PERFORMANCE ANALYSIS

FOR CF-105

SKID CONTROL SYSTEM

Bendix-Pacific

A DIVISION OF BENDIX AVIATION CORPORATION

NORTH HOLLYWOOD, CALIF.

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SKID CONTROL SYSTEM

BENDIX-PACIFIC
Division of Bendix Aviation Corporation
North Hollywood, California

TABLE OF CONTENTS

SECTION I

INTRODUCTION

This performance analysis demonstrates that the Bendix-Pacific Skid Control System and its components are capable of providing adequate skid control for the Avro CF-105 aircraft. The actual design values were established by laboratory test and mathematical analysis.

The detailed mathematical analysis has established the performance characteristics and the fail-safe attributes of the system. Use of the skid control system will not contribute to the vibration frequency of the landing gear or adverse pitching of the aircraft. False brake release, such as might be caused by landing gear deflection or eccentricity of the detector drive coupling, are effectively prevented.

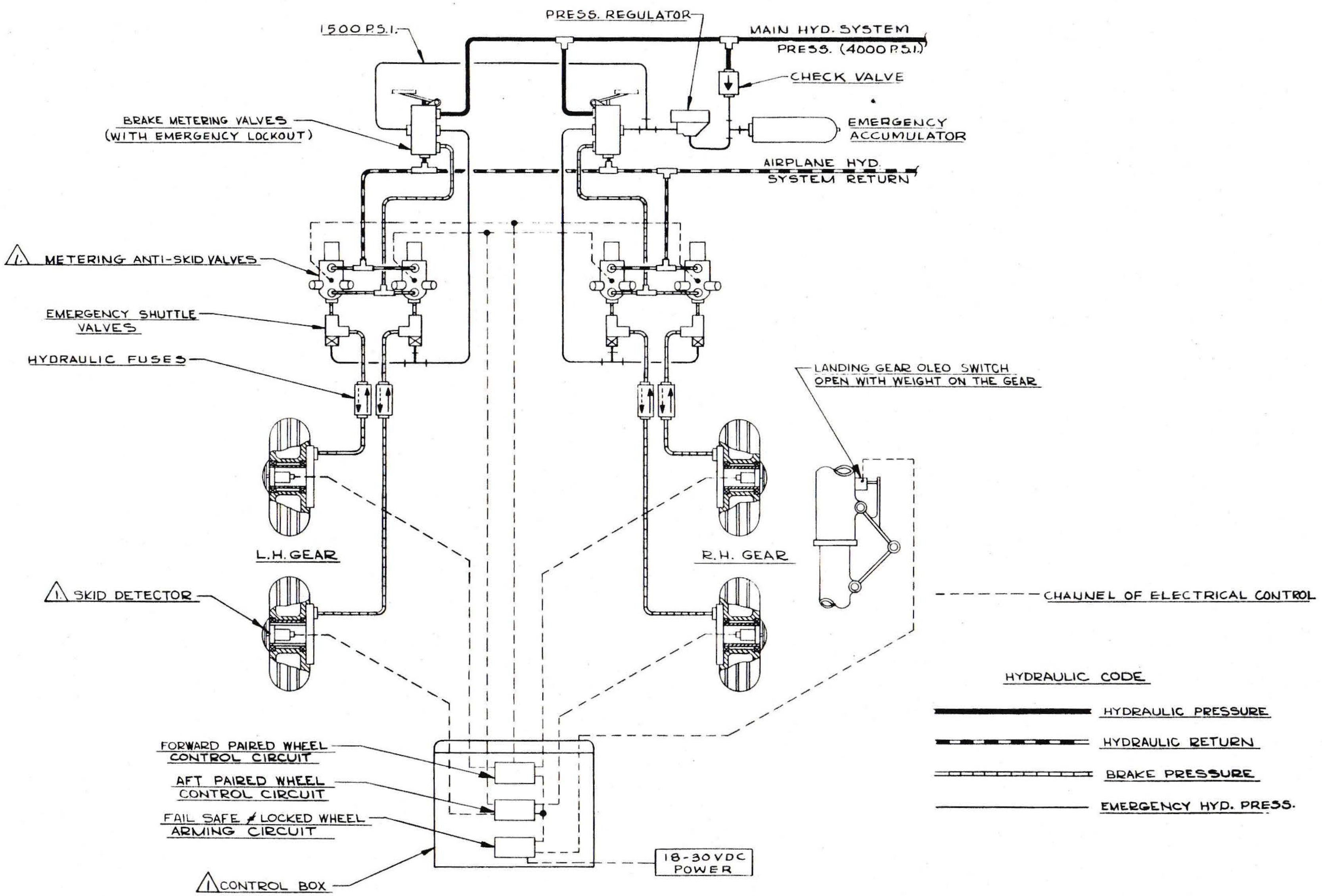

Figure 1. Hydraulic and Electrical Schematic, CF-105 Skid Control System

SECTION 2

SYSTEM DESIGN

2.1 SYSTEM CONCEPT

The Bendix-Pacific Skid Control System is a unique two-step electrical brake skid control system for aircraft. Optimum brake pressure is maintained by metering both brake release and reapplication to provide both incipient skid and locked-wheel control. This assures maximum safety on all runway surface conditions from dry to very slippery.

The smooth performance of the Bendix-Pacific Skid Control System, thoroughly proved in a series of tests, provides greater landing safety, decreased landing roll, and reduces tire wear, with minimum fatiguing stress on the landing gear. The system is simple in operation, extremely rugged, lightweight, and easily installed.

Components of the skid control system are:

a. Skid Detector, a small rugged unit which is installed in each wheel. The unit contains two electrical alternator sensing devices, in which all electrical leads are from stationary windings. There are no slip rings, commutators, or moving contacts.

b. Skid Control Metering Valve, a solenoid operated valve which modulates both brake pressure release and reapplication to provide continual brake retarding force and prevent skidding.

c. Control Box, a small lightweight transistor unit containing all necessary electrical circuitry.

The skid detector is mounted in each braked wheel at the centerline of the axle and is directly driven by the hub cap. The control box is mounted in the airplane in the most convenient location requiring the least amount of wiring. The skid control metering valve is located in the brake line between the brake metering valve and the brakes. A switch in the electrical power supply line allows the skid control system to be turned off whenever immediate restoration of complete manual braking is desired.

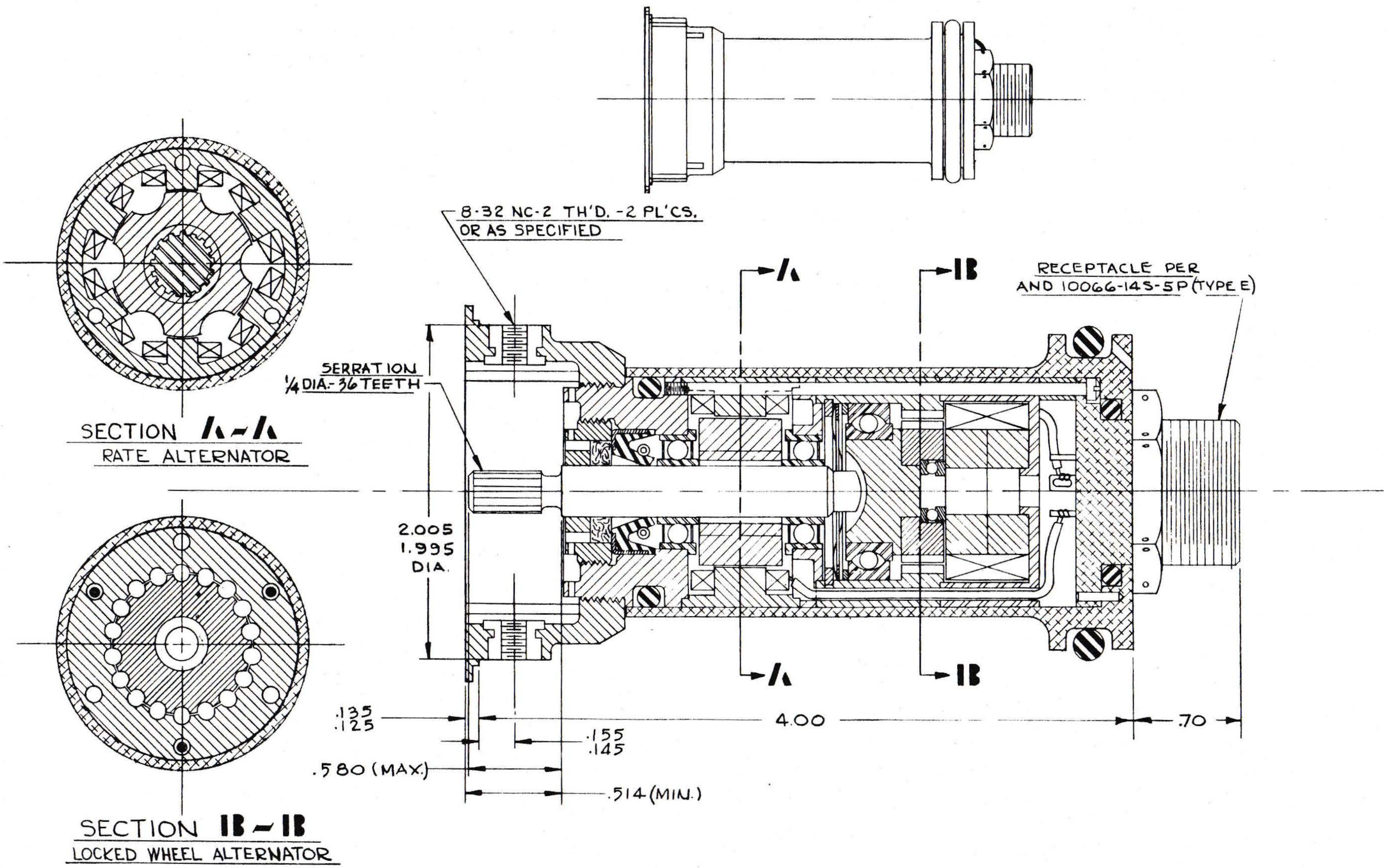

Figure 2. Wheel-Driven Skid Detector Unit

2.2 SKID DETECTOR

The skid detector (shown in figure 2) consists of two very small alternators to supply alternating signal current to the control box. One alternator supplies current for detecting speed change rate and the other supplies current for detecting rotation.

