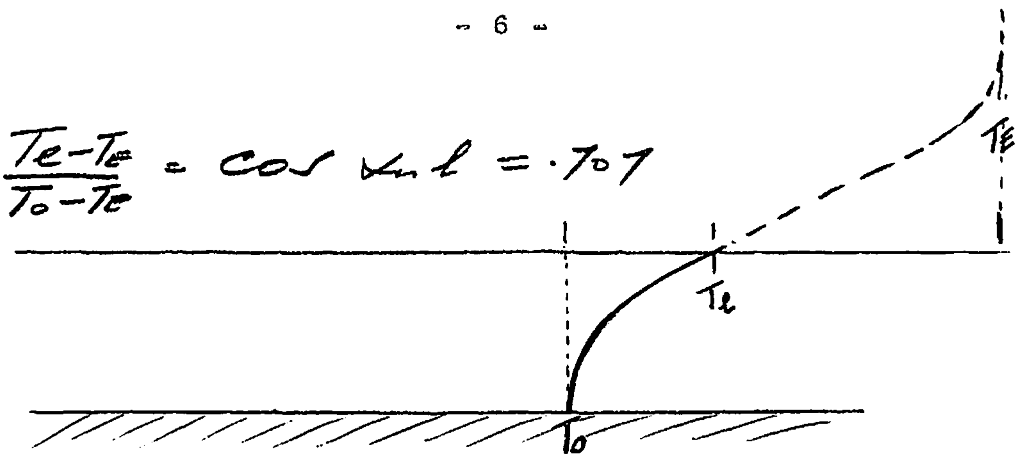
$$\sum \frac{2}{T_0 - T_E}\, b_n = 1$$

This gives

$$T_e - T_E = 2\sum \frac{T_0 - T_E}{2}\,\frac{\cos\alpha_n l}{\alpha_n l}$$

$$= \cancel{2}\,\frac{T_0 - T_E}{\cancel{2}}\cos\alpha_n l \sum \frac{1}{\alpha_n l}$$

Thus $\frac{T_e - T_E}{T_0 - T_E} = \cos \alpha_n l = .707$



This is the condition we are forced to take as the initial condition by virtue of the fact that $\cos \alpha_n l$ is a constant and not a function of α_n and this applies no matter what value is ascribed to b_n

It will be clear from the discussion to follow, that the above condition correspondsto the condition when the temperature gradient has its maximum value throughout the slab. This is shown rigorously in the appendix. Moreover, it is clear from the proof given in the appendix that, the time taken for an isothermal slab to reach the condition when the gradient is a maximum everywhere must be greater than the time given by the equation

$$\frac{Kt}{l^2} = 1 \qquad \text{i.e. } t > \frac{l^2}{K}$$

<u>Discussion</u>

The results of the present analysis differ profoundly from the results given by previous solutions to the problem. However the present method is more acceptable both mathematically and physically, since it does not imply the usual mathematical and physical contradictions usually necessary to arrive at a solution.

It has usually been assumed that the solution is in the form of a Fourier series, and consequently the assumption has also been made that the depth l of the slab corresponds to an interval of   In the present case, no such arbitrary assumption is necessary, and in fact the depth is found to correspond to   and the function need not even be defined beyond this limit. For a Fourier series to apply, the function must be defined over an interval of

In addition, an infinite discontinuity is assumed to exist at the boundary l in the usual solution. This discontinuity is implied by the application of the initial and boundary conditions;—

$$T_x = T_0 \quad \text{all } t$$
$$\left(\frac{\partial T}{\partial x}\right)_l = \frac{h}{k}\left(T_E - T_0\right) \quad \text{at } t = 0$$

This makes it necessary to assume that $\left(\frac{\partial^2 T}{\partial x^2}\right)_l$ is infinite while $\left(\frac{\partial^2 T}{\partial x^2}\right)_{x \neq l}$ is zero. A Fourier series may represent a function only when the function contains no infinite discontinuities.

The initial and boundary conditions, in any case, contradict Newtons equation defining the heat transfer co-efficient, for

$$k\left(\frac{\partial T}{\partial x}\right)_l = h\,(T_l - T_E)$$

$$k\left(\frac{\partial^2 T}{\partial x^2}\right)_l = h\left(\frac{\partial T}{\partial x}\right)_l$$

which shows that the second derivative is finite and equal to times the gradient at the surface.

Finally, (Ref 1), to apply conditions involving both temperature and gradient in the case of the diffusion equation causes the solution to be overspecified.

Physically, it is reasonable to suppose that all materials, not only fluids, possess the property that their heat transfer rate is limited by their physical properties. If the slab in the present problem was heated, not by the proximity of a hot fluid but by another solid slab, it is evident that the heating slab must have associated with it a property exactly similar to that ascribed to the fluid and designated as the heat transfer co-efficient. And since it makes no difference which slab is being heated and which cooled, as far as the fundamental process of heat transfer is concerned both slabs must, in fact, possess a "heat transfer co-efficient." In other words, the process is controlled, not only by the rapidity with which one body can give up heat but on the rapidity with which the other body can accept and diffuse it. Thus, whether both bodies are solid, or one solid and one fluid, the heat transfer process is controlled by the thermal properties of both materials. The formula

$$N_{NU} = \frac{hl}{k} = 1$$

thus is universally true for solids being heated or cooled under the conditions described above. This formula has far reaching implications both in problems of heat conduction in solids and in boundary layer problems.

The classical Fourier series type of solution makes it necessary to believe that, if one body has the ability to transfer heat at a rate of say the other body will accept is at this rate, regardless of its ability to diffuse heat away from the common surface. Such an idea is physically implausible.

The reason the present series gives a solution which begins only at the time the temperature gradient has its maximum value is easy to see physically. This is the first moment at which Newton's equation may be assumed to hold. After time zero, both the temperature difference and the temperature gradient decrease in magnitude as expressed in the equation

$$h\,(T - T_E) = k\,\frac{\partial T}{\partial x}$$

However, before this time, the temperature gradient must increase in magnitude, since it must begin at zero and reach some finite value, but the temperature difference must still decrease. Therefore the boundary condition for this phase of the operation must be more like

$$(T - T_E)\,\frac{\partial T}{\partial x} = h'$$

where h' is a parameter whose nature can only be determined by solving the differential equation of heat diffusion.

Unfortunately, it is known that the diffusion equation cannot be solved except for an open boundary, and in order to make the solution up to the time our present solution becomes valid, fit the initial conditions, it would be necessary to close the boundary. This would seem to indicate that the process which takes place up to the time of maximum gradient throughout the slab, may not be a diffusive process in the usual sense of the word at all.

Fortunately, enough information is derived from a consideration of what happens after the maximum gradient has been reached, to give useful engineering results.

Applications

The above solution fundamentally changes present concepts of heat transfer and heat conduction within a solid body. While it would be necessary to carry out careful testing to evaluate the constant in the series, it is possible, without this check to draw certain quantitative and qualitative conclusions:-

(1) The heat transfer process from a fluid to a solid is controlled, not by the thermal properties of the fluid alone but by the thermal properties of the body with the lower thermal capabilities. The other body adjusts itself to this state of affairs. In the case of aerodynamic heating in general, for flight at Mach 2 in the tropopause, heat transfer to metals is completely determined by the heat transfer capabilities of the air, since all metals are capable of such high heat diffusion rates that they can absorb any heat the air is capable of generating and transferring. In the case of insulators however, the process is completely controlled by the insulator, and the heat transfer rate may be as little as a few percent of what the classical solution would indicate. In this case, even during a transient heating condition, the heat transfer co-efficient settles down to a constant value after a period of increase which depends on the thermal properties of the insulator only. Since the temperature gradient at the surface is inextricably bound up with the velocity gradient, it follows that the velocity gradient at the surface must be less than previously estimated, and hence the skin friction reduced, in the case of an insulator.

(2) There is a characteristic maximum heat transfer co-efficient for all materials when insulated which depends only on the conductivity and geometry. Thus the maximum temperature gradient may be calculated without calculating the complete temperature history, from a simple universal formula.

(3) A "thermal efficiency" may be defined for any material, in terms of the time taken for the material to heat up to a condition where it is able to absorb heat at its maximum rate. For insulators this is so low that the time it takes to reach this condition may be hundreds of times the time necessary in the case of good metallic conductors. From the table it is apparent that one of the best insulators is hard rubber of the neoprene type used for de-icing boots. Its thermal lag is the highest of any material listed, not a desirable property for de-icing boots.

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& Keith Bateman.

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- Hydraulics for A/C.
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OOT 17.) Bound, R.H. & Conway H.G.
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✓ 19.) Conway, H.G.
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✓ 20.) Field, Howard (Jr.)
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- Tendencies in the hydraulic controls and undercarriages:
- Interavia, Vol. 6, 1951 pp455-459 (C5B3)

OUT 23.) McLaughlin, George:
- Progress in hyd. design engineering
- Aero. Digest. Vol. 69. Oct. '54 pp. 42-46 (C5B1)
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OUT 24.) Parker, S.M.
- The Development of ultra-high press hyd. syst.
- I. Mech. E., Vol 156, 1947 pp. 282-285.
OUT.

✓ 25.) Stone-Irving:
- Making the hydraulic system reliable
- Aviation Week, Vol. 58, May, 1953.
pp. 43-55 (C5B1).

Design Project. Oct. 15/56.

The following work estimate was prepared for the Tues. aft. design meeting.

Evaluation of work to be done in designing these systems :-

A.) Hydraulic system :-
1.) Determination of components to be serviced.
2.) Determination of air loads, power required, and size of actuators.
3.) Selection of type of system and corresponding equipment from manufacturers' catalogues
4.) Placement of equipment in a/c.
5.) Losses for system evaluated and the hydraulic (energy) grade lines plotted.

B.) Pneumatic system :-
1.) As in section A.

C.) Weight comparison of the two systems.
D.) Stressing of an hydraulic cylinder.

The End.

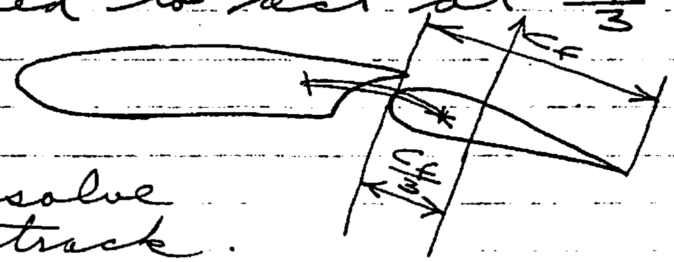
Units which should be operated :-
a.) Landing-gear extension & retraction
b.) Landing gear emergency system.
c.) Flaps & dive brake operation.
d.) Door operation (landing gear)
e.) Power boost req'ts for control surfaces.
f.) Application of brakes.
g.) Power supply for automatic pilot.
h.) Locking mechanisms.

RESUME' OF MEETING
WITH MR. SPILLMAN. OCT. 10/56.

1.) References were obtained in order to obtain air loads on flaps, wheels, etc.

2.) All air loads should be determined by using pitching moments.

3.) Normal force on flaps & controls (from RAeS. 05-01-01 FLAPS) are assumed to act at $\frac{C_f}{3}$



Must resolve along track.

4.) A comparison must also be made with the system designed in pneumatics.

5.) Drag on odeo legs is given in Hoerner p.128.

6.) Example calc's are given in Aero. Eng. Review Ref. No. 6. Ref. Mr. Newell.

OCT. 17/56.

1.) Meeting with Mr. Frotman.

a.) procured Dowty Equipment Catalogue.
b.) it was suggested that the system should be compared in all aspects - role of a/c, wt, temp, etc. as a comp. as well as wt with pneumatics system.

c.) A much fairer comparison could be gained if we worked at the following pressures:-

i.) hydraulic:

4,000 psi.

3,000 psi.

ii.) pneumatic:

3,000 psi.

A pneumatic catalogue is to be procured @ a later date.

d.) The best start will be to draw a start @ the system showing units to be operated, then start working out first approximation to loads.

Oct. 17/56.

Finished reviewing Hydraulics text "Aircraft Hydraulics".

DESIGN PROJECT.

GENERAL RESEARCH A/C.

HYDRAULIC SYSTEM:-

"REVIEW."

TEXT. "AIRCRAFT HYDRAULICS"
NAVY TRAINING COURSES.
NAVPERS 10332-A.

CH. 1. INTRODUCTION TO HYDRAULICS.

i.) Operation:-
- folding wings
- brakes
- flaps
- landing gear
- cowl flaps
- arresting hook
- propeller pitch
- bomb-bay doors
- releases bombs
- charges guns
- rotates gun turrets
- power operated controls
- operates mechanical pilot.

ii.) Hydraulics & Mechanical:-
- Efficiency:
  Mech. 60-70% Hydraulic - 99%.
- Installation:
  Mech - requires str. runs.
  Hydr - piping can be put in any shape.
- Weight:
  Mech - flex cable is heavy.
  Hyd. - tubing is light.
- Wear & Lubrication:

iii) Hydraulic & Electrical :-
- Weight & Size :
  - electric m/c are very heavy c.f. actuators.
- Inertia :
  - electric motors, because of high inertia cannot stop instantly.

CH. 2. HYDRAULIC PRINCIPLES:

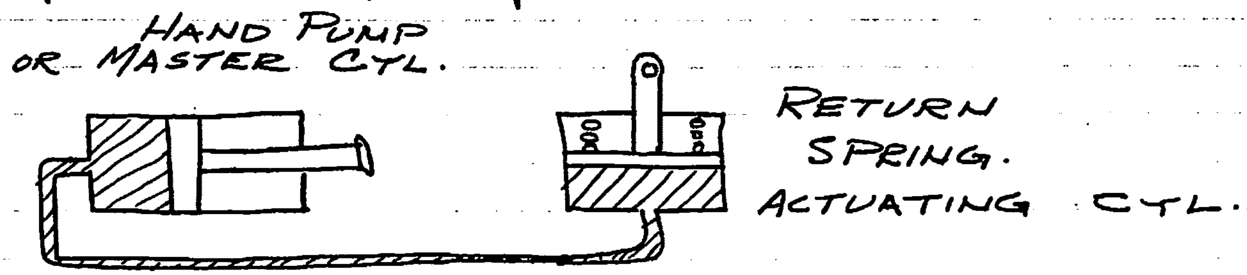
- hydraulic fluids are noncompressible.

i.) Force & Pressure:
A pressure is a force / unit area.
The standard is p.s.i.

$$F = P(A)$$

where F = force, P = press., A = area.

ii.) Pascal's Principle:
- the pressure exerted on any part of a confined (fe) liquid is transmitted to all parts of the liquid, regardless of the shape of the container.



A Basic Hydraulic System.

- Additions to basic system:
  - reservoir (source of hydraulic fluid).
  - check valves (non-return valves.)
  - selector valves (flow in any of several directions)
  - power pumps
  - relief valves
  - pressure regulators
  - accumulators

  etc.

CH. 3. FLUIDS, SEALS, AND TUBING:-

i.) HYDRAULIC FLUID:-

Vegetable & Mineral Oils:

Never mix because of resultant damage to packings.

(blue) Veg. oil → natural rubber packings.

(red) Mineral oil → synthetic rubber packings.

- dirty fluid causes most trouble.
- filter - micronic type external.

Ref. Table I. p. 23.

ii.) Seals and Packings.

Ref. Table II. p. 23.

Metallic (crush washer) - seals in both directions

Cup & V-rings - seals in one direction.

square - seals in both directions

O-ring - " " "

Function:

- seal press. in.
- keep air out of hyd. lines.

① V-RINGS:- on shock struts.
- require reinforcement (male & female packing)
  - packing formers made of fibre, plastic, or metal.
- open end of V, or lips, face press. or dir of flow.

② CUP SEALS:- - on selector valves & brakes.
- seal against dirt & air as well as fluid.
- one direction sealing.

③ O-RINGS:- prevent internal & external leakage in stationary & moving parts.
- seal in both directions.
- in piston heads, selector valve sleeves.
- syst p > 1,500 p.s.i. leather back up rings used to protect the O-RING. (prevents extrusion of ring).
- O-RINGS should be soaked in hydraulic liquid before installation.

~~④ O-Ring.~~

④ METALLIC SEALS:- (or crush washers.)
- high-pressure use as air valve seats on accumulators and shock struts & for seats on fittings which screw into units. (soft aluminum.)
- require fine sealing grooves on seat.

⑤ Square seals - being replaced by O-RINGS.

⑥ LAPPED SURFACES:- (expensive operation.)
- tolerances: .0001 → .0003 in.
- used on high press. systems.

iii.) Hydraulic Tubing:-

a.) RIGID TUBING:-
- Aluminum alloy tubing (52SO)
  - press. up to 1,500 p.s.i.
- Aluminum alloy tubing (61S.T.)
  - press. up to 3,000 psi.
- Stainless steel tubing (18-8)
  - where lines are subject to heat.
- sizes are given in O.D. in 1/16 in.
  i.e., No. 8 = 8/16 = 1/2 in. O.D. *

b.) FLEXIBLE HOSE:-
- to & from actuating cyls.
- wherever excessive vibration is encountered.
- seamless rubber hose inner-tubing bound with wire or cotton braids imp'd with syn. rubber.
- sizes - 1/16 in. (I.D.) *

Low-Press. Hose - 3-plies. - one fabric.
- detachable end fittings.
- p < 300 psi.

MED. Press. Hose. - fire resistant.
- rubber + 1 fabric + 1 braid + outer fabric.

HIGH. Press. Hose. - for 3000 psi.
- available only in assemblies.
- syn. rubber + 2 wire braids + fabric & rubber with attached end fittings.

iv.) Hydraulic Color Code -
- visible @ ends and in each compartment.

Bend radius - tubing 3 d. flex tubing 9 d.
2 & 1 piece connectors (flared tube) - quick disconnects.

CH. 4. RESERVOIRS AND FILTERS.

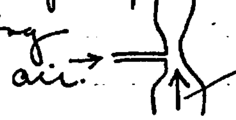
1.) DESCRIPTION:-

- tank in which fluid is stored.
- starting point & place of return for fluid circulating through the lines.
- purpose:
  - supplys operating needs
  - replenish losses through leakage.
  - allows air to escape from system fluid.
  - " for excess fluid due to thermal expansion.
  - aids in cooling fluid.
  - removes foreign matter with its filters & pumps.
- position:
  - reservoir highest pt. in system so gravity will keep pumps primed.
- mat'l:-
  - welded alluminum alloy sheet. (or magnesium)
  - mts - padded supports & ~~fla~~ felt-lined straps.
  - @ top of fwd fire-wall - or in engine nacelle.
- Ports:- 2 @ bottom.
  - larger → to engine-pump supply.
  - smaller → " hand-pump suction lines.
- Standpipe:-
  - attached to eng. pump port.
  - maintains reserve supply for hand pump.
  - prevents dirt from entering system.
- Hand pump:-
  - from bottom of tank → filter → hand pump.
  - drain line & shut-off valve take from this line.
- Main Return line:-
  - @ side & below fluid level.
    - prevents boiling
    - permits bubbles to escape freely.
  - or - @ top & reaches main port thru ~~fi~~ filters
- Baffles and Fins:-
  - prevent excessive vortexing & surging, thus eliminating air from fluid.
- Filler Opening:- sufficiently low to prevent over-filling + finger strainer.

- Vent Line:
  - allows tank to "breathe".
  - line overboard & below tank level.
  - check valve to prevent oil from being spilled o'b'd.
- Sight Gauge: (or dip-stick.)
  - visual checking of fluid levels.

ii.) RESERVOIR CAPACITY:
- provide for changes in Vol. caused by temp chges & chges in internal vol. of all operating mechanisms.
- @ least two inches above outlet pipe.

iii.) PRESSURIZED RESERVOIRS:
- by introducing air into top of reservoir.
- ensures flow to pump at alt. (low press.)
  (may cause vapour lock in pump)
  (& produces high press. peaks in syst.)
- Venturi Fitting – injects air into reservoir.



fluid under pressure.