The alternator used for the rate-sensing signal current has a linear voltage-to-speed relationship of approximately one volt per 100 RPM. The rotation-sensing alternator has a non-linear voltage-to-speed relationship that is relatively high at low speed and drops off at high speed. At maximum wheel speed, the rate-sensing alternator may have 20 volts output while the rotation-sensing alternator has only five volts. The power output of these alternators is very low since only signal current is supplied to the control box for amplification. The detector is sealed from all adverse environment, and has an exceptionally long life expectancy since there are no slip rings or wearing parts.

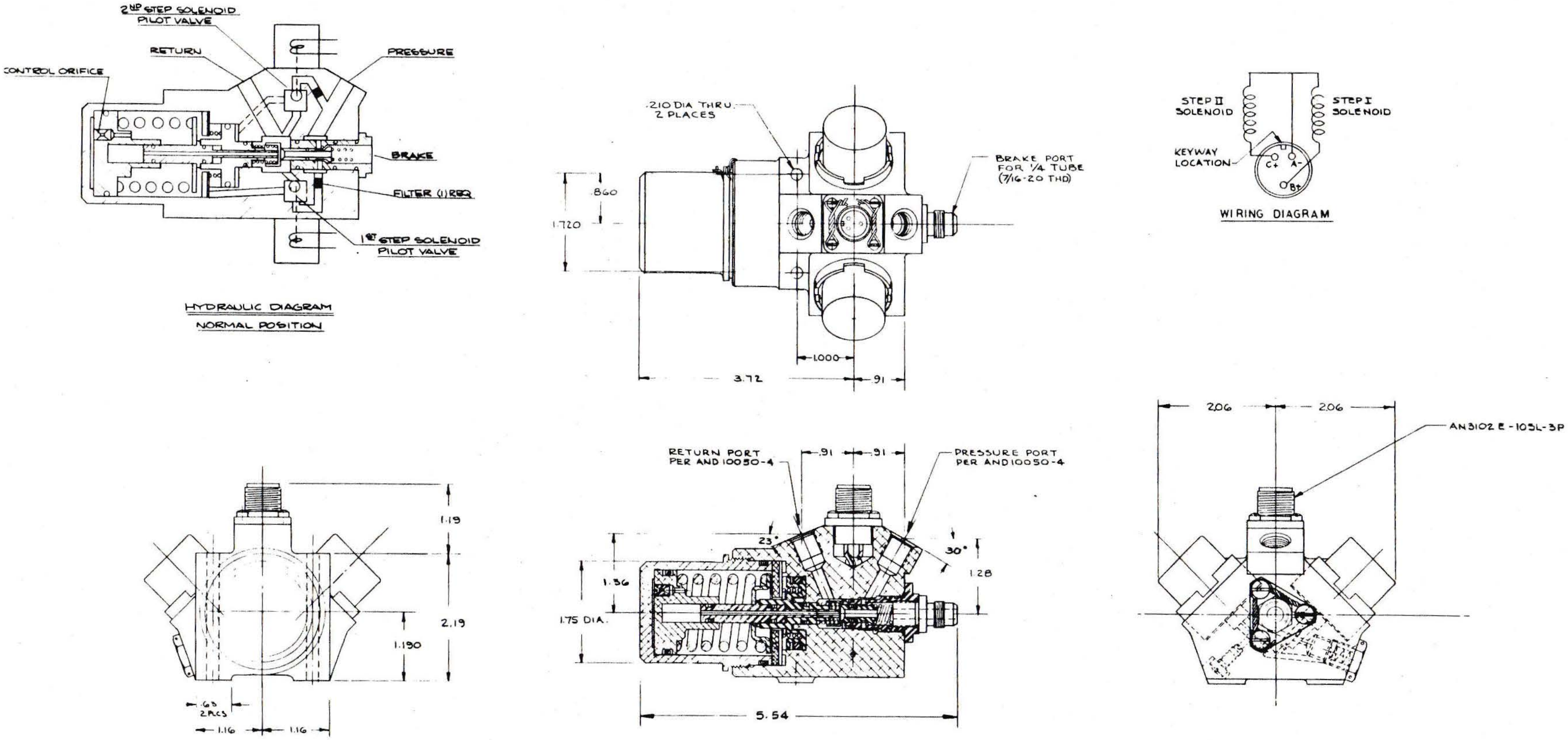

Figure 3. Skid Control Metering Valve

2.3 SKID CONTROL METERING VALVE

The skid control metering valve (see figure 4) is a solenoid-operated three-way valve with two steps of operation, each controlled by the solenoid-actuated pilot valve. The first step provides modulated brake pressure by controlling its increase or decrease to a relatively low rate of pressure change. The second step provides rapid complete brake release followed by rapid return of pressure to a value slightly less than the pressure existing at the time of release. Upon first application of brake pressure, the valve is full open from pressure point to brake port, to allow fast flow of brake fluid into the brakes until the brakes are filled and low pressure braking action starts. At this pressure, the solenoid valve meters brake pressure into the brakes at a predetermined rate that requires approximately 1.5 seconds for full brake pressure to be applied. The relatively slow build-up of brake pressure assures that skid control can take place before there is an overshoot of brake pressure and thus prevents violent wheel deceleration.

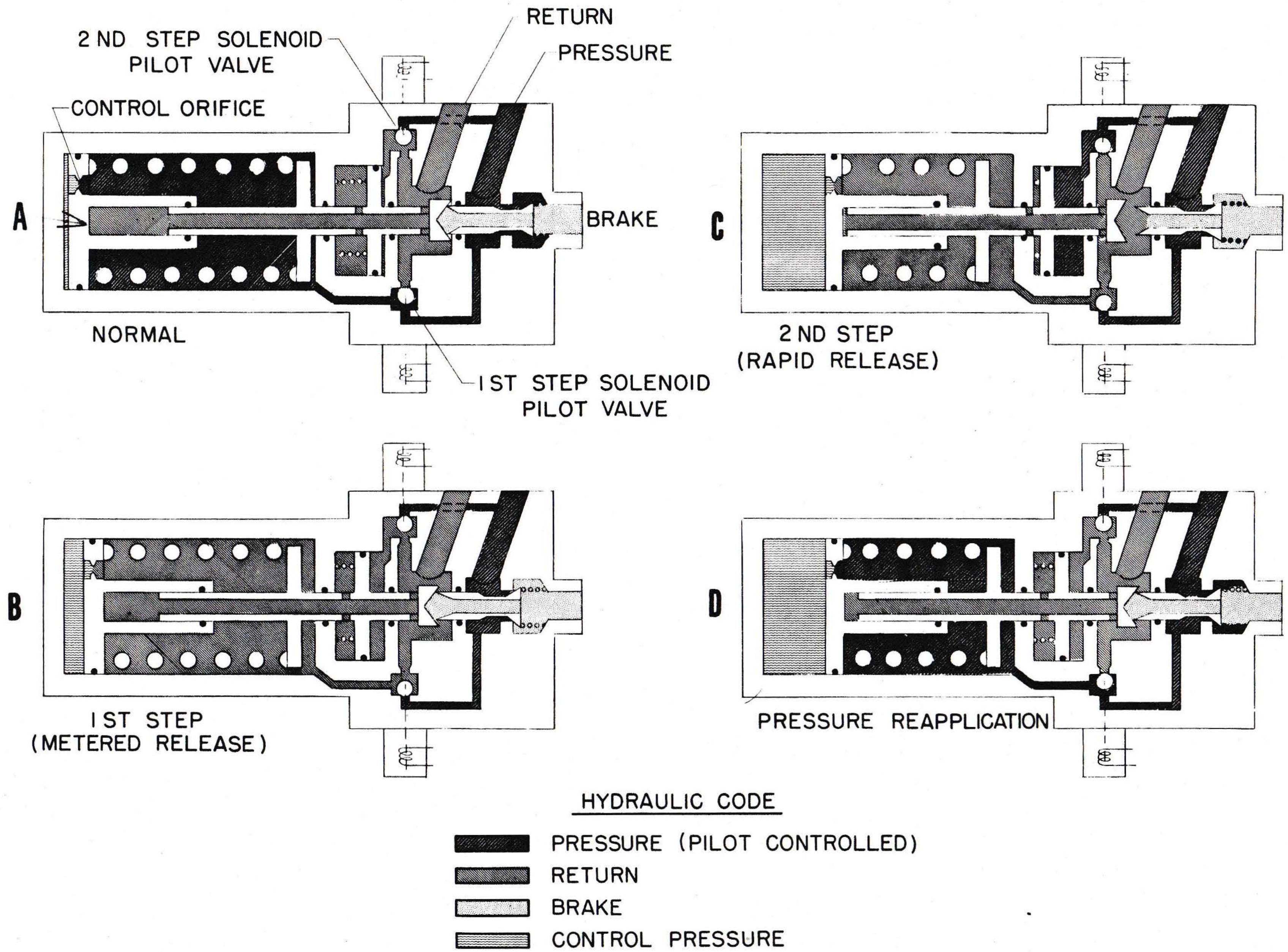

Figure 4. Flow Diagram, Skid Control Metering Valve

Figure 4A shows the de-energized valve position at the initial application of the brakes. The poppet is open, permitting pressure to act on the brake due to the pre-load of the control spring. When the brake pressure reaches 300 psi the force on the return seat area balances the spring and metering action starts.

During Step 1 metered release, shown in figure 4B, the lower pilot valve is actuated to allow flow of fluid out of the control cylinder. The return seat opens to return and allows the brake pressure to be reduced proportional to the decreasing spring force.

Figure 4C shows the Step 2 release condition. Both pilot valves are energized. Flow through the upper pilot valve causes the release piston to move to the left, opening the return seat, which releases the brake pressure. At the same time the control spring force is being reduced by flow out the lower pilot valve. The longer the Step 2 release lasts, the lower will be the pressure at which reapplication starts.

Figure 4D shows the position during metered application (or reapplication) over 300 psi. Hydraulic fluid flows through the lower pilot valve to the control cylinder. The differential area between the rod and head end of the control piston causes flow through the control orifice. The control piston then moves to the right at a rate dictated by the size of the orifice, increasing the spring load. This causes opening of the pressure poppet to a degree such that the brake pressure on the return seat area always balances the increasing spring force.

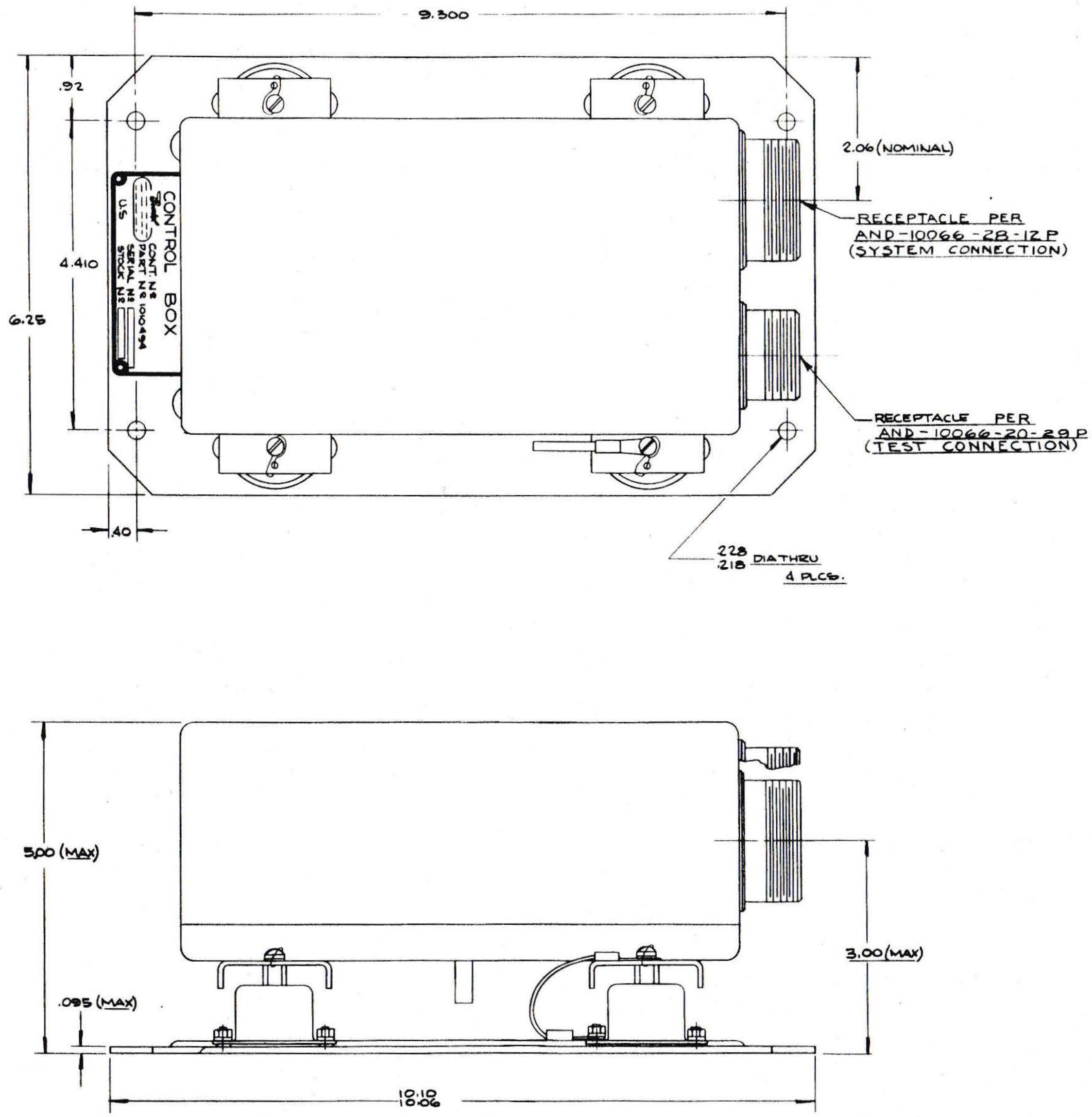

Figure 5. Skid Control Box

2.4 CONTROL BOX

The control box assembly is fastened to a mounting plate by four vibration isolation mounts. One control box contains all the skid control circuit components for four braked wheels. Where practical, printed circuit wiring is used and identical circuits are interchangeable.

An electrical test receptacle is provided in addition to the functional electrical receptacle so that the control circuits may be checked with the control box installed in the airplane. Sealing techniques used in manufacture permit reuse of the box and cover. Prior to hermetic sealing, the box is pressurized at 1 to 2 psig with dry nitrogen.

The control box has two basic control circuits, one for detecting incipient skids and the other for detecting a locked wheel.

The incipient skid is detected in the rate-sensing circuit which receives alternating current from the rate generator. This current is rectified into direct current and then filtered and sent to a deceleration-sensing circuit. The output of this circuit is amplified by two transistors that operate two relays for step one and step two brake release. Two levels of sensitivity for operating these two steps are provided in a sensitivity-ratio control circuit which divides the current flowing from the step one deceleration amplifier and uses only part of this current through the step two deceleration amplifier. This results in reduced sensitivity for step two. A time delay of approximately 0.1 second in the operation of step two is provided by a capacitance time delay circuit at the input to the step two transistor amplifier.

Brake release for locked wheel control occurs only when both of two conditions exist.

a. The wheel is not rolling, and

b. The aircraft has forward motion in excess of 33 knots.

A locked wheel is detected by the rotation-sensing circuit which is part of the locked-wheel control system. This system uses the current supplied by the rotation-sensing alternator which is increased in power through a transistor amplifier. This amplified