Ref. FIG. 20. p. 50.
- Closed-type pressurized reservoir:
  - has piston to force fluid
- Open-type pressurized reservoir:
  - has a relief valve in vent line.
  - may have air pump.

iv.) FILTERS:-
- within reservoir
- in pressure line
- in return line + etc.

a.) classification:-
- Cuno-type --- EDGE FILTRATION:
- Micronic-type :-- SCREENING.
  micronic is most effective.
- Size: ∝ to rate of flow (gallons/min.).
  - cartridge filters 10 microns (.000394 in)
  - shape depends upon position: FIG. 21. p. 52.
  - contain a by-pass valve with check valve in event of valve clogging.
  - filters outside to inside. - line filters are small

CH. 5. HYDRAULIC PUMPS:

i.) DEVELOPMENT:

- convert mechanical energy into fluid pressure.
- it creates flow.
  - single-action pump - too slow, flow pulsates & intermittent.
  - double-action pump (FIG. 22.)

ii.) POWER PUMPS:-

a.) CONSTANT-DISPLACEMENT PUMPS:

- fluid output is constant for any rotational speed of the pump.
- <u>example</u>:
  - designed to ~~give~~ deliver 3 galls/min, @ 2,800 r.p.m. regardless of the press. demands made upon it - up to a design max figure.
  - on F9F PANTHER:
    - VICKERS 7-CYLINDER axial-type pumps
    - deliver nonpulsating flows with constant displacement/rev.

      max. recommended press for cont duty = 1,500 psi

      & " " speed of 3,750 r.p.m.

b.) VARIABLE-DISPLACEMENT PUMP:

- fluid output is varied to meet the demands of the system:
  - Example:

    a V-D pump may be designed to maintain the press @ 1,200 p.s.i. by varying its fluid output from zero to seven gallons/min.

c.) GEAR PUMPS:

- engine driven pump - supply high flow and high pressure req'ts.
- 2 counter-rotating grs in alloy covering. (FIG. 23 p 61.)
  - 1 gear driven - other idles.
  - import connected to bottom of reservoir.
  - outport " " press. line.
  - Shear pin on drive shaft. (or shear sect'n)

- a pressure loaded gear pump
  - 4 check valves -
    - 2 connected by communication passageways.
      - 1 set puts press to outside of brass bushings, ∴ forcing on shaft, & closing tolerances.
    - com. pass'ys & hollow shafts → cooling.
    - relief valves dump oil @ 15 p.s.i. to inlet side.

d.) PISTON PUMPS: FIG. 24. p. 65.
- creates highest pressure of pumps.
- $\eta \approx 94\%$
  - 7 or 9 cyls. → 3,000 psi.

e.) HYDRAULIC MOTORS:
- converts hydraulic energy into rotary ~~motion~~ energy.
  - to operate turrets & wing flaps.
- seven piston most generally used.
- reversible in service.
  - housing drain port & reservoir are connected by direct line.

CH. 6. PRESSURE REGULATORS:-

i.) REGULATOR PRINCIPLES:

- control the amount of pressure built up in hydraulic systems & ~~to~~ unload or relieve the hydraulic pump when desired press. is reached.
- prevents power pump from working against a load when syst. is not functioning.
- By-passes fluid back to the reservoir.
- prevents rupture of lines & maintains correct press.

System FIG. 25. p. 73.

a.) AUTOMATIC TYPE REGULATOR:

- "cut-in" pressure – lower press.
- "Cut-out" or system press – higher press.
- press. differential = diff of cut-in & cut-out.

ii.) COMPARISON BETWEEN OPEN-CENTRE & CLOSED-CENTRE SYSTEMS:-

- press. regulator – maintains a const. high press. in syst. ← closed-centre system.
- Closed-centre system:
  - fluid under press. is trapped in syst when selector valves are set in a neutral position. (no fluid flow thru valve.)
- Open-centre system:
  - fluid flow: reservoir → pump → selector valve → reservoir when s/v. is in neutral position.
  - requires no regulator.
  - no press. exists when syst not in operation.

System:- reservoir, eng. pump, relief valve, press. gauge, open-centre s/v's in series & actuating cyls.

FIG. 26. p. 76.

- pp. 78 - 83 - Electrol regulator, Vickers reg, & Bendix reg. (3000 psi.)

CH. 7. SELECTOR VALVES:

i.) PURPOSE AND CLASSIFICATION:

- control the direction of the operation of a mechanism by directing fluid under press. to the desired end of the actuating cylinder while simultaneously directing fluid from the opposite end of the actuating cyl. to the reservoir.
  - TWO-WAY SELECTOR VALVES:
    - in conjuction with an actuating cyl. with piston return by spring.
  - FOUR-WAY SELECTOR VALVES:
    - in conj. with actuating cyl. with piston return by hyd. fluid (most common).
  - OPEN-CENTRE SELECTOR VALVE:
    - all valves in O-C. syst. connected to a common pressure supply & return lines.
    - valve in neutral, pressure port is open to return port.
    - operating position, fluid flow → act. cyl. → valve → o.p. return line to the reservoir.
  - DIRECT-PRESSURE SYST:
    - 4-port valve → press. supply line → act. cyl. return fluid → res. return line.
  - CONTROLLED PRESSURE VALVE:
    - output press. controlled within set limits by operator - manipulation of valve controls.
    - <u>must</u> be used in conjunction with an accumulator that maintains a const. press. @ valve inlet
    - example: power-brake control valve.
  - BALANCED VALVES:
    - press. assists in manipulation.
    - very small press. drop.
  - <u>LOCATION:</u>-
    - in cockpit - direct engagement.
    - othe part of a/c - remote control.
  -

iii.) SEMI-AUTOMATIC TYPE REGULATOR:
SNJ power control valve:
- a manually-controlled regulator.

ii.) ROTOR-TYPE SELECTOR VALVE:
- 4 Ports :- (@ 90° pitch)
  1 press. port, 1 return port, 2 cyl. ports.
  - from press. man. / to press. man. — 180° apart; opp. ends of act. cyl. — 180° apart.
  - rotary plug connected to handle.
  - CLOSED-CENTRE TYPE SELECTOR VALVE:
    - can be used for partial actuation by turning valve to neutral position (no flow thru channels.)

iii.) POPPET-TYPE SELECTOR VALVE:
  - IN-LINE OR CO-AXIAL (FIG. 32. p. 91).
    - Balanced cone
    - unbalanced cone
    - Ball.

iv.) PISTON-TYPE SELECTOR VALVE:
  - Sliding hollow piston with drilled passage ways.

V.) OPEN-CENTRE SELECTOR VALVE: (Piston type)
  - automatically returns to neutral when cyls have reached end of stroke.
  - simultaneously: hp fluid to piston & l.p. fluid to return.
  - in neutral position, fluid passes thru centre of valve and returns to reservoir.
    (Refs. FIGS 33 & 34.)
  - relief valves :- (150 psi above operating press.)
    - relieving thermal expansion from cyl. lines.
    - insuring full operation of units actuated
    - starting piston back to normal position after operation.
  - metering pins :- build up back-pressure behind piston to start piston travel toward neutral position.

VI.) FLEETWING PRE-SELECTOR (FIG. 35 p. 96).
  - closed centre piston type
  - prevents greater than 3° creepage of flap.
  - follow-up arm is connected to ~~also to~~ flap.

VII.) AIREX BALL-TYPE SELECTOR VALVE:
  - unbalanced poppet-type.
  - relief - higher press unseats valves & press.

viii.) ADEL SELECTOR VALVE:
- unbalanced poppets
- units may be stacked
  -- 1 press. port, 1 return port, several (2+) cyl. ports.
- return poppet opens 2° before the opposite pressure poppet opens, thereby preventing line chatter.
- when gear actuated reaches desired position, operator puts valve in neutral.
- relief by unseating poppet by higher press.

ix.) ELECTROL SELECTOR VALVE:
- 4 way closed-centre balanced-type
  - pressure has no effect on this poppet.
- @ end of act. travel, valve remains in open position

x.) HAND PUMP SELECTOR VALVE:-
- diverts flow from hand pump to system, one unit at a time.
- unit has no return port.

CH. 8. ACTUATING CYLINDERS:

i.) TYPICAL ACTUATING CYLINDER:
- usually double acting.
- single - acting
  - actuate brakes & charge guns.

ii.) Pin-pulling actuating cylinders:
- balanced double acting.
- FIG. 44. p. 116.
- used extensively in automatic pilots.

iii.) Dashpot Actuating cylinder.
- raise gear, but prevent damage to units.
- FIG. 45.
  - check flow in one direction.
    free flow in other.
- units being replaced by restrictors, restrictor checks, or orifice checks in unit or lines.
- slow travel during lowering of gear - restr. in up press. line or in return line.

iv.) Shaft oil Pickups Cylinder. FIG. 46.
- flex hose attached to end of shaft (@ clevis.)

v.) CYLINDER LINES & FITTINGS:
- flex hose.
- slack - 5-8% of length.
- min bend rad - 9 x O.D.
- swivel fittings (instead of flex hose)

CH. 9. ACCUMULATORS:

i.) PURPOSE:-

- to store hydraulic fluid under pressure:
- performing the following fns:-
  a.) maintains press. in the press manifold by storing energy in fluid form under press. Enables the accumulator to supplement power pump when it is under a peak load.
  b.) supplies a limited amount of fluid under press. to actuating units when power pump fails to operate.
  c.) dampens press. surges, caused by pulsating fluid delivery from power pump.
  d.) absorbs fluid shocks, such as those occurring when the press. reg. seals the press. manifold and directs the fluid to the reservoir.
  e.) prevents too frequent cut-in & cut-out of a press. reg. thus reducing wear on pump & press regulator.

- usually used in conjunction with a press. regulator (unloading valve) in one type of direct press. syst. to maintain high press @ control valves, while press is relieved from power pump when eq't not in use.
- incorporated @ discretion of designer.

ii.) CLASSIFICATION:-

a.) DIAPHRAGM-TYPE ACCUMULATOR:- FIG. 47. p.124
  - cyl. - hemisphere - steel.
  - top have fluid - bottom half compressed air.
  - screen prevents rupture of diaphragm.
  - air valve.

b.) Bladder-Type Accumulator:- FIG. 48 p.125.
  - hollow steel cyl. with rounded ends.

c.) Piston Type Accumulator. FIG. 49. p.129.

CH. 10. LOCKS AND SEQUENCE VALVES :-

i.) PURPOSE :-
- provision for locking units (landing gear.)
- operated by the landing gear actuating cyl.
  - detent-ball types
  - spring-loaded locking pin.
  - horseshoe or J-hook.

ii.) WING-LOCK CYLINDER :- p. 132.

iii.) SEQUENCE VALVES :-
- cause one hydraulic action to follow another in a definite order or sequence. (timing valve or load & fire check valve)
- unbalanced type most common.
- automatic by-pass valve.
  - housing with 2 ports, poppet or ball, & seat, 2 return springs, & seals + external device for unseating poppet.

CH. 11. RELIEF VALVES:

i.) PURPOSE:-
- keep hydraulic pressure @ predetermined safe value & control it when it threatens to get out of hand.

ii.) GENERAL FUNCTION of ~~SYSTEM~~:- R.V.'s.
- 2 or 4 port housing; ball or cone on seat with springs, adjustable screw. FIG. 50/p136

iii.) CLASSIFICATION:-

a.) MAIN SYSTEM RELIEF VALVE:
- relieve above system pressure.
- immediately following the main system filter. → bypasses to ~~regulator~~ reservoir.
- BALANCED RELIEF VALVES:
  - most commonly employed to control press. in autopilot systems.
  - fluid under press. acts on both sides of a piston having equal areas on both sides.
  - metering hole & return spring.
- UNBALANCED RELIEF VALVES:
  - ball or poppet type
  - ball held on seat by spring

b.) THERMAL RELIEF VALVES:-
- operation similar to unbalanced M.S.R.V.
- ex., F8F - T.R.V. in landing gear door line outdoor aft face of firewall - exhaust caused cylinder swelling & rupture

CH. 12. AUXILIARY UNITS:

i.) DUMP VALVES: FIG. 53. p. 144.
- "dumps" or releases hydraulic fluid.
- used in conjunction with emergency operations of landing gear, bomb bay doors, & system pressure dumps.
- eg. - landing gear system - so that wheels can be lowered in event the hydraulic act. syst. should fail completely.
- alloy housing, 3 ports - from selector valve, to l/g. actuating cyl. & back to reservoir.
- co-axial poppet valve with cam.

ii.) CHECK VALVES:- FIG. 54 p. 145.
= allow free fluid flow in one direction while prohibiting flow in opposite direction.
- may be used to trap fluid in part of syst; maybe installed in pressure or return manifold.
= ball, cone, flapper plate + spring.
- ORIFICE CHECK VALVES: FIG. 55 p. 146.
  - free flow in one direction, restricted flow in other.
  - retard operation of flaps, landing gears etc.
  - check valve with drilled passage.
  (prevent air from forcing flaps up to quickly.)
  (" l/g. from dropping to quickly.)

iii.) MANIFOLD OR JUNCTION BLOCKS:
- junction box for hydraulic lines
- saves wt & space (lessen leakage danger)
- located @ branch-off points of pressure lines to selector valves, working lines to cylinders, & return lines from selector valves.
- may incorporate check valves & thermal relief valves.

iv.) RESTRICTORS:
- limit the rate of flow in both directions in a line, causing unit to function slowly.

- orifice & variable restrictors (needle valve).
- l/g - in up line, restricting fluid emerging from actuating cyl.

V.) FLOW EQUALIZERS:-
- flow divider, in unit systems where simultaneous operation of 2 or more actuating cyls is desired.
- piston & gear types:
- gear type not accurate in reverse flow.

vi.) CONTROL BOOSTERS:
- one end attached to structure, piston end attached to moveable control.
- emergency bypass, controlled manually.

vii.) GAUGES & GAUGE-SNUBBERS:- FIG. 58 p. 151.
- measure hyd. press. in p.s.i.
- snubber dampens oscillations & protects gauges.

viii.) PRESSURE SWITCH:-
- turn electric switch on or off in response to pressure.
- used to shut off electric motor when pump is motor driven.
- require a master switch in cockpit (during ldg & take off)

ix) ARRESTING HOOK:-

x.) HYDRAULIC FUSES:-
- preventing the loss of hydraulic fluid from broken lines.
- shut-down (close) after passing a given quantity of liquid.
- quantity measuring type & return flow type.

xi.) ELECTRICALLY OPERATED HYDRAULIC UNITS:
- to operate selector & shut-off valves.
- automatically controlled by press. switches, thermostats, or toggle-switch. - solenoid operated.
- FIG. 59. p. 155.

CH. 13. SHOCK STRUTS: (landing gear struts).

1.) PURPOSE:
- hydraulic-pneumatic type.
& spring-loaded hydraulic type.
- absorb & dissipate the landing shock on the compression stroke of the strut.
- hard & soft struts – different metering pins.

CH. 14. BRAKE ACTUATING SYSTEMS:-

i.) PURPOSE:-
- application of brakes during landing, taxiing, & parking.
- provision for any amount of either brake, by pedal operation.

ii.) TYPES & USES:-
- mechanical, hydraulic, & pneumatic.
- power boosted master cylinder brake system or a power brake control valve system.
- power boost - can operate brakes when main syst is not up to pressure, but p.b.c.v. must have syst. press. to operate.

iii.) TYPICAL MASTER-CYLINDER BRAKE SYSTEM:-
- master cyl = energizing unit - separated from main system.
- one for each main wheel. → supply press.
- maintains correct volume, compensating for climatic conditions, exp & contr., leakage & prevents air entry into system.
- manually-operated, single-acting RICIPROCATING PISTON PUMP. (toe pedal.) - mechanical linkage.
- have their own reservoir.
- brake actuation cyls located in brake assembly.
- PARKING BRAKE MECHANISM:- depress toe & pull lever.

FIG. 70 p. 183.

iv.) TYPICAL POWER BRAKE SYSTEM:-

- line from main pressure line between system accumulator & first selector valve.

① - check valve - prevents loss of brake system pressure in case of main syst. ~~press.~~ failure.

② - accumulator - store fluid under press. for emergency operation. (absorb surges.)

③ - power brake valve.

④ - de-boosters - ~~release~~ press., alt greater fluid displacement, faster return, smoother operation

⑤ - Emergency air bottles.

- POWER BRAKE VALVES:- p. 184.
    - release & regulate press to brakes.
- POWER BRAKE CONTROL VALVE. p. 187.
- COMBINATION POWER BRAKE VALVE & MASTER CYLINDER: p. 190.

CH. 15. HYDRAULIC BRAKES:

i.) INTERNAL EXPANDING SHOE BRAKE:-
- for single engined a/c.

a.) SINGLE-SHOE SERVO:-
- operate for one-direction wheel rotation. (non-interchangeable).

b.) TWO-SHOE SERVO:- FIG. 75. p. 199.
- either direction & reversible.

ii.) HAYES REVERSIBLE BRAKE:
- 2 piston, single lining.

iii.) EXPANDER-TUBE BRAKE:
- brake frame, expander tube, & brake blocks.
- single & double row.

iv.) MULTIPLE-DISC-BRAKE:
- for heavy a/c.

v.) SINGLE-DISC BRAKE:-
- fixed disc or floating disc.

CH. 16. SHIMMY DAMPERS:

i.) PISTON-TYPE SHIMMY DAMPER:
- 2 cyls attached to outer cyl. of nose-wheel shock strut - piston rods connected to the inner cyl of shock strut. (FIG. 79 p. 212.)
- snubber valves (restricted flow in one direction, free flow in other). → when wheel moves from neutral
- preload accumulator

ii.) VANE TYPE SHIMMY DAMPER:-
- mtd externally or within inner cyl of n/w. strut.

CH. 17. HYDRAULIC SYSTEMS:

i.) TYPES of SYSTEMS:

- supply adequate supply under press. greater than that which is likely to be req'd.
- OPEN CENTRE SYSTEMS
  CLOSED CENTRE SYSTEMS.
  - pressurized systems
  - non-pressurised systems.
- Pressurised hydraulic systems ÷ when the operation of a unit requiring low press. has been completed, the system will automatically return to operating press.
- Non-pressurised systems ÷ when the op'n of a unit is completed during "in flt" cond, the entire syst. is returned to the max allowable back press.
- <u>NON-PRESS SYST.</u>
  ① Open-centre ÷ <u>variable delivery pump control</u>
  - under press only when services are operated.

  ② Open-centre ÷ <u>constant delivery pump press. relief valve control</u>:
  - under press only when service operated.

  ③ Closed-centre ÷ <u>variable delivery pump control</u>
  - only during "in flt" op'ns, no service being used, is system depressurised.
    - automatic or manual depressurisation.

  ④ Closed-centre - <u>constant delivery pump ~~pressurization~~ regulator control</u>:
  - depressurised only during "in flt" opns when none of services are being used.
- <u>PRESS. SYST.</u>
  ① Closed centre - controlled by a variable delivery pump.
  ② Closed centre - constant delivery pump & press. regulator.

ii.) OPEN CENTRE SYSTEM:-

common to most systems. {
- reservoir → house reserve supply of fluid.
- engine driven pump → provide fluid flow.
- filter → clean fluid.
- main system relief valve → protect syst.
- system press. gauge → indicate degree of pressurisation
}
- open centre or automatic neutral selector valves (instead of conventional piston or poppet selector valves)
  - in neutral, output from power pump circulates thru them to reservoir.
  - valves connected in series rather than in ll'l. (i.e., all valves connected in same press. line)
  - with one valve working, others are inoperative.
  - valve relieves the pump of ld when mechanism reaches the end of its stroke.

iii.) CLOSED CENTRE SYSTEM:-

above: + (or pressure regulator hydraulic system)
- pressure regulator (or unloader valve) → reg. syst. press. & take load of the eng. driven pump when no units are oper'tg
  - syst. under press. all times eng. in running & @ cut-out press. diverts pump flow back to reservoir under free flow, thus unloading the pump.
- accumulator: aids regulator, absorbs shocks & surges, aids pump during peak demands by storing fluid under press.
- power brakes may be used on a C.C.S. as syst. is always under press. when pumps are operating (not running, hand pump.) (hand pump + h.p. selector valve → single unit operation)
  (- manifold block + built in check valves & thermal relief valves in conj with h-p. sel. valve.)
- shut-off valves: to isolate sects of syst.