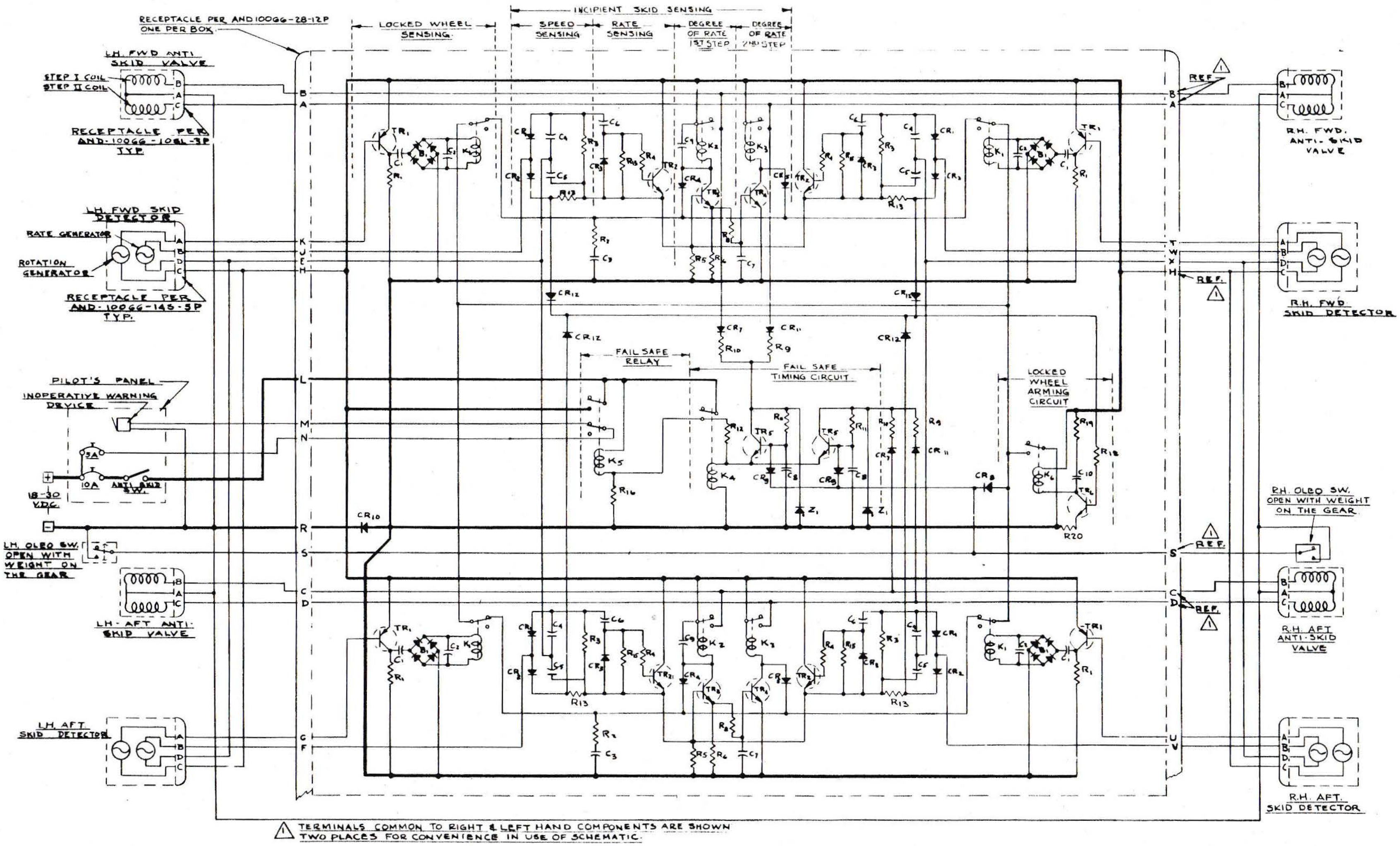

Figure 6. Circuit Diagram, Paired Wheel Skid Control System

alternating current is then rectified and filtered into direct current to energize the locked-wheel control relay. Whenever a wheel comes to low speed or stops and the locked-wheel arming relay is energized, the locked-wheel control relay drops out and causes step one and step two brake release relays to be energized and allow fast brake release.

Prior to touchdown, the locked-wheel control circuit is armed through the landing gear safety switch. After touchdown, each locked-wheel control relay is armed through the locked-wheel arming circuit. Only one locked-wheel arming circuit is required per airplane. This circuit receives its energy signal from each of the rate-sensing circuits and is energized as long as any one wheel is rotating at a speed in excess of (approximately) 520 RPM. This relay also has a release time delay of 0.8 to 1.7 seconds to provide time for locked-wheel control even if all wheels stop momentarily. In this manner, each locked-wheel control relay is armed and performs its function until the airplane speed has dropped down to taxi speed.

The fail-safe circuit operates from the power source supplied to operate each actuating solenoid. Current from this power source is sent through the fail-safe time delay circuit to a transistor amplifier which causes the fail-safe relay to drop out after a time delay of approximately 3.5 to 4.5 seconds if malfunction causes a continuous brake release signal.

At this point, the skid control system is turned off and the brake system restored to normal manual braking. A warning device informs the pilot that the skid control system has been shut off.

The electrical control circuit is particularly adept for setting sensitivity and filtering out all false skid signals due to landing gear oscillation or "walking". Use of transistors in this system provides sufficient power to operate relays of high contact force and good vibration resistance characteristics. As a result, the control box is rugged and reliable and, with the aid of vibration isolation mounts, can withstand the most severe vibration encountered in today's aircraft.

2.5 CIRCUIT DESCRIPTION

The incipient skid or wheel deceleration sensing circuit receives an alternating current signal from the skid detector. The amplitude of this signal is directly proportional to wheel speed. When wheel speed is lost due to incipient skid, the deceleration sensing circuit converts this change in speed to an electrical signal which is amplified to control relays for step one and step two brake release. Circuit operation is as follows. During wheel spin up the rate generator charges capacitors C4 and C5 through diodes CR1 and CR2. C4 and C5, being connected additionally, deliver to resistor R3, and through diode CR3 to capacitor C6, a direct current voltage approximately one and one-third times the generator root-mean-square voltage. During the charge cycle, the forward voltage drop of CR3 and R15 impress a negative voltage on the base of transistor TR2. This voltage drops to zero when the voltage across C6 equals the voltage across R3. Under both of these conditions, there is no current flow thru TR2.

In the event of loss of wheel speed due to incipient skid, the voltage output of the generator will drop accordingly. This voltage drop will reduce the voltage level across C4, C5, and R3. Under these conditions C6 will have a voltage level higher than that across R3, and will discharge through the base emitter diode of TR2 through resistor R4 causing current flow in TR2. Part of this discharge will be dissipated by resistor R15. If the voltage differential between that across R3 and C6 reaches 0.7 volts, TR2 will begin to conduct.

When TR2 is conducting, power from the aircraft d-c voltage system is delivered to resistor R5 and to the base emitter diode of transistor TR3 in series with resistor R6. This causes TR3 to conduct and operate relay K2. If the voltage differential across R15 rises to 0.9 volts or more, the voltage developed across R6 will be sufficient to cause TR4 to start conducting. TR4 is prevented from conducting immediately by the time delay of R-C circuit R8 and C7. This time delay is approximately 0.05 to 0.1 second. When TR4 is conducting it will operate K3. The operation of relays K2 and K3 delivers line power respectively to the step one and step two solenoids in the skid control metering valve.

The rotation sensing circuit used for locked wheel control, receives an a-c voltage from the skid detector and amplifies this voltage by means of transistor TR1. The output of TR1 appears across resistor R1 as a square wave with amplitude approximately equal to the line voltage. The square wave voltage is applied to bridge rectifier B1 thru a d-c blocking capacitor C1. The d-c output voltage of B1 is applied to relay K1 and capacitor C2 which serves as a filter. Pull-in of the relay occurs at wheel speeds of between 19 and 32 RPM and drop-out between 6 and 11 RPM wheel speed. Whenever a wheel stops while the locked wheel arming relay is energized or when the oleo switches are in right position, the locked wheel relay drops out. This causes step one and step two relays to be energized and allows fast brake release.

Prior to touchdown the locked wheel arming is provided through the landing gear safety or oleo switch. After touch-down, the locked wheel arming circuit is activated by the voltage drop across resistor R13 which results from the flow of current to capacitor C5 and load resistor R3. This voltage drop provides a positive signal to transistor TR6 through resistor R18 and the base emitter diode of TR6 in series with R20. Any one wheel rotating in excess of 520 RPM will cause TR6 to conduct and operate relay K6. Capacitor C10 and resistor R19 provide a time delay on the release of K6 of approximately 0.8 to 1.7 seconds. This delay provides locked wheel control even if all wheels stop momentarily. In this manner each locked wheel relay is armed and performs its function until the airplane speed has become very low.

Fail-safe operation is provided to prevent a continuous release of brakes in excess of 4 seconds. But in order to allow continuous brake release prior to touchdown, fail-safe operation is not available until after the landing gear safety or oleo switch has been actuated to the on-ground position. For the remainder of the landing roll, if continuous brake release occurs in excess of four seconds, the fail-safe circuit operates relay K4. Operation of relay K4 causes relay K5 to drop out which removes line power from the system and activates a signal to the pilot that the skid control system is inoperative. Full manual braking is available when fail-safe action occurs.

When the cause of operation of the fail-safe circuit has been removed, the K4 and K5 relays may be restored to their normal position by removal and reapplication of line voltage.

2.6 PRINCIPLE OF CONTROL

The skid control system is primarily based on controlling the skid in its incipient stage. Electrical skid signals are generated when the braked wheel deceleration is slightly greater than with non-skid braking. Skid signals are generated in a resistance-capacitance circuit where the signal strength is a function of rate of change of wheel speed. Rectified direct current energy to a capacitor in the rate circuit is supplied by a six pole alternator that is directly driven by the braked wheel. During deceleration, the voltage potential of the electrical energy decreases and as the capacitor of the rate circuit discharges its stored electrical energy at a rate in excess of a predetermined value, skid control is initiated. Two steps of skid control are obtained by employing two levels of signal strength. Step one control is initiated by a relatively lower wheel deceleration than step two. (Step one control provides modulated brake control while step two provides fast on-off brake release.)

Locked wheel control is provided in addition to incipient skid control. This is accomplished by a rotation-sensing circuit that uses the alternating current from a second alternator with 18 poles. The alternating current is increased in power by a transistor amplifier and then rectified into direct current to operate a relay continuously at all wheel speeds above that encountered at very low airplane speed of approximately 2 knots.

2.7 BASIC DATA

Airplane Landing Speed	150 knots
Wheel rolling radius:	
At touchdown	14.0 inches
At rest	12.5 inches
Wheel Speed (See figure A-1):	
At touchdown	2,080 RPM
At minimum skid control speed (20 knots)	320 RPM
Main Landing Gear:	
Natural frequency	9 cps
Deflection	±4 inches

Length:

Fully extended	106 inches
Under Load	100 inches

Brake displacement (See figure A-2):

Brake Pressure (psi)	Brake Volume (cu. in.)
192 - 203	0.78
1583	0.891
1833	0.900
2508	0.923

Wheel, tire and brake rotating parts, mass moment of inertia — 2.2 slug-ft^2

2.8 DESIGN DATA

2.8.1 Airplane

Coefficient of friction for runway surface.
Maximum steady state — $u = 0.55$

Maximum steady state deceleration of the airplane

$$a = ug$$

$$a = 0.55 \times 32.2 \text{ ft/sec}^2 = 17.7 \text{ ft/sec}^2$$

Maximum steady state deceleration of the braked wheels

$$\alpha = \frac{a}{R}$$

$$\alpha = \frac{17.7}{\frac{12.5}{12}} = 17.0 \text{ rad/sec}^2$$

Natural period of oscillation of the landing gear.
Time per cycle (T)

$$T = \frac{1}{9} = 0.111 \text{ sec}$$

2.8.2 Components

Transistor voltage (E_B) required at the base to cause collector current to flow with sufficient strength to pull in a relay:

$$E_B = 0.65 \text{ volts}$$

Skid signal voltage (E_R) required to provide (E_B) = 0.65 volts

Step 1 signal = 0.7 volt
Step 2 signal = 0.9 volt

2.8.3 Actual Performance Data

The values of voltage supplied to the rate capacitor (C_E) vs wheel speed for various load resistance (R3) are shown in figure A-3. The slopes of these curves were plotted on figure A-4 to determine the relationship of rate capacitor voltage per RPM to load resistance. This relationship is expressed in the equation

$$E_C/N = 0.000272 \, (R3)^{.46}$$

which can be used to determine the voltage at the rate capacitor for any load resistance for any wheel speed. (The capacitance values for C4, C5, and C6 do not effect the voltage output over a very wide range from 50 to 400 mfd.)

The skid signal is produced during deceleration by discharge of current from the rate capacitor (C6) through resistance (R15) and transistor (TR2). With decreasing voltage supplied by the voltage doubler to the load resistance (R3), a positive voltage (E_R) is produced on the transistor base in respect to the emitter. When this voltage rises to the threshold level of the transistor (about 0.65 volts), the transistor conducts a current through the collector and emitter which is used as the skid signal. The sensitivity of the control circuit is set to cause the first step signal with 0.7 volts and the second step signal with 0.9 volts supplied to R15.

The strength of the skid signal voltage (E_R) is a function of the rate of decrease of voltage at the voltage doubler. This relationship has been determined empirically to be as shown in figure A-5 and as expressed by the equation:

$$E_R = K_1 \left({}^{de}/_{dt} \right)^{.41}$$

K varied from 0.4 to 0.42 with the load resistance (R3) varied from 5600 to 2200 ohms

$$\text{at } E_R = 0.7 \text{ volts}$$

$$de/_{dt} = 3.6 \text{ to } 4.0 \text{ volts/sec}$$

The nomograph used to select values of resistance (R3) and capacitance (C_t) used in the rate sensing circuit is shown in figure A-6. This nomograph was established by calculations based on actual laboratory test data.

To provide first step control at a minimum value at approximately 20 knots and second step control at approximately 30 knots, let

$$R3 = 4000 \text{ ohms}$$

then the total capacitance (C_t) can be chosen at

$$C_t = 150 \text{ mfd (approximately)}$$

The voltage (E_C) at maximum wheel speed will be

$$E_C = 26 \text{ volts (approximately)}$$

The voltage (E_C) supplied to the rate capacitor is shown in figure A-7. The values used for C4, C5 and C6 were nominally 100 mfd each and the load resistor (R3) was 4000 ohms. The relationship of voltage (E_C) to wheel speed (N) shows that there is 1.23 volt dc for each 100 RPM of wheel speed.

SYMBOLS AND ABBREVIATIONS

a = linear deceleration (considered as a positive value)

α = angular deceleration in radians per second per second

C = capacitor (identified numerically)

C_t = total capacitance

cps = cycles per second

cu. in. = cubic inches

de = increment of change in voltage

dp = increment of change in pressure

dn = increment of change in angular velocity in revolutions per minute

dr = increment of change in radius in inches

dt = increment of change in time in seconds

e, E = volts

$\mathcal{E}$ = 2.72 (Natural log base)

E_B = volts, base to emitter of transistor

E_C = voltage across rate capacitor C3

E_R = rate, volts

g = gravity accelerating rate, 32 feet per second per second

I = mass moment of inertia in slug-feet^2

in. = inches

psi = pounds per square inch pressure

K = coefficient

K = relay (identified numerically)

mfd = microfarad

N = angular velocity in revolutions per minute

R = resistor (identified numerically)

RC = resistance-capacitance

RPM = revolutions per minute

T, t = time in seconds

To = torque in foot-pounds

TR = transistor (identified numerically)

u = coefficient of friction

∞ = infinity

SECTION 3

MATHEMATICAL ANALYSIS

3.1 BASIC EQUATIONS

The maximum steady state non-skid deceleration of the braked wheel is 17 radians per second^2. To prevent brake release during this maximum braking condition, the first step skid signal is set arbitrarily at not less than 30 radians per second^2 before it is initiated.

The angular deceleration of the braked wheel expressed in terms of rate of change of wheel speed (dn/dt) is:

$$\alpha = \frac{dn}{dt} \cdot \frac{2\pi}{60} = .1048 \frac{dn}{dt}$$

The relationship between voltage (Ec) supplied to the rate capacitor and wheel speed (N) is shown in figure A-7 and can be expressed by the equation:

$$E_c = .0123N.$$

During wheel deceleration, the rate of change of voltage de/dt supplied by the alternator to the rate capacitor is expressed by the equations

$$\frac{de}{dt} = .0123 \frac{dn}{dt},$$

and, by substitution for dn/dt

$$\frac{de}{dt} = .0123 \frac{\alpha}{.1048} = .1175\alpha$$

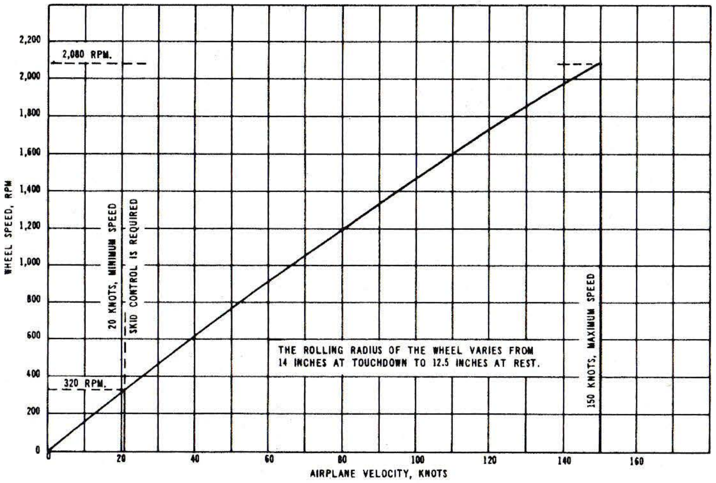

Figure A-1 Wheel Velocity vs Airplane Speed

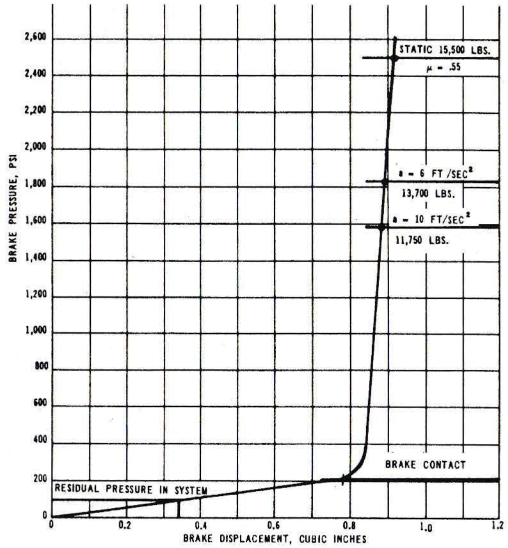

Figure A-2 Brake Volume vs Pressure

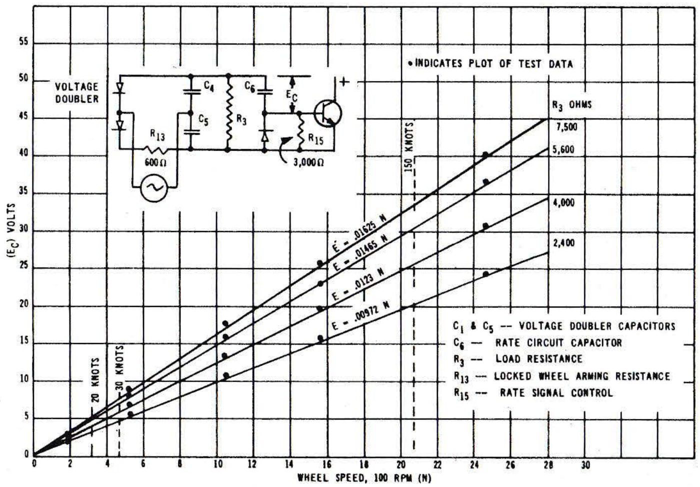

Figure A-3 Rate Circuit Capacitor vs Wheel Speed for Various Values of Load Resistance R3

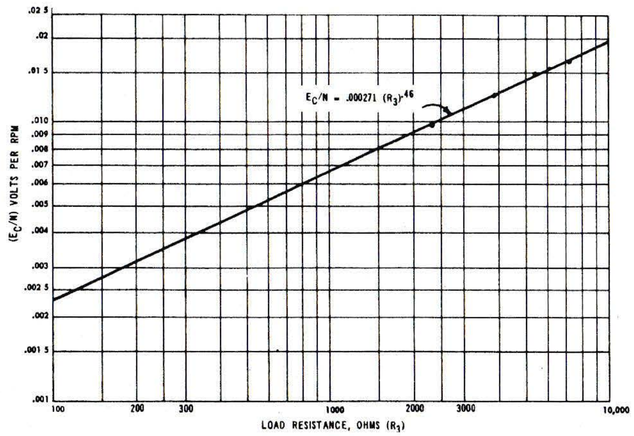

Figure A-4 Voltage at Rate Capacitor per Wheel Speed (RPM) vs Load Resistance (E_C/N vs R3)

3.2 RESISTANCE-CAPACITANCE CIRCUIT DISCHARGE

The discharge of an R-C circuit can be expressed by the equation

$$e = E\varepsilon^{-t/RC}$$

The time to discharge the capacitor (C) from voltage (E_c) to voltage (e), is expressed by equation

$$t = RC \log_{\varepsilon} \frac{E_c}{e}$$

The discharge time (t) from stabilized speed (N) to the drop-out of step one is shown in figure A-8 and expressed in the equation

$$t = .56 \log_{\varepsilon} 0.00456N.$$

From this, the effective value of the resistance-capacitance is,

$$RC = .56$$

Since the load resistance (R3) was measured at 4000 ohms and the transistor resistance drops to less than 50 ohms after E_R exceeds 0.7 volts,

$$C = \frac{.56}{4050} = 138 \text{ mfd}$$

By equating from the equations above it can be shown that

$$\frac{E_c}{e} = 0.00456N$$

and since $E_c = .0123N$,

$$e = \frac{.0123}{.00456} = 2.7 \text{ volts,}$$

the drop-out point of step 1 signal. Extensive oscillograph data substantiates this value.