- primary system - units needed to effect a safe landing .. can be isolated from secondary syst. by closing a shut-off valve
- h.p. → primary syst.
  - landing gear, flaps, power brakes.

iv.) EMERGENCY HYDRAULIC SYSTEMS:
- hand pump. - partial failure
- extension by gravity } complete hyd.
- aux. force - compressed air or CO_2 } failure.

a.) GRAVITY-TYPE SYSTEM:
- l/g. drops under own wt.
  - lock-up pins pulled by cable
  - " -down " - spring loaded cyl.

b.) COMPRESSED AIR SYSTEM:-
- control handle in cockpit. + cable
- C.h. down →
  1.) cable movement causes air vent to close & seal the air system.
  2.) bypass dump valve is opened to permit fluid to bypass to the return.
  3.) t/w. is unlocked, spring snaps it down air bottle press. opened → air to shuttle valves which seal off normal fluid entry port. & allow air to enter actuating cyl. & extend l/g.
- press. sufficient for one operation only.

REVIEW of "AIRCRAFT HYDRAULICS."
Harold W. Adams.
McGraw-Hill Book Company. Inc. (1943)

CH. I. INTRODUCTION.

i.) Advantages
- light weight, controllability, low inertia
- become heavy at low power.

ii.) Line sizes:-
pressure lines: $(\frac{1}{4})$ $\frac{5}{16}$ – $\frac{1}{2}$ in.
suction lines 1/2 – 1 $(1\frac{1}{2})$ in.

CH. II. FLOW OF FLUIDS:

A. Flow in Pipes:-

i.) Viscosity
kinematic viscosity – ν
absolute viscosity – μ
where $\nu = \frac{\mu}{\rho}$ ... ρ = density.

ii.) Reynold's Number:

$$R = \frac{Vd}{\nu} = \frac{Vd\rho}{\mu}$$

iii.) Resistance flow through a pipe:

$$h = f \frac{V^2 L}{d\,2g} \qquad \& \; p = \rho h$$

where V = velocity of flow.
L = length
d = diameter
g = acceleration of gravity
f = friction or resistance factor
h = resistance loss (head of fluid lost)

iv.) Friction factor:

$$f = \frac{64}{R} \quad \text{-- laminar flow.}$$

$$f = .0056 + \frac{500}{R^{0.32}} \quad \text{--- turbulent flow.}$$
(R > 2000)

B. Flow Through Orifices & at Changes of Section in Pipe:-

i) Potential Energy = Kinetic Energy.

$$Wh = WV^2/2g$$

$$\text{or } V = \sqrt{2gh}$$

ii.) $Q = A.V. = A\sqrt{2gh}$ -- through orifice

iii.) Coefficient of contraction:
= ratio of area of strm to area of orifice.
Coefficient of velocity:
= ratio of actual to theoretical velocities.
Coefficient of discharge = $C_c \times C_v = C_D$

iv. Hence $Q = C_D A_{orifice} \sqrt{2gh}$ -- through orifice.

$$\text{Loss @ expansion} = \frac{(V_1 - V_2)^2}{2g} \quad (7).$$

Bernoulli's Eqn:- $P_1 + \frac{V_1^2}{2g} = P_2 + \frac{V_2^2}{2g}$

$$\therefore P_2 = P_1 + \frac{V_1^2 - V_2^2}{2g} - \frac{(V_1 - V_2)^2}{2g}$$

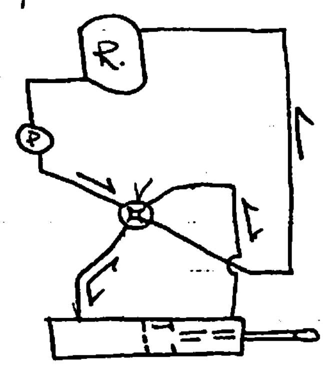
<u>ETC.</u>

v.) Example of Forces in a check valve.
p. 31.

CH. III. HYDRAULIC SYSTEMS:-

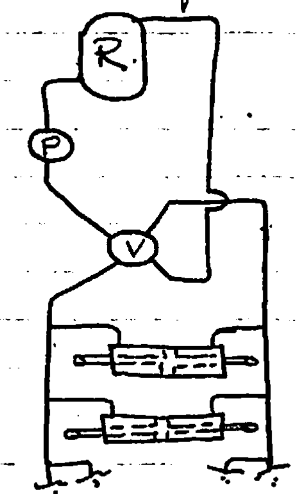
i) Development of the Modern Hydraulic System:-

a.) Basic system:-



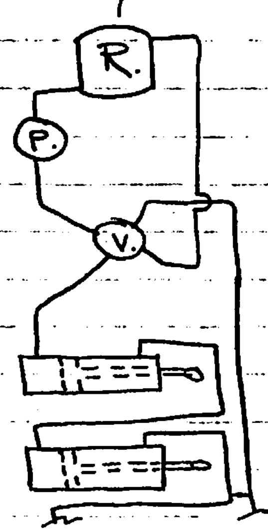
R = reservoir
P = pump.
V = valve.

b.) Parallel System:-



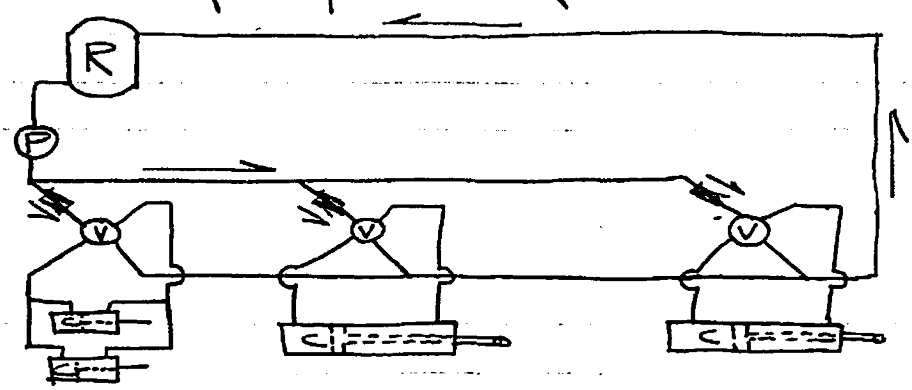
- not a synchronised system.
- sequence of operations is determined by the load on cyls.
- eg. one l/g. retracting before the other.

c.) Series System:-



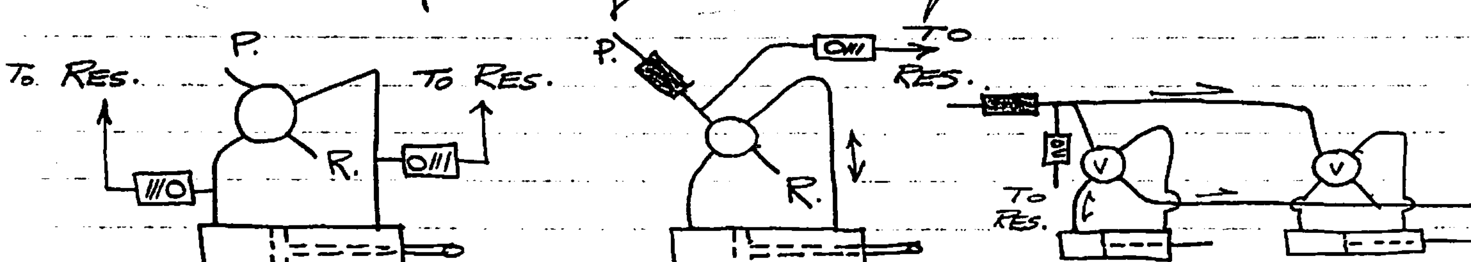
- all cyls (if of same area) operate at same rate.
- leakage between cyls, get out of synch. 2nd cyl. may not reach end of travel when first has.
- trapped fluid expansion
- overcome by using synchronizing valves.
- <u>Excessive heat</u>.

d.) Addition of valves to basic airplane hydraulic system :- (for operation of more than one system).



- as in ||'l system, system is not synchronised if more than one valve is op't'd at one time.

① Flow in a hydraulic system always tends to equalize pressures, i.e., to build up low press. & to lower high press.
② Fluid is incompressible, & so the vol. in a subsyst. remains the same (plus pump input minus flow to reservoir).
Hence it can be seen that check valves can be incorporated to prevent interflow between valves. (shown above.)
Require spring-loaded expansion chambers or relief valves. - if it is required to maintain pressure, a spring loaded expansion chamber is req'd - eg. on parking brake systems.

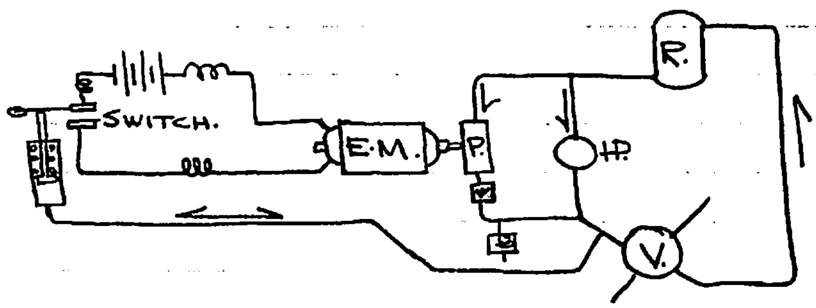


e.) Use of relief valves in cylinder lines.

f.) Use of relief valve in valve press. line.

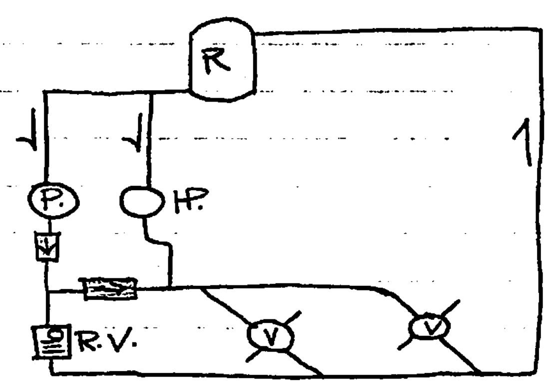
g.) Use of relief valve in common press. line.

ii.) Development of the Power System :-
a.) Original system : reservoir & hand pump.
b.) Electric-motor-driven hydraulic pumps - (gear type) in ||'l with hand pump. (emergency) + press. switch.



- inertia of motor drives pump several rev's after the press. switch opened ∴ adds press. relief valve after pump.
- during cold weather, or acceleration (bump) switch can close system down before operation is complete.
- lower viscosity, but pump wear increased.
- raise press of cut-out switch - shortened pump life, increased wt. of strg lines, cyls, etc. increased maintenance cost.
- Satisfactory solution never found.

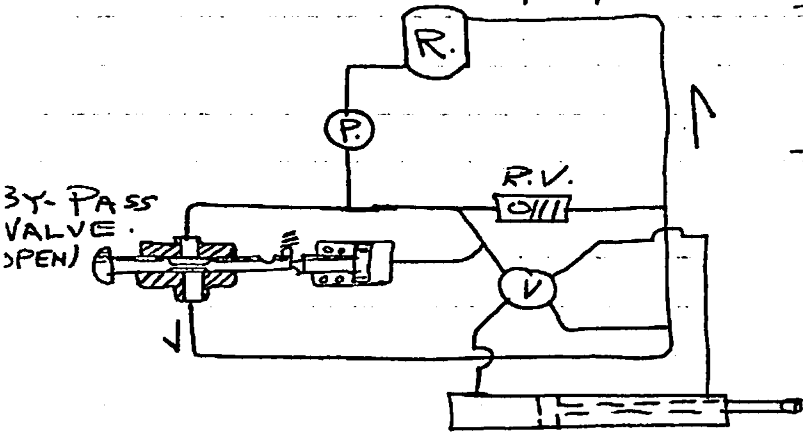
Next Came :-
iii.) Engine Pump Systems :-
constant pressure, manual pump by-pass & automatic pump by-pass.
a.) Constant-press type :- pump → syst. press @ all times.



- suitable for low HP. (excess HP → heat.)
- It is better to let pump circulate ~~press~~ fluid freely under no press (reduces heating).

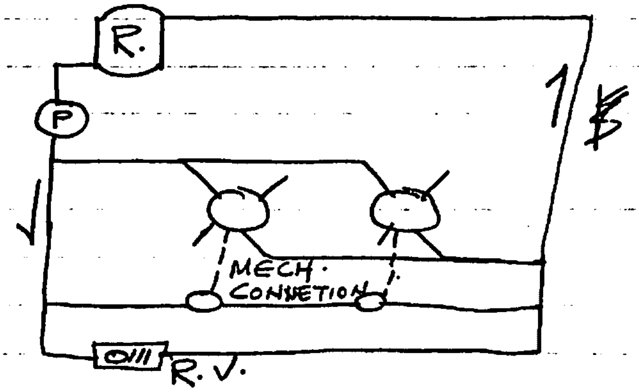
Hence :-

b.) Manual By-pass :-



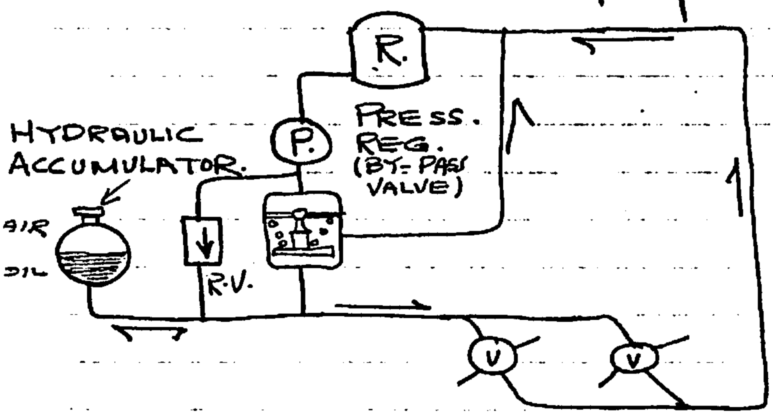
- By-pass valve can be kicked out before operation is completed.
- Requires 2 motions on part of pilot.
- heavy because of high ratio between normal working and maximum pressures.

By-pass valves operated by the directional control valves: (i.e., open-centre system).



- pilot may forget to return valve to neutral - flow must go through R.V. & ∴ heats up.

c.) Automatic By-pass :-



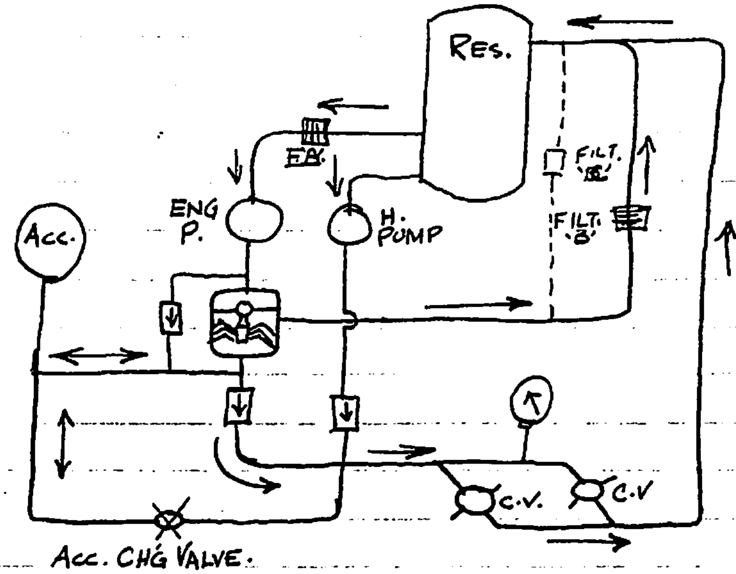
- accumulator - prevents overriding of P.R. & absorbs shocks.

Could also use a system with an automatic variable-displacement pump.

PART II.
DESIGN.

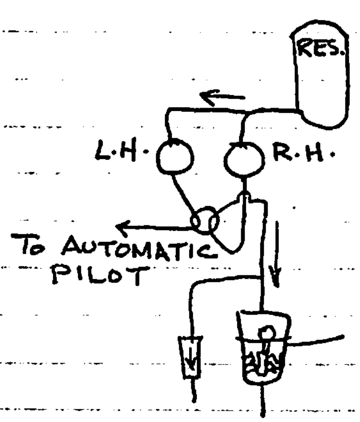
CH. IV. POWER SYSTEM:-

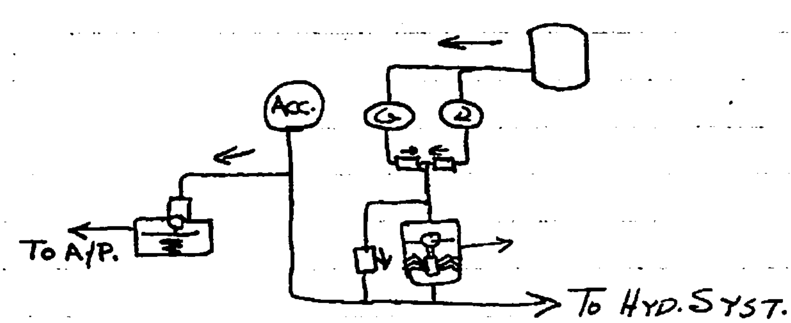
i.) DESIGN REQUIREMENTS:-



SYSTEM INCORPORATING ACCUMULATOR CHARGING VALVE.

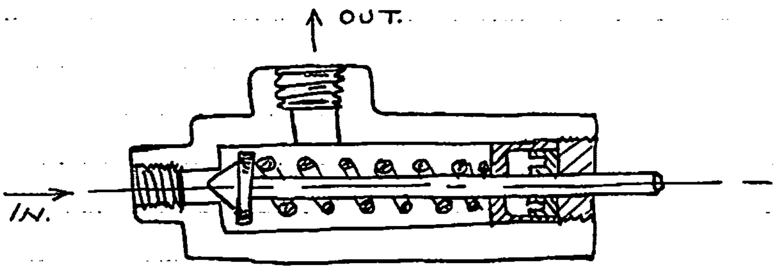
- Filters → most commonly part of (power press.) syst.
  - a.) In suction line — ('A')
    - best protection for pumps.
    - increases press. loss in suction line.
  - b.) In return line (by-pass line from reg.) ('B')
    - more press drop available
    - does not detract from the perf. of any subsystem.
  - c.) By-pass filter ('C'):
    - extremely high filtration on line with considerable back pressure.
    - poorest protection → filters only portion of flow. (used on automobile engines)
  - d.) Reservoir Filters → 30 to 170 mesh screens.

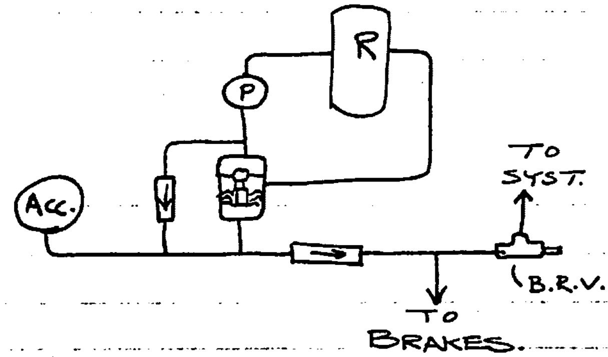




e.) Automatic Pilot Demands.