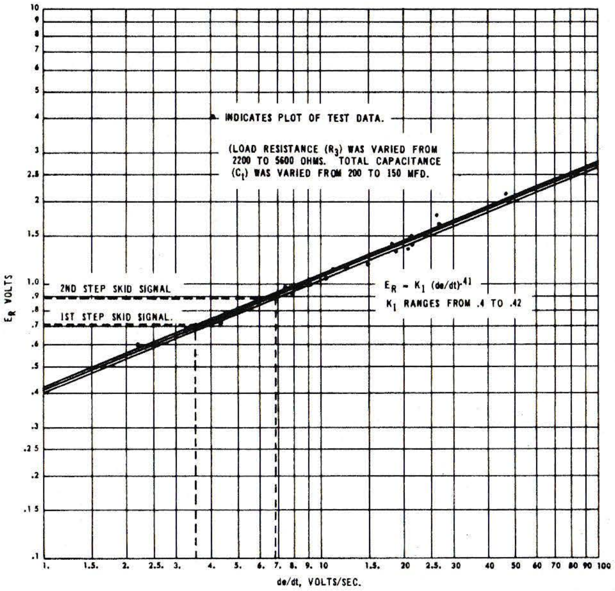

Figure A-5 Skid Signal Voltage (E_R) vs Rate of Voltage Change (de/dt) at the Rate Capacitor

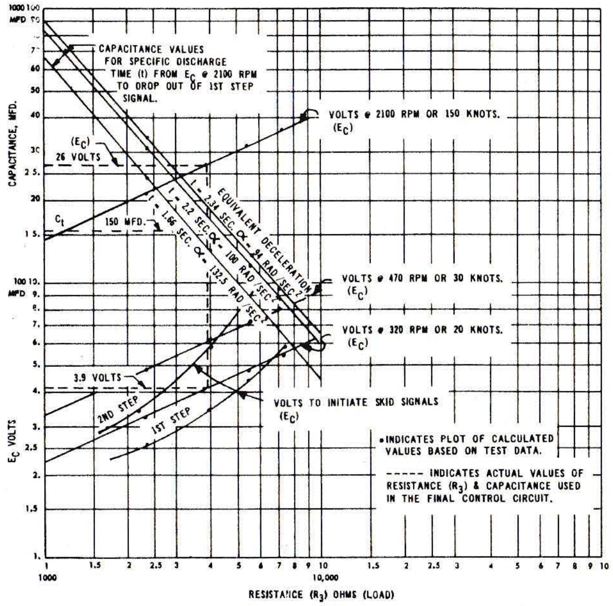

Figure A-6 Nomograph to Determine Optimum Values for the Load Resistance and Total Capacitance in the Rate Sensing Circuit

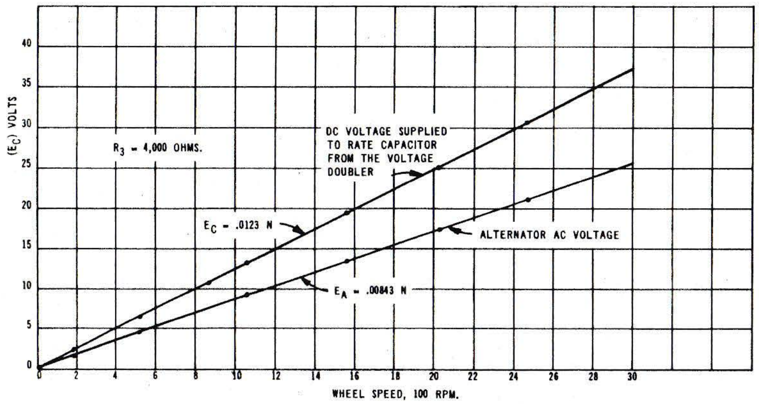

Figure A-7 Rate Sensing Circuit Voltage vs Wheel Speed

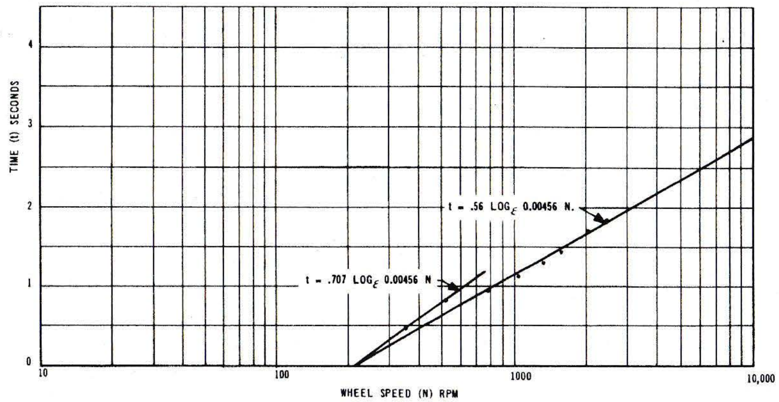

Figure A-8 Skid Signal Time vs Wheel Speed at Time of Signal

At low speeds, the discharge time of the R-C circuit is greater than expressed by the equation due to the increased resistance in the transistor with lower signal strength. The equation $T = .707 \log_{\varepsilon} 0.00456N$ shows RC = .707.

3.3 MINIMUM SKID CONTROL SPEED

The minimum speed to which skid control can be maintained is determined below. From the basic equation for discharge of an R-C circuit,

$$e = E_c \, \varepsilon^{-t/RC}$$

by differentiation

$$\frac{de}{dt} = \frac{-E_c}{RC} \varepsilon^{-t/RC}$$

$$E_c = -RC \cdot \frac{de}{dt} \cdot \varepsilon^{t/RC_1}$$

With very rapid deceleration, the time to generate enough rate voltage (E_R) to initiate skid control is 0.02 to 0.05 seconds. The rate of change of voltage (E_R) required to pull in the first step and second step skid control is shown in figure A-5.

For first step control, $\frac{de}{dt} = 3.6$ to 4 volts/sec and at low speed, RC = 0.707, and $E_c = .0123N$. From the equations above:

$$E_c = -RC \frac{de}{dt} \varepsilon^{t/RC}$$

$$.0123N = .707 \times 4 \times \varepsilon^{\frac{0.05}{0.707}}$$

$$N = \frac{2.83}{.0123} \varepsilon^{.0707} = 230 \times 1.0733$$

$$N = 247 \text{ RPM.}$$

The airplane velocity (V) = 15.5 knots (see figure A-1).

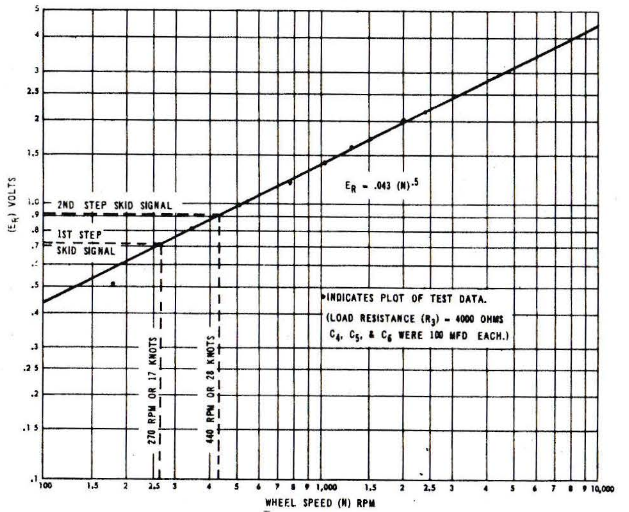

Figure A-9 Skid Signal Voltage (E_R) vs Wheel Speed (N) with $\alpha = \infty$

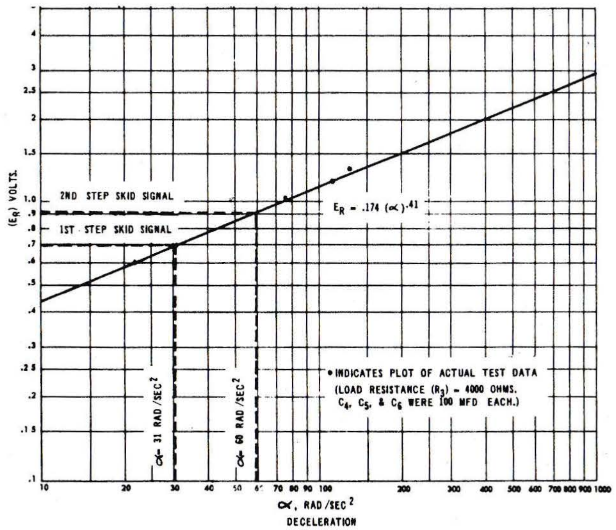

Figure A-10 Skid Signal Voltage (E_R) vs Braked Wheel Deceleration

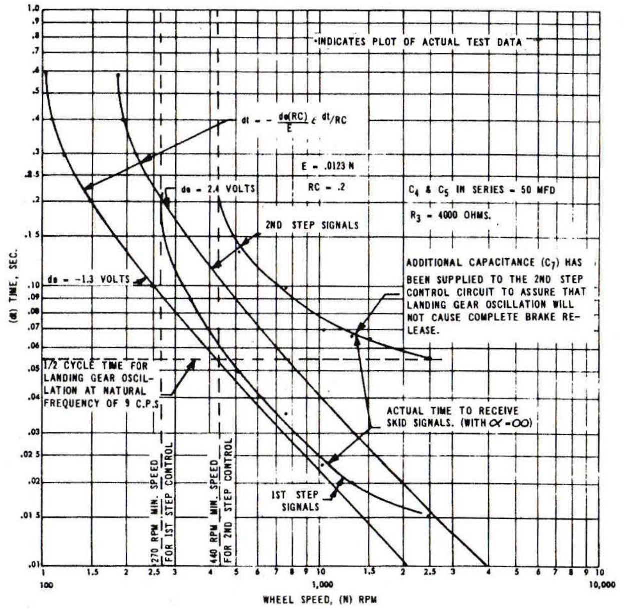

Figure A-11 Time Required to Receive Skid Signals vs Wheel Speed with $\alpha = \infty$

For second step control, $\frac{de}{dt} = 6.7$ to 7.3 volts/sec.

$$N = \frac{.707}{.0123} 7.3 \, \varepsilon^{0707}$$

$$N = 450 \text{ RPM}$$

The airplane velocity (V) = 29 knots (see figure A-1).

The actual skid signal voltage (E_R) vs wheel speed (N) for $\alpha = \infty$ from oscillograph data is shown in figure A-9. The relationship of skid signal voltage (E_R) to wheel speed (N) is expressed by the equation;

$$E_R = .043 \, (N)^{.5}$$

From this equation, the speeds down to which first and second step skid control can be maintained, as stated, are closely substantiated.

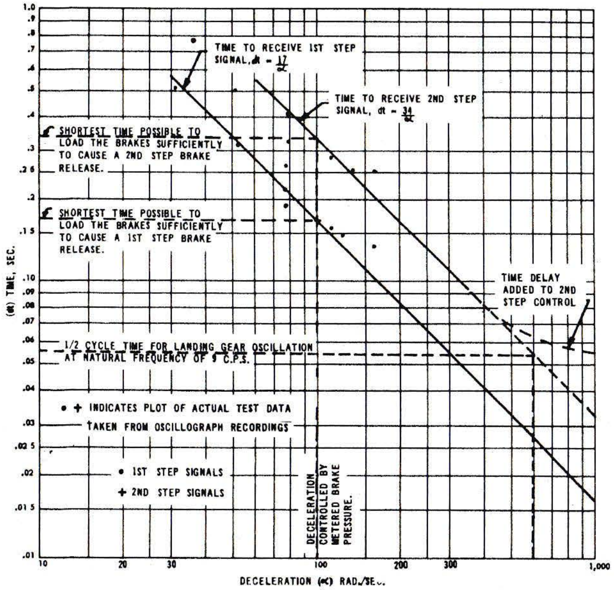

Figure A-12 Time to Receive Skid Signals During Deceleration

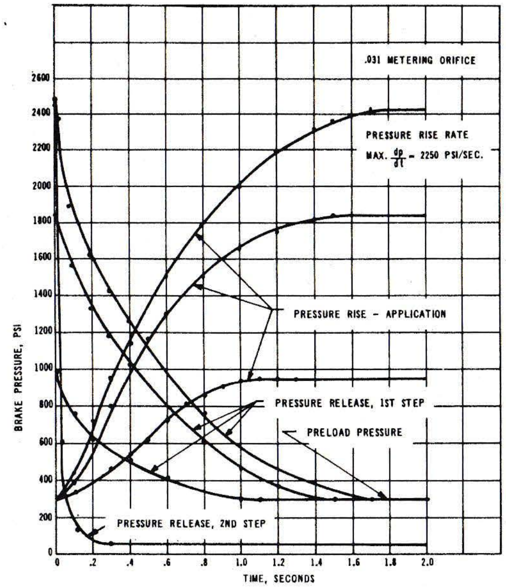

Figure A-13 Skid Control Metering Valve, Modulated Application and Release Time

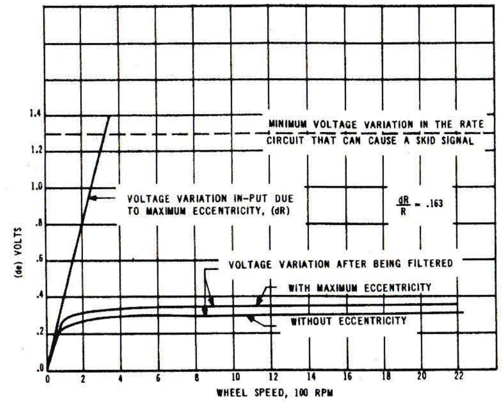

Figure A-14 Voltage Variation in the Rate Circuit in the Rate Alternator Drive Due to A-C Current and Eccentricity

3.4 DECELERATION REQUIRED TO CAUSE SKID CONTROL

The deceleration required to cause skid control is determined below.

from $\frac{de}{dt} = .1175\alpha$ (See paragraph 3.1)

and $\frac{de}{dt} = \frac{-E_c}{RC} \cdot \varepsilon^{-t/RC}$

then with $E_c = .0123(N)$

$$\alpha = \frac{.0123N}{.1175 \cdot RC} \varepsilon^{-t/RC} = .1048 \frac{N}{RC} \cdot \varepsilon^{-t/RC}$$

at low deceleration, the resistance through the transistor has time to average a low value, so RC =.56 approximately. The wheel speed (N) expressed in skid signal voltage (E_R) from paragraph 3.3 is

$$N = \left(\frac{E_R}{.043}\right)^2 = 542\ E_R^{\ 2}$$

then $\alpha = 56.8 \frac{(E_R)^2}{RC} \varepsilon^{-t/RC}$

For first step control E_R =.7 volts/sec.

t = .5 sec. approx

$$\alpha = 56.8 \frac{.7^2}{.56} \varepsilon^{-.5/.707}$$

$$\alpha = \frac{49.8}{2.03} = 24.5 \text{ rad/sec.}^2$$

For second step control, $E_R = 0.9$ volts/sec.

$$\alpha = 56.8 \frac{(.9)^2}{.56} \varepsilon^{-.5/.707}$$

$$\alpha = \frac{82}{2.03} = 40.5 \text{ rad./sec.}^2$$

These values of deceleration are not exactly substantuated by test data shown in figure A-10. This is explained below.

From the equation;

$$\alpha = 56.8 \frac{(ER)^2}{RC} \varepsilon^{-t/RC}$$

we obtain $E_1 = .133\ (RC.\alpha\varepsilon^{t/RC})^{.5}$

At low deceleration (t) can be as high as 0.5 sec. and the resistance thru the transistor can vary as much as 2000 ohms. As a result, the above equation for (E_R) is very complex, but fortunately a more simple equation can be obtained empirically as shown in figure A-10 and expressed as,

$$E_R = .174\ (\alpha)^{.41}$$

The minimum deceleration to cause first step control (with ER = .7 volts)

is, $\alpha = 31$ radians /sec ^{2}

The minimum deceleration to cause second step control, (with $E_R = .9$ volts),

is, $\alpha = 60$ radians/sec ^{2}

3.5 LANDING GEAR OSCILLATION EFFECTS

The effect of landing gear oscillation on skid signals, is determined below. First a study is made to determine the response time of the skid control system for both first and second step skid signals at all wheel speeds. To determine the minimum time to receive a skid signal, assume $\alpha = \infty$ so that the time response will be controlled by the resistance capacitance (R-C) used in the rate sensing circuit. From the equation for discharge of an RC circuit

$$e = E\,\varepsilon^{-t/RC}$$

$$\frac{de}{dt} = \frac{-E}{RC}\varepsilon^{-t/RC}$$

Since dt starts out at $t_1 = 0$

then t = dt.

By re-writing,

$$dt = \frac{-de\,RC}{E}\varepsilon^{dt/RC}$$

at the start of discharge of the R-C circuit, the high resistance of R_{15} (3000 ohms) and the high starting resistance of the transistor TR2 (2000 ohms); the voltage (e) at the voltage doubler drops off fast to develope de. The R-C value for this circuit is,

$$RC = 50 \text{ mfd} \times 4000 \text{ ohm} = 0.2$$

For the first step signal, the decrease in voltage (de) must be at least 1.3 volts. By substituting, de = -1.3 volts,

$$dt = \frac{1.3 \times 2}{.0123N} \cdot \varepsilon^{dt/.2} = \frac{21.1}{N} \cdot \varepsilon^{dt/.2}$$

The response time of the above equation for first step signals is shown in figure A-11. The actual response time with $\alpha = \infty$, is also shown. This curve closely substantiates the equation except at low speed where the ability to energize the control is ending.

Both curves show the response time to range from about 0.1 or 0.2 seconds, at speed under 300 RPM and down to 0.010 or 0.015 second at maximum speed of 2100 RPM. At wheel speed above 400 RPM, the response time of the first step control is such that if there is extremely high, wheel deceleration, oscillation of the landing gear could cause first step on metered brake release. This will not cause serious reduction of braking torque and will not contribute to landing gear oscillation. Also the brake pressure is being metered at a slow rate to prevent rapid deceleration of the wheel and avoid such short signal time. A study of brake control in relation to wheel deceleration follows later in this analysis.