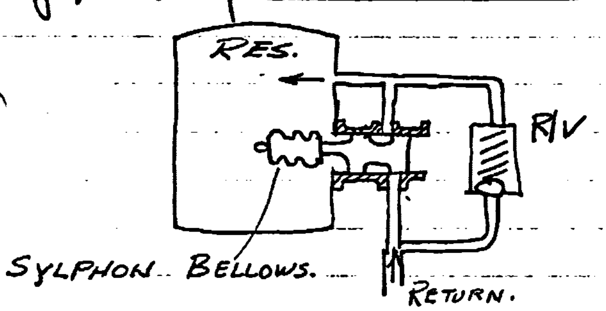
f.) <u>Balanced Relief Valve:-</u>
- balanced relief valves are added in order to have sequence op'n (i.e., units with lowest press. demand need not operate first.)





BALANCED RELIEF VALVE.
&
Schematic showing balanced (selective) relief valve to ensure pressure in brake system.

g.) <u>Temperature controlled system:-</u>

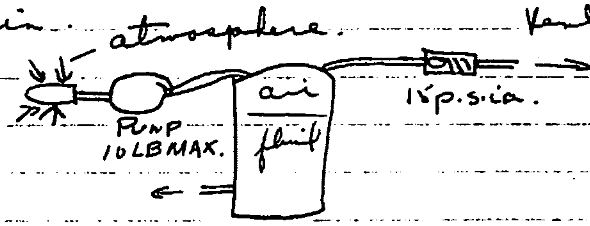


Pump warms fluid up when working against R/V, thus expanding Bellows & eventually opening free port.

h.) Pressure reservoirs:-
i.) piston type:

- foaming
- difficult to maintain.
- low flow systems

ii.) Pump supercharging.



CH. V. SUBSYSTEMS:-

i.) DESIGN REQUIREMENTS:-

Types of systems:

a.) non-control systems.

b.) control systems.

- follow-up (position) controls
- power-amplifying (load-feel) controls
- position plus load feel.
- automatic systems (sequence of events req'd.)

Considerations:

a) loads (operating & design

b.) speeds

c.) special req'ts.

- operating loads → size of cyl.
- design loads → max lds → burst strength
- max speed @ lowest req'd temp → line & pump sizes

ii.) NONCONTROL WEIGHT-LOADED SUBSYSTEMS:

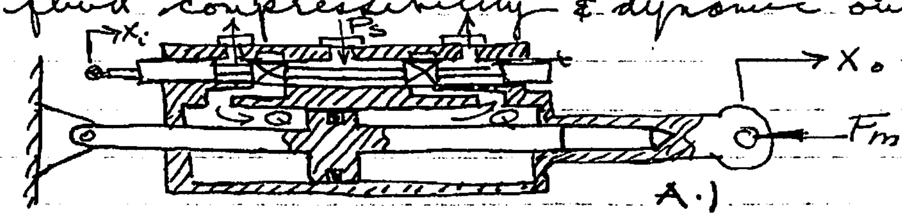
Ex. landing gear:-

- calculate loads due to:

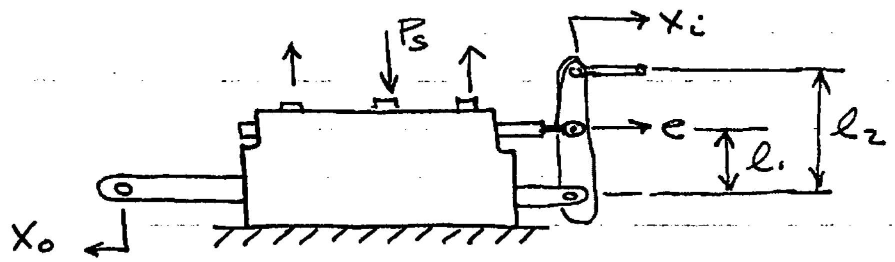
weight, air, friction, door operating - & bungee ~~sep~~ independently, then a change will not alter all work.

- increase max ld by ≈ 10→25% (allow for line loss) & divide by press. available (reg. setting)
- if strut in torsion, A→net area, rod area must be included.

New Techniques for HYDRAULIC SERVO DESIGN.
JAMES M. NIGHTINGALE, MANCH. ENG.
- a new way to determine basic design parameters.
Control Engineering, p. 73, Sept. 54.
- for cyl. actuators, types:
i.) those that relate to overall system response
ii.) " " effect stability.
- ii.) involves a thorough dynamic analysis of the unit & its mountings.
- difficult & results not always reliable
∴ leave certain parameters for adjustment, so unit is tuned under actual op'g cond's.
- at first ignore such destabilising effects as fluid compressibility & dynamic output loading



A.)



- B.)

Closed loop arrangements of a slide valve-cyl. comb'n. In (A) the valve opening is a direct measure of error, while in (B) the opening error relation depends on the ratio of diff't levers.
- The use of negative feedback, either directly or through a linkage connection, ensures accurate input-output relations, with the swamping of inherent nonlinearities & also with suitable characteristics. Power amplification large, as command (input) displ't overcomes axial slide-valve forces.
A.) direct measure of error, as command displ't X_i acts valve stem & feedback is 1/1, with valve & cyl bodies moving an amount equal to the output displacement.

B.) error-valve opening relationships, with rel. movement & feedback ratios depending on ratio l_1/l_2. Results developed apply here too.

<u>Notation</u>:

x_i = input displacement
x_o = output displacement
e = error (valve displacement)
E = maximum valve displacement.
a = valve port area.
E_1 = static deflection under full load.
a_1 = exposed port area corresponding to E.
A = effective cylinder piston area.
X = cylinder stroke
F_m = max. cyl. load.
P_c = cyl. diff'l operating press.
P_m = max. diff'l operating press.
P_o = min. press. in cyl.
P_s = syst. press.
Q = flow from valve tending to displace cyl.
Q_s = sat'd flow.
Q_m = sat'd flow under max. cyl. load.
Q_o = sat. flow with no cyl. load.
T_m = operating time under max. cyl. load.
T_o = " " with no cyl. load.
T_c = creep time
T_e = syst. time constant.
k_x = jack stiffness
k_e = valve stiffness
N = bulk modulus of fluid
A_o = area of bleed hole in piston
K = amplifier gain
p = Laplace operator
C = Valve flow coeff't.
ω = frequency.
ω_n = resonant frequency of system.
M = amplitude ratio at resonant frequency

Hydraulic Servo Design.

Unknown parameters:

- cylinder area, working pressures, pump delivery, valve travel, and port area.

Known quantities:

- system pressure, cylinder stroke, maximum cylinder load, & various operating times.

* the unknowns are expressed as lumped parameters rather than separate factors.

Determination of cylinder area A:

Choose a suitable max op'g diff'l press., P_m, & is usually fixed at $\frac{2}{3} P_s$. Then:

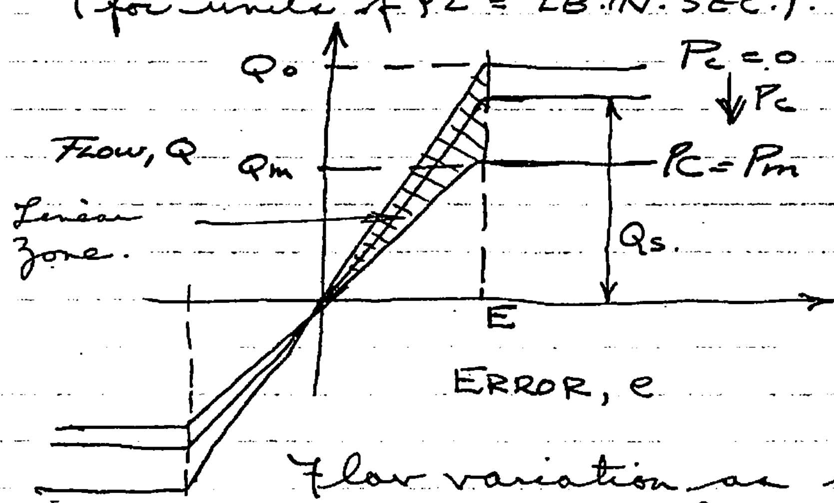
$$A = \frac{F_m}{P_m} = \frac{3 F_m}{2 P_s} \qquad (1.)$$

Assuming the flow thru valve varies linearly with valve opening, flow can be expressed as:

$$Q = \frac{Cae}{E} \left[\frac{P_s - P_c}{2} \right]^{1/2} \qquad (2.)$$

i.e., the flow is equal to the sq. root of half the total pressure drop across the inlet and exhaust ports X the prodct of the flow coeff't & the area of opening of the inlet (or exhaust) port.

C ≈ 100 for wide range of fluids & orifice shapes. (for units of §2 = LB·IN·SEC.).



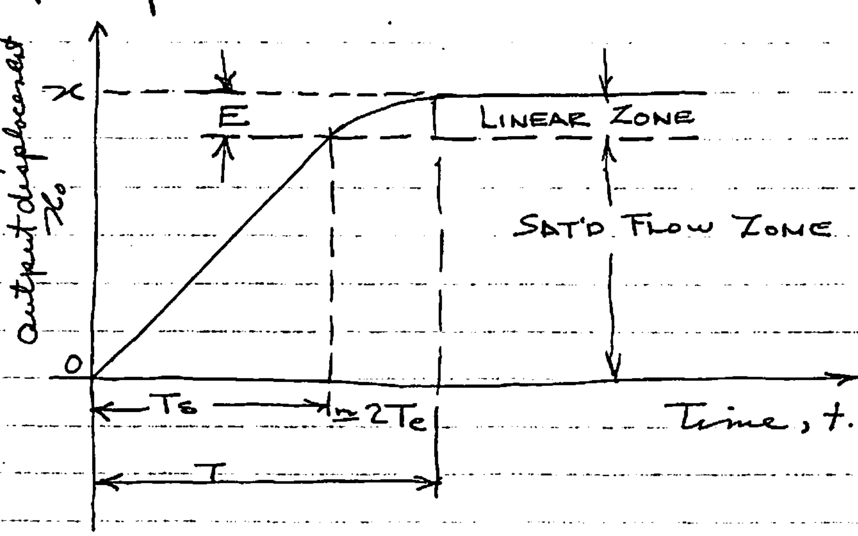
Flow variation as a fcn of error and operating pressure. Linear zone is bounded by max. valve opening & sly pressure corresponding to max & no-load cond'ns.

The flow variation with error curve has 2 important pts.

i.) The flow varies with operating pressure & hence with output load. For no-load cond'n, the diff'l press, P_c, across the piston is zero (neglecting friction) so that the flow is a max for any given error. When the cyl. is driving the max load, the diff'l press, P_c, equals P_m so that the flow under this cond'n is a min for a given error.

ii.) For maximum valve opening the flow saturates. In terms of response this means that when the valve is only partially open, the unit is error-sensitive, but when the valve is fully-open, the output moves @ a saturated velocity that varies only with output load.

The linear response region extends to a pt where the error equals the max. valve opening, E. Beyond this point, the flow is saturated & depends entirely on op'g press & Ld., ranging from Q_0 (no load) to Q_m (full load).



Output displacement over full stroke of cylinder as a fcn of time for one load cond'n. Piston moves @ const. saturated vel until valve starts to shut.

Hydraulic Servo Design.

Plot of time & cyl. ed cond'n, ld.

assuming the valve opens instantaneously, the piston will travel the saturated flow zone (total stroke X minus maximum valve opening E.) at a const. vel in time Ts. The vel. decreases in the linear zone as the valve closes so that the total time T is req'd to travel full stroke. An increase in load will decrease slope (decrease saturated velocity), thus incr.g operating time, & vice-versa. Within the error sensitive region, system equations consist of eq. (2) &

$$e = x_i - x_o \qquad (3.)$$

$$\frac{dx_o}{dt} = \frac{Q}{A} \qquad (4.)$$

Combining to give the overall transfer fcn,

$$\frac{x_o}{x_i} = \frac{1}{1 + T_e P} \qquad (5.)$$

Variation of operating times with ratio of max operating to syst. press. Optimum P_m is selected $= \frac{2}{3} P_s$. – Figure below.

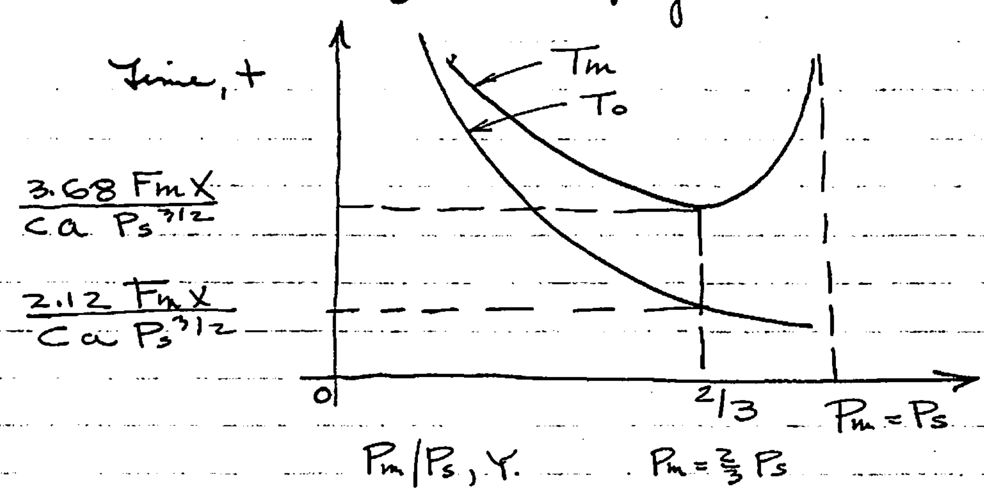


FIG. 5.

where the system time constant, T_e, is:

$$T_e = \frac{EA}{C_a \left[\frac{P_s - P_c}{2}\right]^{1/2}} \qquad (6.)$$

assuming that the time req'd to traverse the linear zone, E, in FIG. 3 is twice the time const, then total op't'g time / ½ cycle of full cyl travel (full stroke in one direction) is approx

$$T = T_s + 2T_e \qquad (7.)$$

and from fig 4,

$$T_s = \frac{(X-E)A}{Q_s}$$

(6) → $$2T_e = \frac{2EA}{Q_s}$$

Subst. in (7), the approx. time is expressed by:

$$T = \frac{AX}{Q_s}\left[1 + \frac{E}{X}\right] \qquad (8.)$$

where Q_s is sat'd flow for any given diff'l press P_c & is

$$Q_s = Ca\left[\frac{P_s - P_c}{2}\right]^{1/2}$$

8) → reduce ratio of valve opening to cyl. stroke (E/X), & reduce cap. of pumps req'd → spec. operating time. Common design values of $E/X \doteq 1/20 \to 1/30$. Using these values, the output can be considered saturated over the entire stroke, resulting in a non-harmonic frequency response for all freq's exceeding a critical value. This wave dist'n, caused by const. vel following in sat'd range, is usually less important than power economy &, if desired, the critical frequency can be fixed above the normal operating freq'y of the whole system.

Operating time varies with diff'l press across the piston & is shorter under no ld cond'n. For max ld, $P_c = P_m$,

$$T_m = \frac{AX}{Q_m} = \frac{F_m X}{CaP_m\left[\frac{P_s - P_m}{2}\right]^{1/2}} \qquad (9.)$$

& for no load, $P_c = 0$,

$$T_o = \frac{AX}{Q_o} = \frac{F_m X}{CaP_m\left[\frac{P_s}{2}\right]^{1/2}} \qquad (10.)$$

Expressing T_m as a fcn of y, where $y = P_m/P_s$ & → (9) & (10).,

Hydraulic Servo Design:

$$T_m = \frac{F_m X}{C a P_s^{3/2}} \left[\frac{2}{y^2 - y^3}\right]^{1/2} \qquad \text{———— (11)}$$

& $$T_o = \frac{F_m X}{C a P_s^{3/2}} \left[\frac{2}{y^2}\right]^{1/2} \qquad \text{———— (12)}$$

(See Fig. 5) – it is logical to minimize the optimum operating time under the greatest cyl. load; that is,

$$\frac{\partial T_m}{\partial P_m} \;\&\; \frac{\partial T_m}{\partial y} = 0.$$

Equivalent to making sensitivity (output power/valve port area) a max under max output load.

Optimum value of $y = \frac{2}{3}$ or $P_m = \frac{2}{3} P_s$. (as before.)

Knowing optimum P_m, → (10) (as T_o rather than T_m is specified) then port area is:

$$a = \frac{3 F_m X}{2C\left[\frac{P_s}{2}\right]^{1/2} P_s T_o} \simeq \frac{0.02\, F_m X}{T_o P_s^{3/2}} \qquad \text{———— (13.)}$$

Max. flow is encountered under no-ld conds & is

$$Q_o = \frac{AX}{T_o} = \frac{3 F_m X}{2 P_s T_o} \qquad \text{———— (14.)}$$

Valve travel, E, controls:

a.) width of the error-sensitive region,

b.) frequency response within this zone.

If input in the overall transfer fcn, (5), is a sinusoidal displacement, under no-ld cond'n a flat-band frequency response is obtained up to a frequency

$$\omega = \frac{1}{2\pi T_o}\left(\frac{X}{E}\right) \text{ c.p.s.} \qquad \text{—— (15).}$$

If ω & T_o are specified, E/X can be determined. ($\doteq$ 1/20 → 1/30 as noted before)

An undistorted response with little attenuation or phase lag can be obtained for inputs given by

$$x_i = E \sin\left(\frac{X}{E}\,\frac{t}{T_o}\right) \text{ NO LOAD} \qquad \text{———— (16.)}$$

$$= E \sin\left(\frac{X}{E}\,\frac{t}{T_m}\right) \text{ FULL LOAD.} \qquad \text{—— (17)}$$

SUMMARY of BASIC EQUATIONS:–

Eq. No.	1	13	14	15
Determines	Cyl. area	Valve port area	Max vel. flow	Valve travel
Eq.	$A = \frac{3F_m}{2P_s}$	$a = \frac{.02 F_m X}{T_o P_s^{3/2}}$	$Q = \frac{3F_m X}{2P_s T_o}$	$E = \frac{X}{2\pi\omega T_o}$
Controls	Operating Press.	Operating time	Reqd. of pump delivery	Response in linear zone.

Factors affecting stability:

Certain parameters associated with the flow characteristics of the unit can be adjusted to limit de-stabilising effects both inside the amplifier and in the control system as a whole. However, as first design approx'n, only complications within the unit itself need be considered. There are three important parameters:

(i.) stiffness of the cylinder
(ii.) stiffness of the valve
(iii.) amplifier gain.

Flexibility of cyl. is almost entirely caused by fluid compression, & is

$$k_x = \frac{2AN}{X} \qquad (18.)$$

As air is present, the bulk modulus, N, is a fcn of pressure ∴ keep minimum jack pressure high, it is:

$$P_o = \frac{P_s - P_m}{2} \qquad (19.)$$

i.e., P_m should not be too high. $P_m = \frac{2}{3} P_s$ is satisfactory.

Ex. if $P_s = 3000$ psi, $P_o = 500$ psi, $N \doteq 200{,}000$
∴ k_x is high & has little effect on syst press.
k_x # LB/IN.

By means of small leakage on side of valve lands, a base pressure is maintained on both sides of the piston even under no ld.

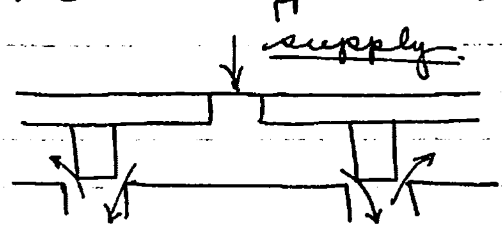


Fig. 6.

Hydraulic Servo Design.

The stiffness of valve, when $Q=0$ is:

$$k_e = A\left(\frac{dP_c}{de}\right) \qquad \text{—— (20.)}$$

or ld on cyl. req'd to move the valve a unit length is equal to the change in cyl. ld, $A\,dP_c$, ÷ by corresponding valve displacement, de, for a no-flow condition. Theoretical stability considerations → $k_e < k_x$.

Physically → chge of ld, tends to shorten column of oil in cylinder. Valve must then open sufficiently, because of cyl. displ't, to allow a diff'l press. to build up in cyl. to balance chge in ld. Failing in this, valve would overcompensate cyl. displacement, further compressing the fluid column & setting up a self-maintained oscillation. ∴ $k_e < k_x$ to permit compensation for chges in ldg.

under full ld, the unit will deflect an amount E_1, (18) →

$$k_x = \frac{F_m}{E_1} = \frac{2AN}{X} \qquad \text{—— (18.)}$$

Subst. $\frac{F_m}{A} = P_m = \frac{2}{3} P_s$,

then $$E_1 = \frac{X P_s}{3N} \qquad \text{—— (21.)}$$

Static deflection, & may be exceeded under fluctuating ld. Output flex'y can be serious from viewpt of syst. stab. w.r.t. a varying output ld, however, unavoidable. De-stab. effects ~~limited~~ reduced by limiting so-called creep vel. with which cyl. corrects for chge in load.

How To Fit Power Booster into Aircraft Controls
(James A. Nightingale – Control Engineering – Dec. '54. pp. 24, 25, 26, 27, 28.)

Power amplifiers between controls and control surfaces helps pilots cope with the high operating loads of todays heavier & faster aircraft. Design requirements make it almost essential that the power control be a closed-loop system. And although the choice of the power source depends largely on the designers preference, there is a slight bias towards hydraulic systems because they are simple and reliable and exact a low weight-power penalty.

For efficient design, the performance of the control servos must be tied in with the performance of the aircraft as a whole, including the pilot or autopilot. This involves at least 2 intricate problems:
→ pilot response and
→ flight characteristics of uncontrolled aircraft.

The characteristics of human operators have been approached analytically for certain simple operations (see for example "Man as a Servo Component," Control Engineering, Oct '54). But the complex procedure of ~~fy~~ flying an airplane – influenced by such uncontrollable ~~features~~ factors as experience, strength, and fatigue – is not easy to analyse. Also, only a limited amount of very speculative information concerning the handling properties of aircraft is available during the pre-flight stages of development. Thus, sound general principles must be established for the initial power-booster design if excessive modification is to be avoided later on. Certain parameters can be varied, so that the system can be tuned during test-rig and flight trials.

Aircraft Performance

An aircraft has several units that operate its control surface. These surfaces – for example, ailerons, elevators & rudder – control the various degrees of freedom of the aircraft by exerting aerodynamic forces that vary with the direction and magnitude of the surface rotation about its hinge.

An analysis of the exact nature and magnitude of the aerodynamic force is beyond the scope of this article. But for small displacements about steady-flight conditions the equations of motion

The Flow of Fluids through Pipes & Orifices

1. Pressure Drop Across a Small Orifice :-

Consider the flow of fluid thru a pipe in which there is a small restriction:

Let:

p_1 = fluid press just before the orifice.
p_2 = fluid press just after orifice.
V_1 = vel. of flow just before orifice.
V_2 = vel. of flow just after orifice.
ρ = density of fluid.

then from Bernoulli's eq. of fluid flow we obtain

$$p_1 - p_2 = \frac{\rho}{2g}\left(V_2^2 - V_1^2\right) \qquad \text{— 1}$$

If A_1 = area of bore of pipe.
A_2 = area of orifice.
c = orifice contraction co-eff.

we have for continuity of flow

$$A_1 V_1 = c A_2 V_2 = Q \qquad \text{— 2}$$

where Q = quantity rate of flow.

Hence we obtain:

$$p_1 - p_2 = \frac{\rho Q^2}{2g}\left(\frac{1}{c^2 A_2^2} - \frac{1}{A_1^2}\right) \qquad \text{— 3}$$

The area term $1/cA_2$ is large compared with $1/A_1$, & hence the above eq. can be written approx. as:

$p_1 - p_2$ = press. drop in p.s.i.

$$= \frac{\rho Q^2}{2g c^2 A_2^2} = \frac{8 Q^2 \rho}{\pi^2 g c^2 d^4} \qquad \text{— 4}$$

Q = flow in cu. in./sec.
d = orifice dia in in.

then $p_1 - p_2 = 7(10^{-5})\, Q^2/c^2 d^4$. — 5.

where specific gravity has been taken as 0.9 (a mean value for hydraulic fluids).

For plain holes the value of the orifice coefficient varies from 0.65 to 0.8; subst.,

$$p_1 - p_2 = 1.65\,(10^{-4})\,\frac{Q^2}{d^4} \quad --- \quad c = .65 \quad — 6$$

$$= 1.09\,(10^{-4})\,\frac{Q^2}{d^4} \quad --- \quad c = 0.8 \quad — 7$$

(Nomogram.)

2. Pressure Drop along a Pipe :-

For fluid flow along a pipe, the press. drop due to friction & turbulence effects is given by:

$$\frac{p_1 - p_2}{\rho L} = \frac{F V^2}{2 g d} \quad ——— \quad 8.$$

where: $p_1 - p_2$ = press. drop.
ρ = density of fluid.
L = length of pipe.
F = friction & turb. factor.
V = rate of fluid flow.
d = bore of pipe.

It has been found that the factor F depends on the value of the dimensionless quantity R, called Reynold's No.

This quantity R is defined as:

$$R = \frac{Vd}{\nu} \quad ——— \quad 9$$

where: V = vel. of flow.
d = bore of pipe
ν = kinematic viscosity of the fluid.

The Flow of Fluids thru Pipes & Orifices.

For laminar flow, the value of F is given by:

$$F = \frac{64}{R} \quad 10$$

and for turbulent flow, the value becomes

$$F = .3164\, R^{-.25} \quad \text{(Blasius' formula)} \quad 11$$

It has been found experimentally that the value of the Reynold's No. determines the type of flow and we have the following result.

For $R < 1200$ — flow is laminar.
$R > 2500$ — " " turbulent.

For $1200 < R < 2500$, the flow is in the transition region & is very sensitive to pipe cond's. To be conservative, flow should be considered turb.

Summing up, if

$p_1 - p_2$ = press. drop, p.s.i.
ρ = sp. grav. of fluid.
L = ~~density~~ length of pipe – ft
Q = rate of flow. – cu. in./sec.
ν = kin visc. – centistokes
d = bore of pipe – in.

then

$$\frac{p_1 - p_2}{\rho L} = \frac{Q\nu(10^{-4})}{1.403\, d^4} \quad \text{for lam. flow.} \quad 12$$

$$\frac{p_1 - p_2}{\rho L} = \frac{Q^{1.75}(10^{-4})\,\nu^{.25}}{1.875\, d^{4.75}} \quad \text{for turb. flow.} \quad 13$$

$$R = \frac{820\, Q}{\nu\, d} \quad 14.$$

$$\frac{Q}{\nu d} < 1.46 \quad \text{for lam. flow.} \quad 15$$

$$\frac{Q}{\nu d} > 3.05 \quad \text{for turb flow.} \quad 16.$$

Points of Arguement:—

1.) Arguement for electrical servooperated systems.
- failures p. 578
- solenoid-operated valves. p. 579. col 2.

"Controversy Over the Choice of a Medium for A/C Power Transmission"
R. L. Haymon.
A.S.M.E Transactions. Vol. 66, 1944.

2.) The Evolution of the Hydraulic Pump as Applied to Aircraft.
Dale Herman.
A.S.M.E. Transactions Vol. 66., 1944.

- The v.d.p is gaining more acceptance on the larger-plane designs, where larger volumes of oil are req'd. & there is a continuous varying demand for hyd. power during flt. Another feature of the v.d.p. is that it will supply a system requiring a constant max. vol. in flt., irrespective of eng. spd. The pump will operate @ rel. short stroke during take-off, but @ max stroke while eng is idling, so that its delivery will remain constant throughout normal operating spd range of eng. Controls:—
  1.) power boosters....
- The c.d.p. — desireable on installations requiring intermittent hyd demands in flt. For p.b. cnt, the unloading valve would be continually cutting in & out — & pressure surges might introduce complications with p.b. sept.

* hyd. HP = displacement (g.p.m) X pressure (psi) X(0.00058).

- accumulator still req'd to operate brakes on ground when eng. is not running.

3.) The Development of Ultra High-Pressure Hydraulic Systems :-
S.M. Parkes. B.Sc.

'The Institution of Mechanical Engineers Proceedings', 1947. Vol. 156.

a.) First consider temperature range :-
- must not vaporize @ highest temps.
nor lub. props fall in power pumps.
- @ lowest temps, viscosity must not rise
to cause unacceptably high press. losses
(DTD. 585) - max. operating viscosity ≏ 500-1000 centistokes
- min - 20°C below (36°F) vaporizing point.
additive - "corbitol".

b.) Pipe materials:

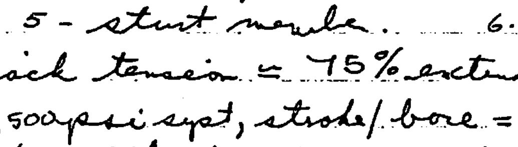
	ULT. TEN STRENGTH	DENSITY	RATIO (St/wt)
Stl drawn & rolled	25	7.8	3.2
Bronze drawn	25	8.85	2.92
Al. alloy drawn	9	2.70	3.33
Copper drawn	14	8.8	1.59

- steel preferred in U.H.P. system - security with compression or flared joints.
- A.G.S. (a/c general spares) flared jt. (l.p) no good for U.H.P.

c.) Save most wt of U.H.P. by decrease in size of reservoir.

d.) Must check to see that ~~strut~~ jack does not fail as strut as size can be decreased.

e.) Jack :-



1 - jack thrust. bulk & press. 2 - bursting press. & on press for thrust 3 & 4 - adeq support for telescoping motion
5 - strut mode. 6. thrust.
- jack tension ≏ 75% extending thrust. ∴ 5 = ½ dia of 2 (max.)
on 2,500 psi syst, stroke/bore = 4/1 - 6/1 small jacks, 8/1 - (10/1) large jacks.
6/1 without wt. penalty. ∴ piston rod = 12/1 - 16/1 - wall t ≏ 10% (15 max)

suggested jack →

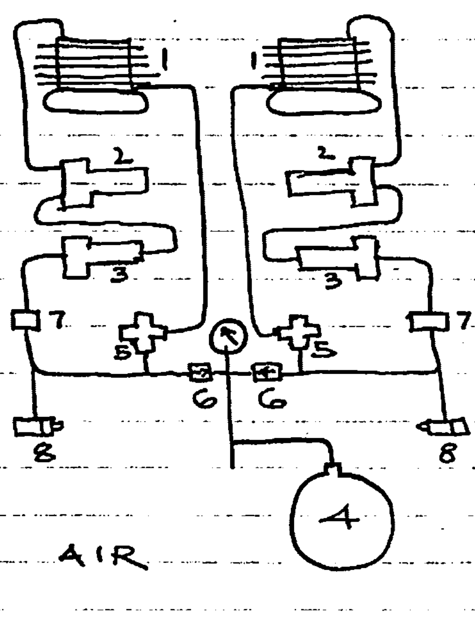

Points of Argument:

4.) Hydraulics or Pneumatics:-
R.H. Bound
De Ingenieur, 16 December 1955.

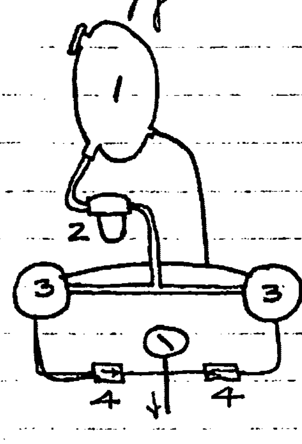
a.) Introduction:-
- hydraulics - well developed & established
- pneumatics - adventageous on some types of a/c.
- considerations:-
  (1) sizes. (2) wt. (3) reliability (4) maintenance
  (5) vulnerability & safety.

b.) Size:-
- both rely on jack actuation.
- hyd. press. = 4,000 psi.
- pneumatic - store at highest possible press & thru reducing valve to lowest practical working pressure.
  ex. - compressed to 3000 psi } 3:1 expansion
  working at 1000 psi } ratio.

c.) Weight:-
- air compressor (3000/3,500 psi)
- lighter than hyd. pump, but larger
- require a great deal of cooling air.
- HP out is only a fraction of that of hyd. pumps.
  ∴ must store energy



AIR



OIL.

Pneumatic
1- air compressor
2- oil & H_2O trap
3- dehydrator
4- air storage bottle
5- pressure reg.
6- non-return valve
7- filter
8- thermal relief valve.

Hydraulic.
1- reservoir.
2- filter
3- pump
4- non-return valve.

Power System Wt Comparison.

Air - 15 components		Oil - 6 components	
2 air compressors	20.0	1 Reservoir	4.0 LB.
2 oil & water traps	4.2	1 Filter	6.0 LB.
2 De-hydrators	5.4	2 Pumps	27.5 LB.
1 Air storage bottle	20.5	2 Non. r. v's.	0.5 LB.
2 Pressure Reg.	3.0		
2 Non return valves	0.5		
2 Filters	0.4		
2 Thermal relief valves.	3.0		
	57.0 LB.		38.0 LB.

Piping for air system, 3/16 or 1/4 dia.
Piping for oil system, 3/8 ~~or~~ 1/2, & 1 dia.
Air wt. ≈ 6 LB
Oil wt ∝ piping + jacks.

air	OUTPUT	oil
Contin. rating	≈ 0.1 Fluid HP	Cont. rating 28 F.HP. (14 F.HP. cont./eng.)
Intermittent Rating	14 F.HP. for 5 secs	
Recharge time	12 min	
(Compressors normally aspirated)		

Weight Penalties

stroke 15.6" max ld. 800 lb.
{- hyd. jack 4,000 p.s.i., dry wt. 9 LB oil wt. 1.5 LB.
{- pneumatic jack 1,000 p.s.i., dry wt 18 lb.
(require the addition of silicone grease filled damper within piston rod.)
- lower press. cyl. requires larger brackets.
- larger dia gives greater offset loads & hence greater B/M's.

d.) Reliability:

A comparative analysis of degrees of reliability between hydraulics and pneumatics is not possible because there are so few air-equipped operational a/c in existence that a fair compilation of relative statistics cannot be made. Pneumatic equipment may appear safe & eff't on prototype a/c, but it is only when the same eq't is produced in quantity and carried by large

Points of Arguement.

numbers of a/c over a long period of and under all conditions that an overall picture of reliability can be obtained.

It must be remembered that hyds went through a long process of major successes & minor failures before achieving the universal acceptance it enjoys to-day in the a/c industry all over the world. Pneumatics have still to travel this arduous road. Research and exp't on pneumatic equipment has been going on for years, especially in U.S.A. It is, perhaps significant that in spite of the advances made - & they have been considerable - most of the American prototype a/c designed to carry pneumatic equipment have never reached the production stage. Reasons never published - certain European mfr's have persevered & achieved success.

Air leakage - cleaner, no oily droppings.
- but oily drops show where leakage occurs
- low temps leak tendency increases due to hardening of seals.

Flat system - cannot run engines 12-15 min to charge bottles - require ground charging ~~handling~~ equipment - hyd. syst. full power as soon as engines started.

e.) Maintenance:
- pneumatics require more maintenance.
- some oil & moisture traps automatically blown out.
- moisture filters & absorbents require attention & replacement to prevent reaching saturation.
- small amount of water freezing →
- no oil in system as destroys rubber seals. (natural rubber necessary to withstand lower temp's encountered in air systems).
- Hyd. - self lubricating.

f.) <u>Vulnerability & Safety</u>:-
- shrapnel effect of exploding bottles.
- res's not so.

g.) <u>Altitude</u> -
- very reduced eff. (30,000')
- tap from engine - beware of methyl contamination
- rely on storage bottles.
- so limits operation of dive brakes.

h.) <u>Control</u>:
- compressibility of air is a serious drawback when used for services requiring accurate control - air expands & ram continues to ~~cut off~~ travel to limit after press. cut off. → require follow up control.
- with pneumatically positioned controls, changes of load try to cause the services to take up a new position which causes further air consumption as the valve follow-up system corrects this tendency. (With nose wheel steering, this results in a lack of positive directional control).
- hyd. operated ram can be stopped @ any point along its travel by simply cutting off the pressure feed, accurate control is always maintained & rigidly held. The high bulk modulus, i.e., stiffness of the hydraulic fluid is the first essential of a satisfactory servo mechanism upon which the modern mil a/c is so dependent.

i.) Functions performed by hydraulic services:

Points of Argument:-

Occasional Use	two position	landing gear doors canopies	1
	multi position	flaps dive brakes nose U/C steering	2
Continuous Power.	servo controls	flying controls radar scanners turrets	3
	power	a.c. generator drives cabin blower drives	4

1) oil or air
2.) oil or air - air lacks control fineness.
3 & 4) oil only.

j.) Air Compressors:-
- @ high speed, temp of ram air increases - cooling problem.

k.) Hydraulic Pumps:-

l.) Summing Up:-

	air	oil
Power system	61	38
Jacks	63	35
piping & connectors	20	44
Valves & selectors	10	18
Fluid	6	23
Emergency eq't (stored air)	12	12
	190	170

Services use L/G. & nose U/c steering.
Flaps electrically op't'd.
Brakes not included. Hyd. act. = +14 LB.
Penalty on Pneumatic Nose U/c due to Mech. damping +4 LB.
- pneumatics the power service & jacks are heavier than corr. hyd. sest., but balance is restored by extra wt of hyd. piping & fluid.

1). What Kind of Power for Aircraft Actuators:-
by Robert C. Dreseder & Howard M Geyer.
Applied Hydraulics - February 1955.

Comparison by Wt., Size, & overall Eff'y.

a.) Power Generation:-

(i.) A-C & D-C Generators:

wt. see graph - reduction due to improvements in insulation, higher operating temps, blast cooling, & higher drive speeds. (perhaps curve should show a leveling off.).

- a-c gen lighter than d.c generator.
- overload allowance: 125% for 5 min.
- a-c gen + const. spd drive ≈ d.c. gen.
- η ≈ 73% smaller sizes
  ≈ 83% larger sizes.

(ii) Hydraulic Pumps:-

- graph for 1,500 & 3,000 p.s.i. pumps.
- wide variation in porting etc.
- HP of C.D. pump ∝ pressure.
- In const. press. syst., hyd. pump has very little over-load capacity as far as output HP is concerned.

η ≈ 75% small sizes } overall eff, volumetric
≈ 90% larger . . } + mechanical.

- Part load efficiency, like that of the electric generator, is lower than the full-load value.

iii.) Pneumatic Compressors:-

- less data available
- high compression ratio, especially @ high altitudes require use of several stages.
  ∴ not built in large sizes.
- 186.5 LB/HP — .016 HP
  to 40.1 LB/HP — .523 HP.
  lower efficiency.

$\frac{.131}{1.5 HP} = \underline{8.75\%}$

Points of Arguement.

b) ~~Power Generation~~:
(1:) ~~AC & D-C Generators~~:—

b.) Power Storage :-

- as actuators are used intermittently, & the integrated power demand of a series of actuators is so small that the power storage appears, at first glance, to be attractive.
  - Electrical energy → storage battery.
    - standardised design procedures.
  - delivery of stored energy is dependent upon the rate @ which it is to be delivered. Increase the rate, drastically reduces amount of stored energy that can be removed from battery @ one time. For short time periods, however, the battery recovers &, except for the greater I^2R losses, delivers approx the same total energy whether that energy is taken in short spurts @ high i or as a continuous drain @ low i.

FIG. 2. - Hyd & Pn. acc's show reduction in specific wt @ larger size.
- pn acc's show lower sp. wt., as can be expected, since all their volume is usable.

N.B. - the storage battery line does not cross the generator line for any period of actuator discharge. Eg for 20 sec. ld duration, battery weighs 3X as much as generator with equal capacity. For this reason, a storage battery is used to provide power only when the primary source of power is inoperative & to offer some voltage stabilization with fluctuating loads.
- Simly, hyd pump is lighter than hyd acc except for duration < 2 secs. - ∴ used for surge damping & unloading pump.
- But. less than 4 min., storage is lighter than compressors.

Hence concl's of FIG. 2

a. el. & hyd. methods use energy storage only for extremely short-duration operation & for surge protection.

b. the pneumatic method uses large storage capacity with the minimum possible size of compressor.

c. Power for actuator operation when the prime source of power is shut down should be provided by a storage battery for long-term demands (over 20 secs.) and by either a hydraulic or pneumatic accumulator for short duration demands. For repetitive short-term demands, it is desirable to use an electrically driven pump to charge an accumulator rather than use either a large accumulator or a large storage battery with a high discharge rate.

C.) Power Transmission :–

- electric actuator syst → grounded return d-c transmission & a 3-wire grounded neutral for 3-phase a-c transmission.
- conductor size is determined by current density as well as voltage drop – rigid spec's. al cable for large sizes.
- high voltage (a.c. or d.c.) is imperative in large a/c for everything but the smaller size actuators.
- st. steel tubing used for high press. hyd & pneumatic transmission.

Most of the wt. in a hyd. syst is in the transmission lines and fluid, reduce this factor and you can have the lightest system for all loads.

FIG. 3. line wt. necessary to transmit power 75'.

- el. – grded return, single power lead + 2 control leads. max voltage drop of 2^V (24^V syst.) current types AN-W-14a

including wt. of working fluid:
- hyd. – press & sump line – 90% η, @ −20°F. @ 3,000 psi.
- pneu – single trans line – op'g press 1,500 psi η ≈ 90%. Temp has negligible effect.

Points of Arguement.

d.) Power Utilisation:-

- electrical actuator:
  - motor, gear reduction, & screw are often coaxial.
  - motor case forms part of structure.
  - high eff of ball-bearing screw jack, even in reverse direction, & high eff of gear reduction assembly, motor is provided with a magnetically released brake to prevent the unit from slipping under load. motor dia/length ratio is kept low to reduce starting time & to minimize the K.E. to be absorbed in brake. (Lt.)
  - Size of ball-brg jack screw is dictated by the Brinelling cap. of nut as well as by column str of screw. (If opt'd in tension, screw can be smaller.) Small sizes (under 1,500 ft-lb.) eff is imp ∴ use ball brg screw. For any one output rating, actuator wts may vary as much as 3/1 because of variation in force-stroke combination & operating time. (short time - large motor, long time - small motor) Vary from trend.
  - overall eff, 40-70% - large
    small, values lower because of eff not important compared to wt reduction that can be realised by other means such as simplified gear boxes.
- hydraulic actuators - less spread on curve cuz not dependent upon rate. (1,500 psi.)
- pneumatic actuators are hyd actuators without provision for limiting travel rate. designed especially for ~~high~~ press tem - slightly heavier

e.) Discussion of Hydraulic, Pneumatic, and Electrical Methods:-

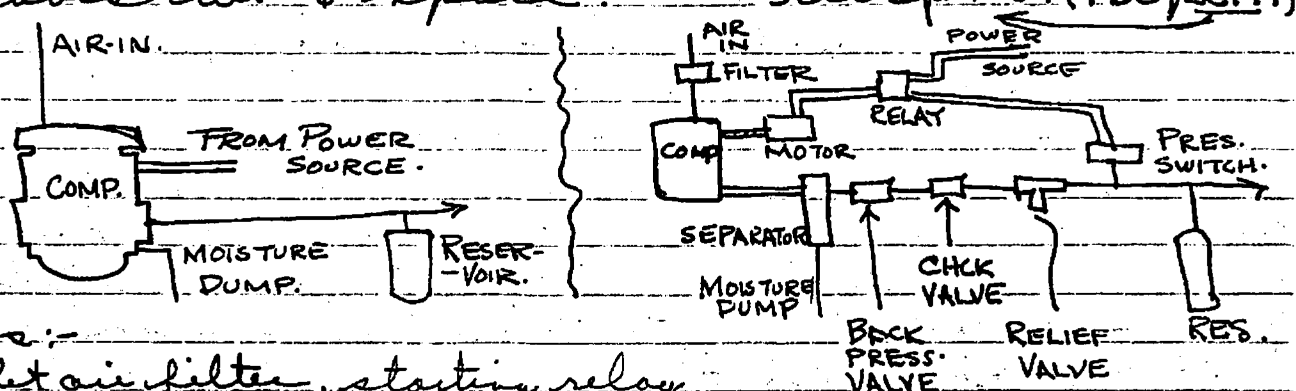
Fig. 5. el. act. eff ≈ 50%
hyd & pneu ≈ 95%.

AVIATION AGE. June 1955. p 132-139

Accessory Systems - Pneumatic

- supersonic heat, the scourge of both electrical & hydraulic systems, has so far less effect upon the operation of pneumatic systems. Not that it leaves them totally unaffected, but pneumatics can operate over a much wider temp range without cooling. When cooling is necessary, just the compressor has to be cooled, not the entire system. In fact, heating ~~th~~ of the air in the system actually imparts more energy to it.
- Kidde tests - 12 c.f.m. 5000 psi comp. }
  25 c.f.m. 3000 psi comp. }
- present op'g range -65 to 350°F - comp.
- actuators 660-900°F - hot parts of a/c

" Cornelius Packaged system "
- saves wt & space. - 3000 psi. (model 130, 2CFM)



Includes:-
- inlet air filter, starting relay, radio noise filter, moisture sep'r. with auto condensate dump & heating element, back pressure valve, check valve, relief valve, & press. switch.
- wt saving ≈ 5LB. (tubing, fittings & flare connections)
- leakage reduced.
- time saving (installation).
- DC, AC or hyd moto drives.

- teflon & metalic seals."
- thin wall st. st tubing
- present standard AN fittings do not have sufficient elastic follow-up. (i.e., loosen with vibration) → flareless tubes

Points of Arguement.

- pre-stressed tubes improves fatigue life.
- require storage bottles @ altitude.

Aviation Age - June 1955. p. 140-
Accessory Systems - Hydraulic.

- increased output & higher operating temps.
(ex. by 1960, 4 eng. bomber → 400 hp. @ 550°F.)
- MIL-O-5606 → -65 to 275°F.
new silicates → -65 to 400°F. (cannot tolerate appreciable amounts of H_2O) & precipitate harmful gelatinous materials.
  - Monsanto Chemicals OS-45 --- 500°F.
  G.E. 81406 — ———— - 700°F.
- lubricity over full temp range.
- seals - sulfur → 500°F.
  teflon → 400°F.
  >500 - synthetic & metallic
  } compatable with fluid.
- Flairless tubing - gives steel tubing & fittings a wt advantage over dural. greater reliability. (1/4 hard.)
  - titanium tubing → 700°F.
  - flex tubing - teflon-lined wire mesh hose 400°F. or swivel jts.
  - actuators → st. st parts for high temp.

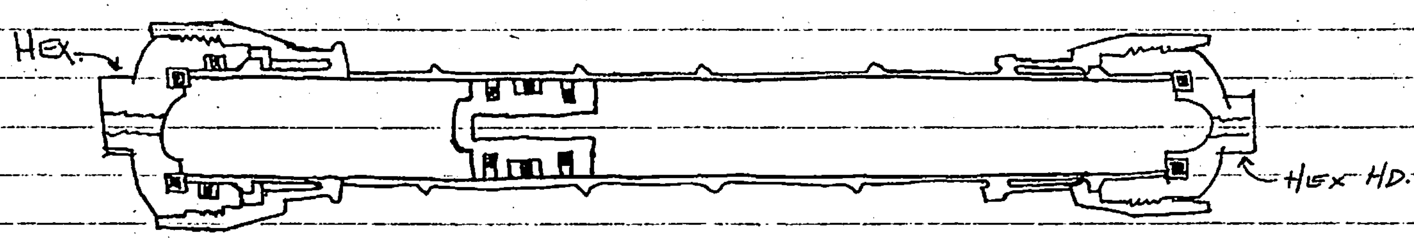
<u>trends</u>: - Dual hyd. systems are being installed on all high-performance a/c. Both operate @ all times. Each syst is emergency for other.
- bleed air turbines.

<u>Emergency Power</u>:-
- ram air turbines for supplying drive to hyd pump. lowered into slipstream when needed. (flameout)
- aux. power turbine & elect. pumps.

KEDCO Tool Div., Red Lion Cabinet Co.

<u>HYD. ACC's</u>		cap.	wt (DRY).	
	D-8401-001	25	3.3	Electrolized cyl.
	- - 02-	50	4.2	Micro-finished cyl.
	- - 03-	50	5.9	Teflon back up rings
	- - 04-	100	7.7	Double sealed (inactive)
	- - 05-	200	11.0	3000 P.S.I.
	- - 06-	200	16.1	MIN. DES. PRESS. 12,000 PSI
	- - 07-	400	22.5	

HYD.
ACC.



Pts of Arguement.
Pneumatic Actuating Systems in the U.S. Air Force. -
- Robert R Bayuk.
S.A.E. Reprint (April 20-24, 1953).

- Each airplane must be carefully evaluated as to its configuration, mission, and actuating services, in order to arrive at the optimum system.
- pneu. syst. utilizes a compressible fluid.
hyd. trans. power or incompressible "
hence can readily store large amounts of energy.
- thus low-powered compressor, running continuously, can store energy for later intermittent use @ unlimited HP. rates while hyd. pump must be sized for largest HP requirement of the system.
1.) air is universally available - no supply problem.
2.) no fire hazard -
3.) Operation independent of temp - viscosity of air is practically independent of temperature.
4.) Small transmitting lines, no return lines (1/4" tubing)
5.) Cleanliness - no messy leaks.
6.) Small HP req'd for prime mover - as power is stored, no power drain @ take-off.
7.) Lightest system yet devised for intermittently actuated devices.
- control surfaces in high performance a/c require continuous power of high magnitude & cannot be economically serviced by a storage type pneumatic system.
- B-26 test results:
1) 11% wt reduction (could be 30%).
2) system was reliable.
3) pilots like the operation.
4) mechanics enjoy the cleanliness
5.) maintenance is simple
6.) wt saving is achieved.
7.) leakage is a problem - especially @ low temp.
- freezing of valves never occurred.

B-46 - ~~Eb~~ Eglin Field Climatic Hangar:
- problems uncovered:
  - freezing of some components & air leakage @ fittings.
  - optical-flat shear type of valve is least susceptible to freezing.
  - freezing can be eliminated by reducing the vapour pressure of the water in the air to a point which will prevent the formation of ice.
    - compression will automatically remove 99.5% of the water @ 3000 psi - in accordance with the laws of partial pressure → dessicant (silica gel) removes the rest. (4 oz. of silica gel is ample)
    - leakage - secure @ tight fitting @ low temp.

(XB48?), F-84 Convair T-29E (340), 2 eng a/c.
- a.) main landing gear.
- b.) nose landing gear.
- c.) brakes, main & emergency.
- d.) nose wheel steering
- e.) main & emergency flaps.
- f.) windshield wipers
- h.) cargo door.
  - part of air stored in landing gear struts → reduce no. bottles.
  - 3000 psi. by two 200v a.c. 400 cycle motor given comps.
  - air taken from pressurized cabin. (uniform delivery @ all altitudes.) (jet → tap comp. as inlet source so that adequate comp. capacity is obtained even @ extreme altitudes).
  - comps feed in ll'l. into the system.
  - failure of one comp. will not hinder the oper'n of the other, due to the installation of shuttle valves in lines.
  - air routed to moisture separators, 1/comp.
  - separators impart a centrifugal motion to the incoming air & assists in trapping 99.5% of entrained moisture. Automatically eject accumulated moisture @ each shutdown of comp's.

Pt. of Arg.

- chem. dryer removes remainder of moisture.
- 1 lb. dryer → several hrs of comp. op'n under sat'd H_2O cond's.
press. actuated electric switch allows comps to maintain 2800-3000 p.s.i. syst. press.
- check valve placed downstream of the driers, & serves to isolate main syst from compressor syst.
- 1/4" tubing, outdoor panel, + pressure transmitter for cockpit indicator. All eq't small (except comps) 10.90 lb.

MAIN L/G.) → main press → 2 legs → isolated by check valves. sufficient air is stored in struts to enable 3 l/g cycles. air → reducer → selector valve (in nacelle) - 2300 p.s.i. in act. cyl for retraction, 50 psi for extension.

NOSE L/G.) → isolated by check valve & similarly arranged. Air stored in 1 leg only. Air in other used for nose wheel steering & emergency air brakes & flaps. all l/g can be retracted & extended several times without further air supply from main system.

BRAKES → on main L.G. wheels, supplied by separate bottles from main line & each isolated by check valves. Main power brake valves are supplied by a bottle which is charged from main line & isolated from it by a check valve. Upon actuating the brakes, press. from the brake valves actuates relay valves which allow pressures from the main brake bottles to actuate the brakes.

W.S. wiper - windshield wiper receives air from the main line thru @ reducer which drops press. to 100 p.s.i. Speed controlled by a regulating valve located in the cockpit.

FLAPS:- op't'd by air motors which receive air from an isolated storage bottle, thru a reducer. Flap motors are synchronised thru connecting shaft. Provision is also made for emergency op'n of flaps thru a shuttle valve which allows air from the emergency storage bottle to operate the flaps motors.

CARGO DOOR:- ind. storage bottle, isolated by check valve. Manually operated selector valve.

ENT. DOOR & STRS. - storage bottle, isolated, manually opt'd selector valve.

EMERGENCY OP'N: - air stored in 1 leg of nose gear strut. air is provided for emergency oper'n of brakes & flaps. Controls for emergency op'n are mtd on pilot's console. Entire pneumatic syst. is properly instrumented with gauges located in cockpit.

Examination of a/c pneumatic picture we see
1st: pneumatics has certain advantages
2nd: components, valves, & compressors are available
3rd: no. of syst's developed & tested.
- if a combination of hydraulics & pneumatics proves optimum, we should utilize both.
- wt. of experience from hydraulics.

Supersonic: air @ high spds, upon striking the surfaces of the a/c, undergoes a deceleration with a conversion of vel. head to press. hd. In effect, air experiences isentropic comp'n, with subsequent htg.

$M=1$, $\Delta t = 80°F$ } Comp'ts must operate @ these
$M=2$, $\Delta t = 320°F$ } surrounding temps.

hyd. fluid (present) < 250°F.
air comp'r at temps below this
high temp will not adversely affect air itself, & in fact could impart @ small amount of energy to it. Cool compressor only. Jacket unit & use fuel as a liquid cooling medium. Comp → 150 BTU's/minute @ full load. 5 gallons/min of fuel (reasonable flow rate) will rise 10°F in absorbing this heat. effect slight.
hyd. - cool all fluid. Use fuel - large Ht exchanger & plumbing → large wt + excessive ht ld on fuel.
faster speeds → need to cool fuel (∴ interim measure only).

Power requirement for operating the control services
High continuous HP req'd for continual movement of these surfaces. Safety measures dictate that these surfaces be actuated by an independent system & such power may likely be furnished by a separate hyd. syst. or by a low press. pneumatic system. (from eng. compressor) l/p. to low in press. to actuate cyl., ∴ energy extracted by ordinary air turbine. air turbs can thus be utilized to operate the control surfaces. Means of furnishing shaft power

Pts of Arg.

is finding great popularity in new a/c.

Ref. to wt analysis.

B.C.A.R.

SUB-SECTION D-6 – EQUIPMENT INSTALLATIONS:

CH. D6-2 HYDRAULIC SYSTEMS:

1. APPLICABILITY:

2. GENERAL:

3. PRESSURE:

MAX. transient press. (surge) ≯ 1.33 P_W.

4. STRENGTH:

4.1 P_W = The max. steady press. permitted by the press-limiting means within its design tolerances, or any higher press. that the designer may declare.

P_R = The max. steady press. permitted by any press. relief means.

4.2 proof & ultimate factors of not less than 1.0 and 1.5 under appropriate loads:

4.2.1 – Components – lds due to pressures of 1.33 P_W or 1.0 P_R whichever is greater.

4.2.2 – Pipes & Pipe Couplings – proof factor on loads due to press. of 1.33 P_W or 1.0 P_R whichever is greater. The ult factor on lds due to assumed press. of 2.0 P_W or 1.5 P_R whichever is greater.

4.2.3 – Parts Bearing additional Loads: – due to use or attachment.

5. TESTS:

SUB-SECTION D.6 - EQUIPMENT INSTALLATIONS:

CH. D6-3 PNEUMATIC SYSTEMS:

1. APPLICABILITY:

2. GENERAL:

3. PRESSURE:

4. STRENGTH:

4.1 P_W = Max. press. permitted by the press. regulating means within design tolerances.

P_R = Max press. permitted by any press. relief means (provided in compliance) within design tolerances.

4.2 Proof & ult factors of not less than 1.0 & 1.5 under the lds appropriate 4.2.1 & 4.2.2 in conj. with most adverse of lds. 4.2.3.

4.2.1. Components: loads due to pressures of 1.33 P_W or 1.0 P_R whichever is greater.

4.2.2. Pipes & pipe couplings: proof factor on lds due to press. of 1.33 P_W or 1.0 P_R whichever is greater. The Ult. factor on loads due to assumed press. of 2.0 P_W or 1.5 P_R whichever is greater.

4.2.3. Parts Bearing Additional Loads: lds applied to a part due to its use in the aeroplane structure or attachment to the A/C.

5. TESTS:

C.D. only. 2.4 Landing Gear:-

a.) extension in not more than 5 secs.

b.) retraction in " " " 7 secs.

@ all speeds between 1.2 V_{S0} & speeds selected for establishing the take-off Net Flight Paths.

A Beginner's Course in Basic Pneumatics.

I Air Properties & Characteristics:

I. Introduction:
- air motor – rotary.
  cylinder – linear actuator
  air chuck – adaptation of air motor for opening & closing jaws.
  air-hydraulic units –
  boosters: inlet air – outlet out 
  pneumatic controllers.

II. not particularly a/c pneumatics – too specialised.
  a/c comp's – 1500 – 3000 p.s.i.
  industrial – 80–125 (working press – ~~too~~ 60–100 p.s.i.)

III. Atmosphere & how we use it:–
  – @ S.L., p = 14.7 p.s.i. (.696) 29.92 in of Hg.
  – wt @ 1 atmosphere, 32°F = .08071 LB/CU.FT.
    (Smithsonian Physical Tables, 8th ed., p. 176.)
- Barometer:
  – absolute press. – measured above vacuum (at. p + gauge p.)
  – ~~atmospheric~~ gauge press. – measured above 17.7.
    ∴ abs. p = 17.7 + gauge p.
    psi = (.491)(in. Hg.).
- Free Air & Normal Air:–
  – Free air is defined as air @ normal atmospheric cond's.
- Normal Air is @ sea level (14.7 p.s.i.), 68°F & rel. humidity 36%.
  density = .075 LB/CU.FT., $\gamma = \frac{C_P}{C_V} = 1.3947$.
- Free Air is air @ normal at. cond's, i.e. standard variations due to bar. press., alt. & temps are assumed. Practically, free air is considered as the normal air on the intake side of a compressor.
- Normal Air is air @ assumed average cond's of atmosphere in a temperate climate. The cond's assumed are that the (above). Normal air cond's are used to arrive at an average figure from which capacities, operating characteristics, & eff's of compressors may be computed.

IV. Gas Laws:-

a.) BOYLE'S LAW:-

① const. temp., i) vol. of gas varies inversely as the absolute press. ii) conversely, absol. press is inversely ∝ to volume.

$$\frac{P_1}{P_2} = \frac{V_2}{V_1}, \text{ or } P_1V_1 = P_2V_2 \therefore V_2 = \frac{P_1V_1}{P_2}$$

$$P_2 = \frac{P_1V_1}{V_2} \quad \text{— (1)}$$

b.) CHARLE'S LAW:-

i) @ const. p., vol. of gas is directly prop'l to abs. temp.

+ ii) @ " vol, press. is dir. ∝ to absol. temp.

i.e. i.) $\frac{V_1}{V_2} = \frac{T_1}{T_2}$ or $\frac{T_1}{V_1} = \frac{T_2}{V_2}$

$$V_2 = \frac{T_2V_1}{T_1}.$$

abs. temp ≑ 460°F = 0°F.

ii) $\frac{P_1}{P_2} = \frac{T_1}{T_2}$ or $\frac{T_1}{P_1} = \frac{T_2}{P_2}$.

$$\therefore P_2 = \frac{P_1T_2}{T_1}$$

V. Combination of Boyle's and Charle's Laws:

(General Gas Law:)

a.) $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$, $P_2 = P_1 \frac{V_1}{V_2}\frac{T_2}{T_1}$.

$$V_2 = \frac{P_1V_1T_2}{P_2T_1}$$

$$T_2 = T_1\frac{P_2V_2}{P_1V_1}$$

b.) The Perfect Gas:-

General gas Law:-

$$pV = MRT$$

where: p = abs. press. (LB/SQ.FT.), p = 144P.

P = abs. press (p.s.i)

V = vol, FT^3

M = wt of air in LB (1 for formula.)

T = absol. temp, °F.

R = exp'ly determined const, representing mechanical work done by the expansion of a unit wt.

Basic Pneumatics:

of a perfect gas @ const. press while heat is added to increase its temp 1°F.

Absolute temp: −460°F & −273°C.

Assumption: air @ 32°F expands $\frac{1}{492}$ of its vol. for 1°F from 32°F.

1 LB of air @ 32°F & 14.7 psi → $\left(\frac{1}{.08071}\right)$ − 12.39 cu. ft.

Determining R:− for a perfect gas,

R = 53.3.

∴ PV = 53.3 MT. table for air.

R ≡ specific heat @ const. press.

as 1 FT.LB = 778.2 B.T.U.,

$\frac{53.3}{778.2}$ = .0686 B.T.U./LB.

c.) Specific Heat:−

≡ no. of BTU needed to raise the temp. of 1 LB of the substance 1°F.

i.) Specific heat at constant pressure (C_p) is the heat expended in doing the "external" work, i.e., the energy used in changing the density of the air.

ii) Specific heat @ const vol. (C_v) is the heat expended in doing the "internal" work, i.e., the heat req'd to raise the temp. of the air only.

Regnault → total sp. ht of air = .2375 B.T.U/LB.

$C_p = R$ = .0686 B.T.U./LB.

then C_v = .1689 B.T.U./LB.

Ratio of specific heat, $n = \gamma = \frac{C_p}{C_v}$ (compression)

i.e., $\gamma = 1$ for isothermal compression

(temp. kept const. with ht of comp. removed.)

$\gamma = \frac{.2375}{.1689}$ = 1.41 for adiabatic compression

(ht of compression retained.)

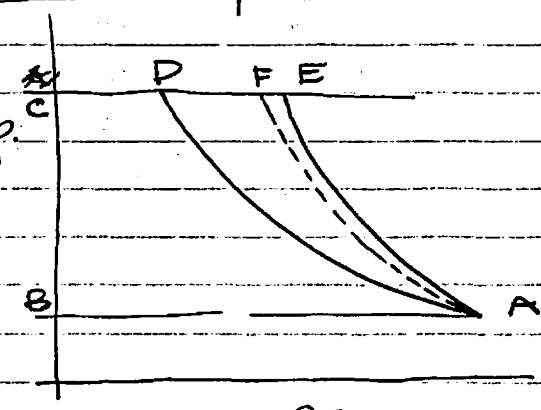
VI. Adiabatic and Isothermal Compression:−

a.) Compression always occurs within range $n = \gamma = 1$ to 1.41.

Power between these 2 & depends on compressor design, operating cond's & efficiency of cooling means.

Isothermal → ideal condition.

b.) Indicator Diagram:



(Boyle's Law).
A-D- isothermal compression - hyperbolic curve.
A-E- adiabatic
Area ADE = power required for ad. comp above isoth.
(loss due to the ht of compression.)
(36% more power to comp air to 100 psig.)
∴ Require effective cooling to bring curve to AF.

* Practically, we can disregard the method of compression since aftercoolers, receivers & the normal transfer of heat by convection & radiation, lowers the temp of the air before it is used.

- Latent heat - heat in the moisture in air or a gas. With sensible heat it makes up the total heat.
- Ratio of compression - relation between final & initial pressures during compression, expressed in abs. units.
- Sensible heat - ht of the air itself. With latent heat it makes up total heat which must be considered in providing cooling means.

VII. Efficiencies:
energy expended / work performed.
compression,
compressor,
mechanical,
slippage,
overall,
& volumetric

Basic Pneumatics:

a.) Theoretical HP.
HP req'd to adiabatically compress air (or gas) delivered by the compressor thru a specific range of pressures.

b) Compressor brake HP:-
- energy supplied by the prime mover to run a compressor. (total power)

c.) Air Indicated HP or ind. HP:-
- delivered HP as calculated (comp. ind. cards.)

d.) Mean Effective Pressure: (m.e.p.)
- comp. ind card = press x piston displacement → work inside cyl.

$$\frac{m.e.p(A)(L)N.}{33,000} = HP.$$

i.e., $i.h.p. = \frac{m.e.p LAN}{33,000}$

L = length of stroke (ft.)
A = piston area (in²)
N = R.P.M (strokes / min)
mep = p.s.i.

$\therefore \frac{LAN}{144}$ = piston displ. (PD), c.f.m.,

then $i.h.p. = \frac{(m.e.p.)\ PD.\ (144)}{33,000}$.

e.) Compression efficiency:
ratio of $\frac{\text{theoretical HP}}{\text{indicated HP.}}$
i.) Isothermal compression efficiency
ii.) adiabatic compression eff'y.

f.) Mechanical Efficiency:
ratio of $\frac{\text{indicated HP.}}{\text{brake HP.}}$

VIII. Volumetric Efficiency:-
Vol. eff. = $\frac{\text{actual air delivered}}{\text{piston displacement}}$
- cylinder vol:- vol. of comp. cyl., = pist. displ. + clearance vol.
- False or boosted pressure - the press. effect on charge of entering air due to ht & inertia or friction that tends to raise the press. above the atmospheric press.

- clearance - vol. of air remaining in the cyl. @ mid-stroke that is not expelled @ discharge.
- overall efficiency - combined eff'y of an air syst'm found by mult'g the several individual eff's. Often it is defined as the prdct of comp'n eff'y & mech. eff'y. (comp. eff.)
- piston displacement - vol displaced by full stroke of the piston in one cycle.
- vol. eff'y: ratio of the actual air delivered to the piston disp't.
- slip efficiency: ratio of air actually measured to the apparent vol as shown by ind. dia. It covers the quantity of air not otherwise accounted for.

Basic Pneumatics:

II. The Distribution System:-

I. Introduction:

i.) friction
ii.) leaks.

a). Effects of friction.
"Compressed air Handbook".
- Δp should not exceed 10%
- use loop system wherever possible to provide 2-way dist'n to the point of greatest air demand; long dist'n lines should have adequate receivers near far ends or @ pts of heavy use; provide frequent outlets on each header or main branch lines or hose connections; & arrange slope of all piping toward one or more moisture traps.

b.) Leaks.
- may be undetected.

II: Calculation of Friction Losses:-

Most common is the Harris formula:

$$f = \frac{cL}{r} \times \frac{Q^2}{d^5}$$

where
f = pressure drop in p.s.i.
L = length of pipe in feet.
Q = cu. ft. of air/sec (free air)
r = ratio of compression (from free air @ entrance of pipe)
d = actual internal dia of pipe in inches.
c = experimental coefficient
$= \frac{.1025}{d^{.31}}$ for ordinary pipe,

$$\therefore f = \frac{.1025L}{r} \times \frac{Q^2}{d^{5.31}}$$

Ex. $L = 300'$, $d = 2''$, $Q = 500$ c.f.m. of free air.
Initial p is at., $p_g = 100$ p.s.i.g.

a) $r = \frac{114.7}{14.7} = 7.8$ ratio of Compression.

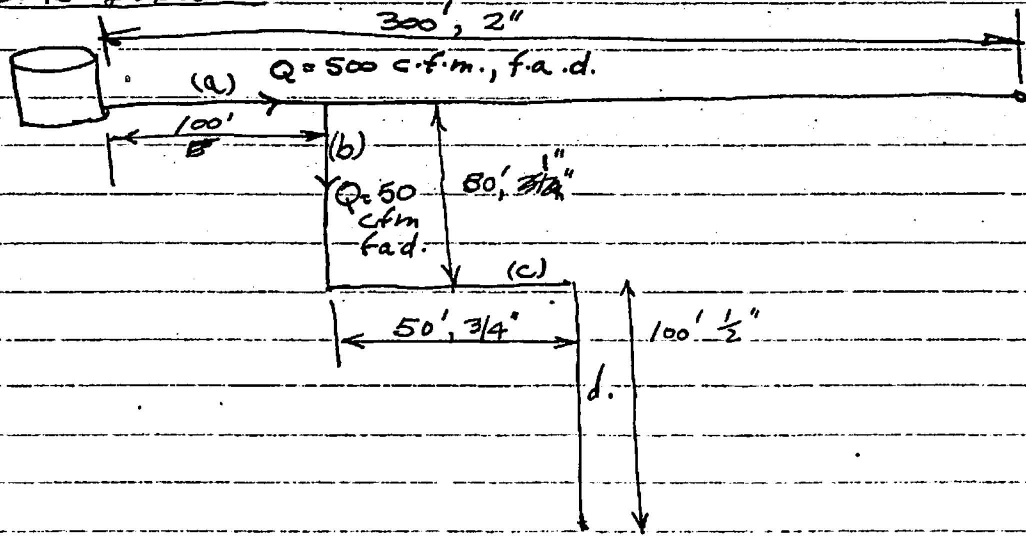
$d^{5.31} = 48.06$

$$\therefore f = \frac{(.1025)(300)}{7.8} \times \frac{(8.3)^2}{48.06} = 5.6 \text{ p.s.i.}, \Delta p.$$

Tables 2 & 3 p. 96 / Nov. '52.

$f = \frac{N}{r} / 1000 \text{ ft.}$

Branch Lines :-



using tables :-

(a) $\frac{100}{1000}(19.2) = 2$ p.s.i

(b). $N = 54.4$ (50 cfm, 1"), $r = \frac{108}{14.7} = 7.34$, $\Delta p = \frac{54.4}{7.34} = 7.4$ p.s.i /100 (110 − 2; $\frac{N}{r}$)

~~(c) p = 108~~ $\frac{80}{1000}(7.4) = .6$ p.s.i for 80'.

(c) $p = 108 - .6 = 107.4$ p.s.i., $N = 199$, $r = \frac{107.4}{14.7} = 7.3$, $\Delta p = \frac{N}{r} = \frac{199}{7.3} = 27.3/1000'$

$\therefore \Delta p = \frac{50}{1000}(27.3) = 1.4$ p.s.i / 50'.

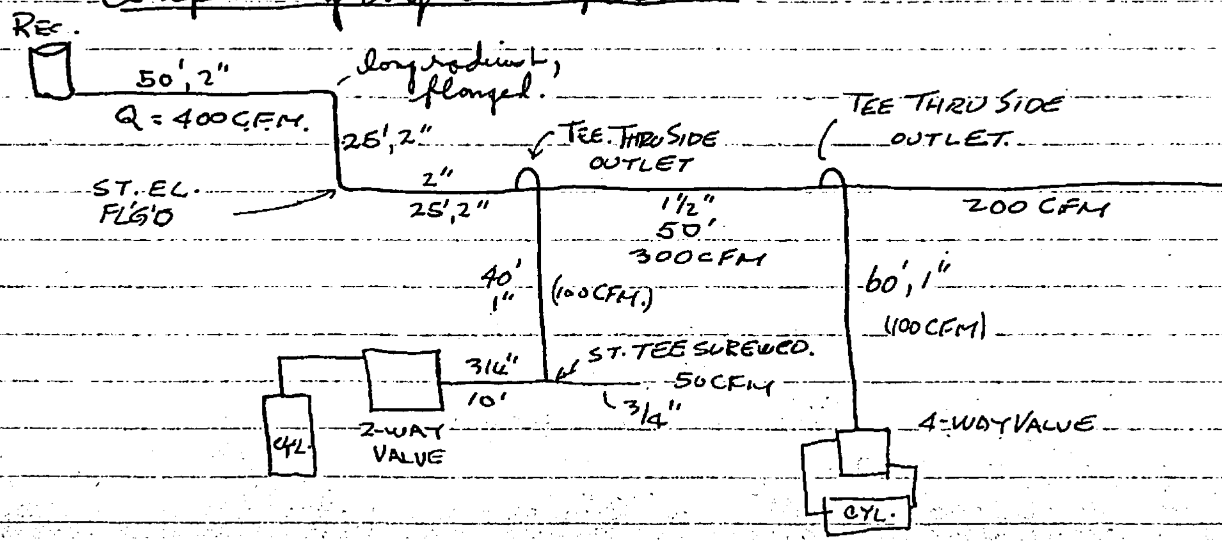
d.) $p = 107.4 - 1.4 = 106$, $N = 885$, $r = \frac{106}{14.7} = 7.2$ $\Delta p = \frac{N}{r} = \frac{885}{7.2} = 122.9/1000$

$\therefore \Delta p = \frac{100}{1000}(122.9) = 12.3$ psi / 100'.

e.) Total $\Delta p = 106 - 12.3 = 93.7 \approx$ 94 psi @ outlet.

III. System Losses – Due to Components :-

Computing System Losses :-



Basic Pneumatics

a) As before, 100' of 2" line,

$$r = \frac{124.7}{14.7} = 8.48 \simeq 8.5$$

$$f = \frac{.1025(100)}{8.5}\left(\frac{6.7^2}{48.06}\right) = 1.2(.934) = 1.12 \simeq 1 \text{ p.s.i.}$$

b) 50 ft of 1 1/2 in line :-

The ratio of compression; $r = \frac{123.7}{14.7} = 8.4$

$$f = \frac{.1025(50)}{8.4}\frac{(5^2)}{12.68} = 1.187 \simeq 1.2 \text{ p.s.i.}$$

c) Losses for turns :-

i) long radius ell, flanged : Table 1 → L' = 2.07, flanged fitting 3/4 screwed fitting,

$$3/4(2.07) \doteq 1.6'$$

$$\therefore f = \frac{.1025(1.6)}{8.5}\left(\frac{6.7}{48.06}\right)^2 \simeq .02 \text{ p.s.i.}$$

Similarly for valves & cyls., (FIG. 2.). p. 54, DEC. /52.

IV. Moisture in Air Lines:

V: Typical Aftercoolers for Compressed Air Systems:

a) Moisture, when condensed, → cause corrosion & scale, thus damaging valves, cyls, etc.

b) " , " " , → collect in low spots & freeze causing blockages & ruptures.

c) wash lubrication of units, thus causing wear

d) excessive water compressed in lines can cause damaging water hammer.

e) condensed H_2O, or oil, may cause erratic component operation (valves, cyls, etc.)

f) oil may shorten lifes of seals & hose.

g) Heat - above desirable & optimum temp. may cause expansion in pipe lines → costly leaks. also cause erratic op'n.

VI. Separators & Traps:-

- immediately after aftercoolers.
- traps @ low pts.

VII. ? May 53 (Missing.)

VIII. Selection, Storage & Care of Air Hose:

a.) - oil resistant.

- strength, to withstand pressures & shock loads
- hard cover - withstand abrasive wear.
- flexible & easy to handle.

b.) Storage.

c.) Care:

- regular inspection.
- no sharp bends.

Basic Pneumatics

III. Power and working Elements :-

I. Air Cylinders :

a.) Force Developed by Cylinders :

$$F = PA - S - f$$

where: F = force in pounds
P = press. in p.s.i.
A = area of piston (in^2).
S = spring force on rod.
f = frictional forces. (negligible)

b.) Air Requirements of a Cylinder :-
capacity :— (air used.)

$$V = L\left(\frac{\pi D^2}{4}\right)$$

$$C = \frac{f(V)}{1728}$$, C = c.f.m, f = no of strokes/min.

This is the requirement @ the operating press. of cyl.

* general practice to select cyl. of $1\frac{1}{2}$ cap.

c.) Conversion to Free Air :-

II. air cylinders (cont'd.).

a.) Mountings :

i.) Foot (||'l base)
ii.) Rabbet
iii.) Centre-line
iv.) Flange, rod or front end
v.) " , blind, rear or cap end.
vi.) Clevis, pivot of pendulum &
vii) Trunnion.

III. Air Valves :-

Low pressure.

2, 3, & 4 way selector valves.

IV. Air Valves:

a.) Flow control valves:—

control spd of (flow &) of piston stroke:

- with free flow in one direction.
- mtd near exhaust port.

b.) Pressure Control Valves: (regulators).

V. & Intr. cont'd.

VI. Poppet air Valves.

VII. Sliding plunger air valves:

VIII. Diaphragm Valves.

How to Determine Tubing Wall Thickness

(Applied Hydraulics, Sept. '52, pp. 76, 77, 78)

	SIZE	SEAMLESS STEEL	WELDED STEEL	STAINLESS STEEL	ALUM.	COPPER ANNEALED	BUNDY STEEL	ER + ERMETO RING I.D. MIN.
	2	+.004 -.000	+.003 -.003	+.005 -.003	+.003 -.003	+.002 -.002	+.001 -.001	.129
	3							.190
1/4	4							.255
	5							.318
	6					+.0025 -.0025		.380
1/2	8	+.005 -.000	+.004 -.004		+.004 -.004		+.000 -.005	.506
	10		+.005 -.005				+.000 -.005	.633
	12					+.003 -.003		.758
	14							.883
1	16				+.005 -.005	+.0035 -.0035		1.008
	18							1.133
	20					+.004 -.004		1.260
1 1/2	24	+.010 -.000		+.010 -.010		+.0045 -.0045		1.510
	28							1.762
	32				+.006 -.006	+.005 -.005		2.014

Table 1 - Recognized tolerances for standard tubing diameters in thousandths of an inch. Numbered sizes indicate tube diameters in sixteenths.

Table 2 – Burst pressure of tubing can be easily computed from the formula, $P_b = S \times \text{Constant}$, where S is the material's tensile strength and the constant for a given size is read from this table.

WALL THICKNESS STUBS GAUGE	INCHES	ROUND TUBING – $\frac{D^2-d^2}{D^2+d^2}$ (IN THOUSANDTHS) 1/4	5/16	3/8	7/16	1/2	5/8	3/4	7/8	1	1 1/8	1 1/4	1 3/8	1 1/2	1 5/8	1 3/4	1 7/8	2
	.500																	
	.480																	
	.450													724	668	618	574	536
	.400													642	590	545	505	471
	.375												658	600	550	508	471	438
	.350												612	557	511	471	436	406
	.320									771	687	615	556	505	463	426	395	368
1	.300								820	725	652	574	518	471	431	397	368	342
2	.284								787	685	606	541	488	443	405	374	346	322
3	.259							925	715	623	549	489	440	400	366	337	313	291
4	.238						924	764	656	569	501	446	401	364	333	307	285	265
5	.220						839	708	604	523	459	409	368	334	306	282	261	243
6	.203						781	652	554	478	420	374	336	306	280	258	239	223
7	.180					855	695	574	485	419	368	327	295	268	245	226	210	196
8	.165				886	793	636	523	441	380	334	297	268	243	223	206	191	178
9	.148			915	811	715	566	464	391	337	296	264	238	216	198	183	170	159
10	.134	[illegible]	960	849	739	646	508	415	358	302	266	237	213	194	178	165	153	143
11	.120	997	898	771	661	574	450	368	310	268	235	210	190	172	158	146	136	127
12	.109	968	832	702	598	517	404	331	279	241	212	189	171	156	143	132	123	115
13	.095	891	734	608	515	445	347	284	240	208	183	163	148	135	124	114	106	99
14	.083	797	640	526	444	383	299	245	207	180	158	142	128	117	107	99	92	86
15	.072	695	550	450	379	327	256	210	178	154	136	122	110	101	93	86	80	75
16	.065	625	491	402	339	292	229	188	159	138	122	109	99	90	83	77	72	67
17	.058	554	433	354	299	258	202	166	141	123	108	97	88	80	74	68	64	60
18	.049	460	359	294	248	215	169	139	118	103	91	81	74	67	62	58	54	50
19	.042	388	303	248	210	182	143	118	101	88	77	69	63	58	53	49	46	43
20	.035	317	248	204	173	150	118	98	83	72	64	58	52	48	44	41	38	36
21	.032	287	225	185	157	136	107	89	76	66	59	53	48	44	40	37	35	33
22	.028	248	195	160	136	118	94	77	66	58	51	46	41	38	35	33	30	28
23	.025	219	173	152	121	105	83	69	58	51	45	41	37	34	31	29	27	25
24	.022	191	151	124	106	92	73	60	52	45	40	36	33	30	27	26	24	22

	SIZE	250	500	750	1000	1250	1500	1750	2000	2500	3000
1/4	4						.020	.020	.022	.028	.035
	5					.020	.022	.025	.028	.035	.042
	6				.020	.022	.025	.032	.035	.042	.049
1/2	8				.025	.032	.035	.042	.049	.058	.065
	10			.022	.032	.035	.042	.049	.058	.072	.083
	12			.028	.035	.042	.058	.065	.072	.083	.109
1	16		.025	.035	.049	.058	.072	.083	.095	.109	.134
	20		.032	.049	.058	.072	.095	.109	.120	.148	.165
	24	.022	.035	.058	.072	.095	.109	.120	.134	.165	.203
2	32	.025	.049	.072	.095	.109	.148	.165	.180	.238	.259

Table 3 — Annealed 1010 Steel Tubing (55,000 psi, tensile) Wall thickness of various OD tubing through a pressure range of 250 to 3000 psi is tabulated allowing a factor of safety of 5.

	SIZE	500	750	1000	1250	1500	2000	2500	3000	4000
1/4	4								.022	.028
	5							.022	.025	.035
	6						.022	.025	.032	.042
1/2	8					.022	.025	.035	.042	.058
	10			.022	.025	.028	.032 ~~.028~~	.049	.058	.072
	12			.025	.028	.035	.042	.058	.065	.083
1	16		.022	.032	.042	.049	.058	.072	.083	.120
	20		.032	.042	.049	.058	.072	.095	.109	.148
	24	.022	.035	.049	.058	.065	.095	.109	.134	.165
2	32	.032	.049	.058	.083	.095	.120	.148	.180	.220

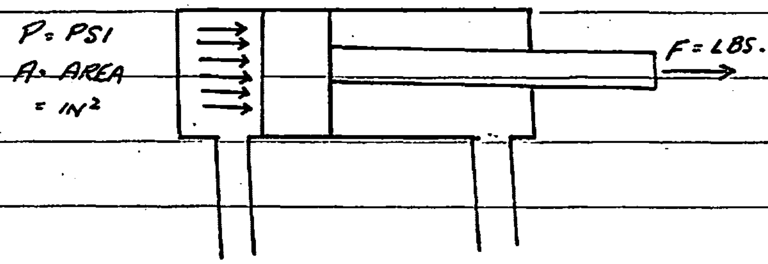
Table 4 — Annealed Stainless Steel tubing (80,000 psi tensile). Wall thickness of various OD tubing through a pressure range of 500 to 4000 psi is tabulated allowing a factor of safety of 5.

	SIZE	500	750	1000	1250	1500	2000	2500	3000
1/4	4					.022	.028	.032	.042
	5				.022	.025	.035	.042	.049
	6			.022	.025	.032	.042	.049	.058
1/2	8		.022	.028	.035	.042	.058	.065	.083
	10	.022	.028	.032	.042	.049	.065	.083	.095
	12	.022	.032	.042	.049	.065	.083	.095	.120
1	16	.028	.042	.058	.072	.083	.109	.134	.165
	20	.035	.058	.065	.083	.109	.134	.165	.203
	24	.042	.065	.083	.109	.120	.165	.203	.238
2	32	.058	.083	.109	.134	.148	.203	.259	.300

Table 5 – Aluminum tubing 61 ST (42,000 psi tensile) wall thickness of various OD tubing through a pressure range of 500 to 3000 psi is tabulated allowing a factor of safety of 5.

Basic Formulas – Applied Hydraulics – July '52 pp 100-1c

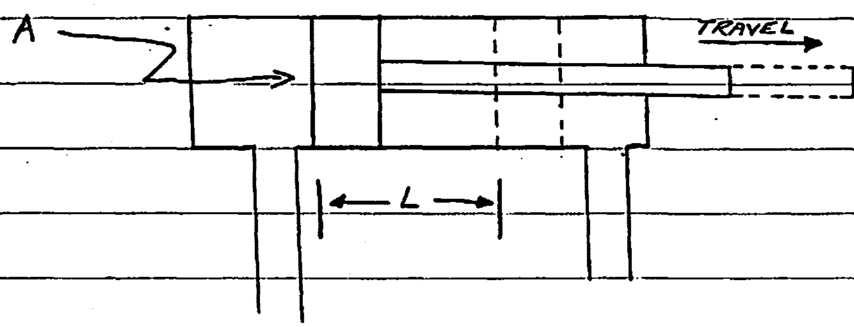
Pressure + Force



$$\text{Force} = \text{Pressure} \times \text{Area}$$

$$= \frac{\text{lbs}}{\text{in}^2} \times \text{in}^2 = \text{lbs.}$$

Rate of Cylinder Travel



A = head end area = in^2

L = cylinder stroke = in

V = volume traversed = LA

Q = pump capacity = $\frac{\text{cu in}}{\text{sec}}$

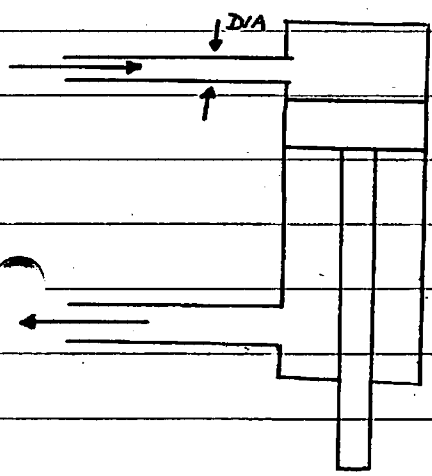
$$T = \text{Time} = \frac{\text{volume traversed}}{\text{pump capacity}} = \frac{V}{Q} = \frac{\text{in}^3}{\text{in}^3/\text{sec}}$$

$$= \text{sec}$$

$R =$ rate of piston travel $= \frac{in}{sec} = \frac{L}{T}$

$$R = \frac{L}{T} = \frac{L}{V/Q} = \frac{QL}{V} = \frac{QL}{LA} = \frac{Q}{A}$$

Quantity of Flow



V = fluid velocity = ft/sec

D = pipe diameter = inches

Q = quantity of flow = gpm

$$\frac{ft}{sec} \times 12 = \frac{inches}{sec}$$

$$gpm \times \frac{231}{60} = \frac{cu\ in}{sec}$$

$$\frac{\pi D^2}{4} = \text{pipe area} = in^2 = A$$

$$Q = AV = in^2 \times \frac{in}{sec} = \frac{cu\ in}{sec}$$

Hydraulic Work

Work = force × distance

= pressure × area × stroke

= pressure × volume

$= \frac{lb}{in^2} \times in^3 = in\text{-}lb$

Basic Formulas

Hydraulic Power

$$\text{Power} = \frac{\text{work}}{\text{time}}$$

$$= \text{pressure} \times \frac{\text{volume}}{\text{time}}$$

$$= \text{pressure} \times \text{capacity}$$

Horsepower Input to Pump

$$P = \text{pressure} = \frac{lb}{in^2}$$

Q = pump capacity = gpm

33,000 ft-lbs. of work per min = 1 hp

E = pump efficiency

$$HP = K \times P \times Q = \frac{lb/in^2 \times gpm \times 231}{12 \times 33000 \times E}$$

$$= \frac{.000583 \times P \times Q}{E}$$

Hydraulic Motor Torque

Torque = turning effort = force × radius

Work = force × distance

$$= \frac{T}{r} \times 2\pi r = 2\pi T$$

d = motor displacement = in^3

p = pressure = $\frac{lb}{in^2}$

Work = $pd = 2\pi T$

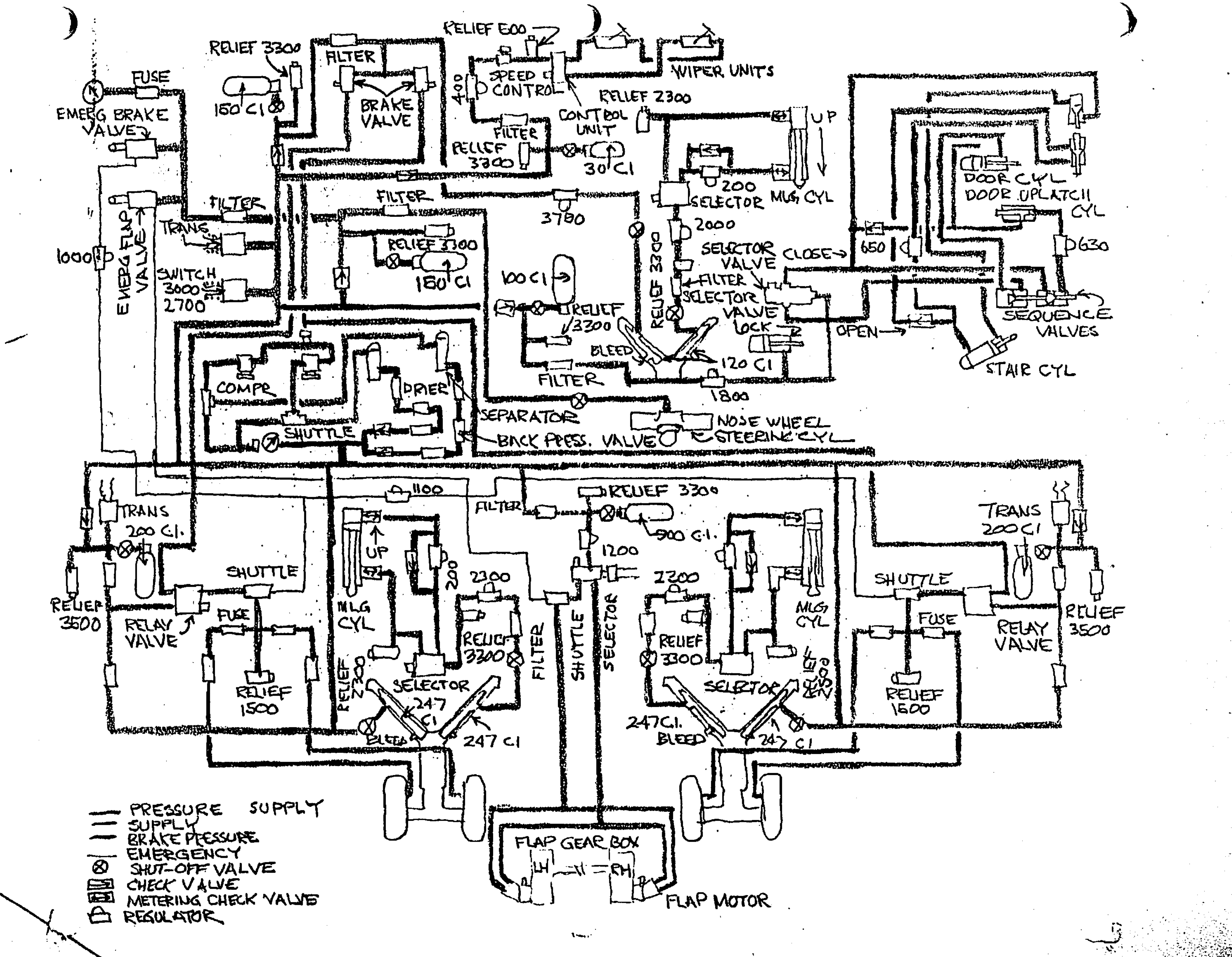
$$T = \frac{pd}{2\pi} = \text{in-lbs}$$

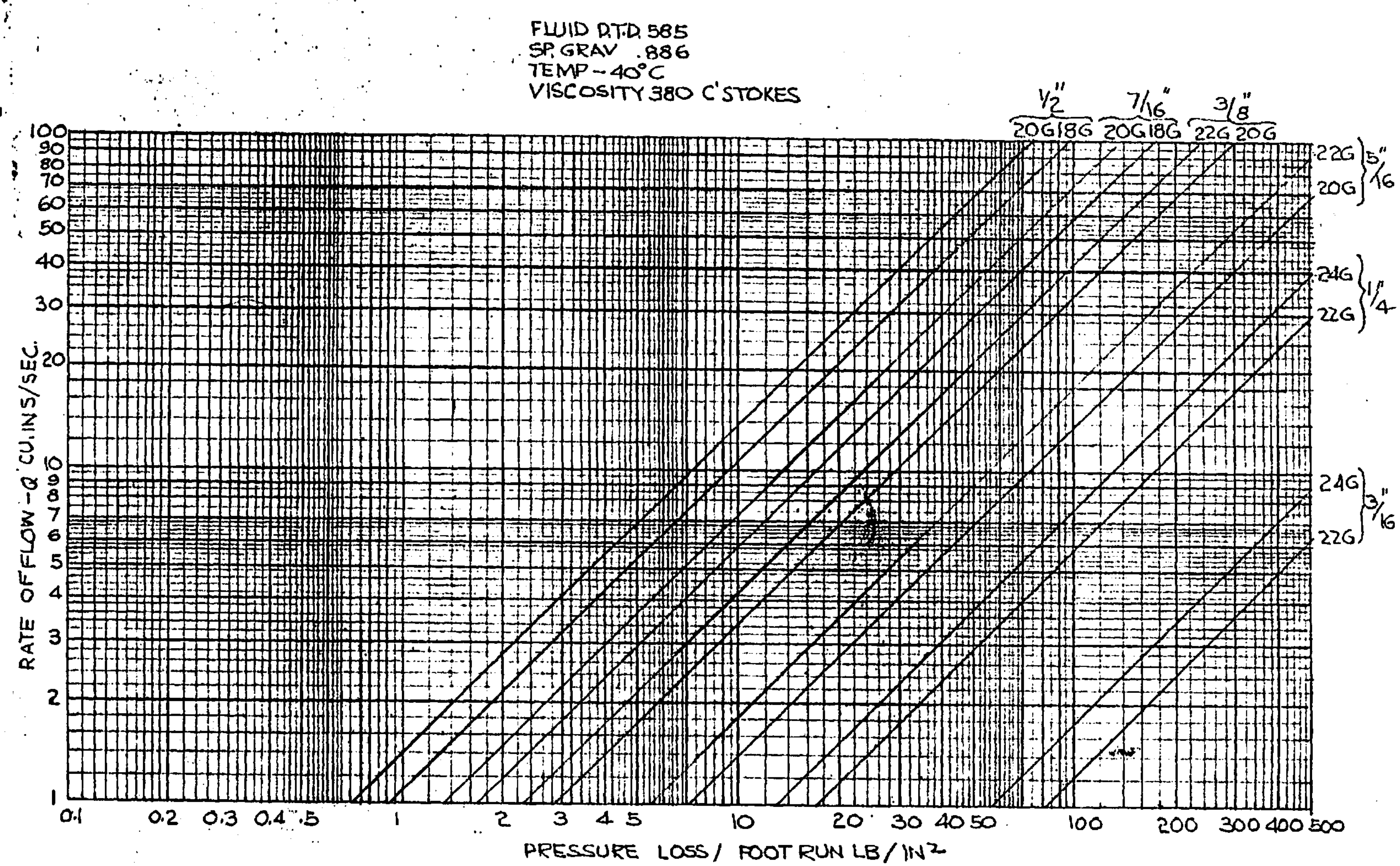
Hydraulic Motor Horsepower

T = torque in-lbs

S = motor rpm

$$HP = \frac{T \times 2\pi \times S}{396000}$$


RELIEF 3300
FILTER
FUSE
EMERG BRAKE VALVE
150 CI
BRAKE VALVE
RELIEF 600
SPEED CONTROL
400
CONTROL UNIT
WIPER UNITS
RELIEF 2300
FILTER
RELIEF 3300
30 CI
UP
200
SELECTOR
MLG CYL
DOOR CYL
DOOR UPLATCH CYL
FILTER
TRANS
3700
1000
EMERG FLAP VALVE
FILTER
RELIEF 3300
180 CI
2000
SWITCH 3000 2700
100 CI
RELIEF 3300
SELECTOR VALVE
CLOSE
650
630
FILTER
SELECTOR VALVE LOCK
RELIEF 3300
BLEED
120 CI
OPEN
SEQUENCE VALVES
STAIR CYL
COMPR
DRIER
FILTER
1800
SEPARATOR
NOSE WHEEL STEERING CYL
SHUTTLE
BACK PRESS. VALVE
1100
RELIEF 3300
FILTER
900 CI
TRANS 200 CI
TRANS 200 CI
UP
200
1200
2300
2300
SHUTTLE
SHUTTLE
RELIEF 3500
RELAY VALVE
FUSE
MLG CYL
RELIEF 3300
FILTER
SHUTTLE
SELECTOR
RELIEF 3300
MLG CYL
FUSE
RELAY VALVE
RELIEF 3500
RELIEF 1500
RELIEF 300
SELECTOR
247 CI
SELECTOR
RELIEF 300
RELIEF 1500
BLEED
247 CI
247 CI
BLEED
247 CI
PRESSURE SUPPLY
SUPPLY
BRAKE PRESSURE
EMERGENCY
SHUT-OFF VALVE
CHECK VALVE
METERING CHECK VALVE
REGULATOR
FLAP GEAR BOX
LH
RH
FLAP MOTOR


FLUID D.T.D. 585
SP. GRAV .886
TEMP - 40°C
VISCOSITY 380 C'STOKES
RATE OF FLOW - Q CU.INS/SEC.
PRESSURE LOSS/ FOOT RUN LB/IN²
1/2" 20G 18G
7/16" 20G 18G
3/8" 22G 20G
5/16" 22G 20G
1/4" 24G 22G
3/16" 24G 22G
100 90 80 70 60 50 40 30 20 10 9 8 7 6 5 4 3 2 1
0.1 0.2 0.3 0.4 .5 1 2 3 4 5 10 20 30 40 50 100 200 300 400 500