For the second step signal, the decrease in voltage (de) must be at least 2.4 volts, By substituting, de= -2.4 volts, in the basic equation

$$dt = \frac{2.4x.2}{.0123N} \mathcal{E}^{dt/.2} = 39.0\, \mathcal{E}^{dt/.2}$$

The response time of the above equation for second step signals is shown in figure A-11. The actual response time, with $\alpha = \infty$, is also shown. This curve shows greater response time than the one for the equation above. The increase in time required to receive a second step signal has been accomplished by the use of a capacitor (C7) placed across the base and emitter of the second step transistor (TR4). The value of C7 has been chosen to cause the time to receive a second step signal to be in excess of the half-period time of landing gear oscillation. This is true for all wheel speeds up to 2500 RPM. (The speed range could be increased whenever required.) With the response time of the second step signal in excess of the half-period of the landing gear, there can be no false skid signals to cause brake release due to landing gear oscillation. Thus, the skid control system will not contribute to landing gear oscillation or "walking".

The time (dt) required to initiate a skid signal in relation to wheel deceleration (α) is studied below.

Under the basic equations (paragraph 3.1), the rate of decreasing voltage $\left(\frac{de}{dt}\right)$ supplied by the wheel driven alternator is expressed by the equation,

$$\frac{de}{dt} = .1175\alpha ,$$

from this, we derive the time to drop the voltage any given amount, that is,

$$dt = \frac{-de}{.1175\alpha}$$

The first step signal is initiated, at low deceleration, under 200 rad/sec ^{2}, within the time required to decrease the voltage approximately 2 volts. This amount of decrease, increases at very low deceleration. For purposes of this study, we can use de = 2.0 volts.

then $$dt = \frac{2.0}{.1175\alpha} = 17/\alpha$$

This is closely substantuated by actual test data as shown plotted on figure A-12.

From this equation and actual performance, it is determined that at wheel deceleration in excess of 306 radians/sec^2, the response time of the first step control is equal to or less than the .055 sec, half-period time of the landing gears natural frequency. To prevent first step brake release during the time the landing gear is flexing backwards, relative to the airplane, under braking load, at its natural frequency, the brakes must be applied gradually enough to hold the wheel deceleration well under 300 radians per sec ^{2}.

The second step signal is initiated at low deceleration, under 200 radians per sec.^{2}, within the time required to decrease the voltage about 4 volts. With de = -4.0 volts,

$$dt = \frac{4.0}{.1175} = \frac{34}{\alpha}$$

This is closely substantuated by actual test data as shown plotted on figure A-12. Since the response time of the second step control is in excess of the half-period time of the landing gear, there will be no complete brake release caused by landing gear oscillation.

3.6 EXCESS BRAKE PRESSURE EFFECTS

The effect of excess brake pressure on wheel deceleration and skid signal is studied below.

From the brake pressure rise curves plotted on figure A-13, the rate of brake pressure rise ($\frac{dp}{dt}$) is shown to have a maximum rate of $\frac{dp}{dt}$ = 2250 psi./sec.

From the brake volume curve shown in figure A-2, the maximum dynamic torque (To) can be determined.

Weight = 11,750 lbs.

a = 10 ft./sec ^{2}

R = 14 inch rolling radius.

$$To = 11,750 \times \frac{10}{32.2} \times \frac{14}{12} = 4250 \text{ lb-ft.}$$

The brake pressure required to develop this torque is 1583 psi. The pressure required to initiate brake torque is 200 psi. The torque developed per unit of brake pressure is

$$\frac{To}{dp} = \frac{4250}{1583-200} = 3.07 \frac{\text{lb-ft}}{\text{psi}}$$

During the half-period time (dt) of the landing gear oscillating at its natural frequency, the increase in brake pressure (dp) will be

$$dp = dt \cdot \frac{dp}{dt}$$

$$dp = .0555 \times 2250 = 125 \text{ psi.}$$

The excess torque (To) to cause skidding is,

$$To = \frac{To}{dp} \times dp$$

$$To = 3.07 \times 125 = 384 \text{ lb-ft.}$$

This excess torque (To) will cause the braked wheel to decelerate at,

$$\alpha_{max} = \frac{To}{I} = \frac{384}{2.2} = 174.5 \text{ rad./sec}^2.$$

The average wheel deceleration due to slip, during the time the landing gear is oscillating backwards is half the difference between starting wheel deceleration and maximum deceleration. From the design data, at the start of the slip deceleration could be,

$$\alpha = 17.0 \text{ rad./sec}^2.$$

$$\alpha \text{ avg} = \frac{174.5 + 17}{2} = 100.7 \text{ rad./sec}^2.$$

By referring to figure A-12, we can see that at 100 radians/sec^2 the response time of both steps of skid control is much greater than the time of the landing gear oscillation.

For the first step, figure A-12 shows that at α = 100 rad/sec the response time for skid control is,

$$dt = .17 \text{ sec.}$$

and even at α = 174.5 rad/sec^2.

$$dt = .0975 \text{ sec.}$$

For the second step, at $\alpha = 100$ rad./sec^2 the response time for initiating complete brake release is,

$$dt = .34 \text{ sec.}$$

and at $\alpha = 174.5$ rad/sec^2

$$dt = .195 \text{ sec.}$$

There will be no brake release in either step 1 or step 2 caused by landing gear oscillation.

The effect of the landing gear movement relative to the airplane due to drag during braking is studied below.

The maximum relative movement is ±4 inches. Then the angular movement for 12.5" rolling radius is,

$$\theta = \frac{4}{12.5} = .32 \text{ radians}$$

The maximum wheel deceleration for one-quarter period of landing gear oscillation at full deflection is,

$$\alpha = \frac{2\theta}{t^2} = \frac{.64}{\left(\frac{.1111}{4}\right)^2} = 830 \text{ rad/sec}^2.$$

If the brakes were applied rapidly enough to cause full loading of the landing gear at its natural frequency, then there could be a first step brake release at approximately 300 radians/sec.^{2} This is avoided by the metered control of the brake pressure. The valve is set to require an approximate rise time shown in figure A-13. On the 2420 psi pressure rise curve at 1300 psi, dt = .48 sec., when the landing gear has moved back half its full deflection and has reached maximum backward velocity, the deceleration of the braked wheel due to landing gear flexibility will then be about,

$$\alpha = 1/2 \; \frac{2 \times .32}{(.48)^2} = 1.39 \text{ rad./sec.}^2$$

This is extremely small compared to the maximum normal deceleration of α = 17 rad/sec^2 and can cause no false skid signals.

3.7 DRIVE ECCENTRICITY EFFECTS

The effect of eccentricity in the drive to the skid detector is analyzed below in its relationship to the performance of the rate skid control circuit. Eccentricity (dR) is expressed as an increment of the radius (R) of the drive arm connecting the detector shaft to the strap from the braked wheel.

The change of detector wheel speed (dn) due to eccentricity is expressed by the equation:

$$dN = \frac{2N \frac{dR}{R}}{1 - \left(\frac{dR}{R}\right)^2}$$

From this equation, by substituting dE = .1023 N, the variation in voltage (dE) can be expressed,

$$dE = \pm .0246N \frac{\frac{dR}{R}}{1-\left(\frac{dR}{R}\right)^2}$$

The voltage output now must be

$$E' = E \pm dE = .0123N \pm .0246N \frac{\frac{dR}{R}}{1-\left(\frac{dR}{R}\right)^2}$$

The total variation in voltage is filtered by the R-C circuit. The variation in voltage at the voltage doubler is determined as follows:

$$\frac{de}{dt} = \frac{-E'}{RC} \epsilon^{-t/RC}$$

By substituting for maximum E' and transposing dt, the equation for filtered voltage variation is,

$$de = \frac{dt \cdot N \left[.0123 + .0246 \frac{\frac{dR}{R}}{1 - \frac{dR}{R}^2} \right]}{RC \cdot \varepsilon^{t/RC}}$$

The time (dt) is that time required to make one half cycle of the alternating current supplied by the 6 pole alternator.

$$dt = 1/2 \times \frac{60}{N} \times \frac{1}{6} = \frac{5}{N}$$

and $dt = t$

by substituting for dt,

$$de = \frac{\frac{5}{N} \cdot N \left[.0123 + .0246 \frac{\frac{dR}{R}}{1 - \frac{dR}{R}^2} \right]}{RC \cdot \varepsilon^{t/RC}}$$

$$de = \frac{.0615 + .123 \frac{\frac{dR}{R}}{1 - (\frac{dR}{R})^2}}{RC \cdot \varepsilon^{\frac{5}{N \cdot RC}}}$$

With dR = 0, the voltage variation (de_1) due to the alternating current from the rate circuit alternator is,

$$de_1 = \frac{.0615}{RC \cdot \varepsilon^{\frac{5}{NRC}}}$$

Since the discharge of the voltage in the rate circuit is limited to coming from the capacitors (C4 and C5) in the voltage doubler circuit until skid signal strength is approached, then the RC value is

$$RC = 50 \text{ mfd } X\ 4000 \text{ ohms}$$

$$RC = .2$$

Then by substitution,

$$de_1 = \frac{.0615}{.2 \, \varepsilon^{\frac{5}{N.2}}} = \frac{.3075}{\varepsilon^{\frac{25}{N}}}$$

The filtering action of the RC circuit is shown in figure A-14. This curve shows that at speeds above 300 rpm, the voltage variation (de_1) has nearly reached its maximum and stays constant at approximately 0.3 volts.

The effect of eccentricity is such that it will increase the voltage variation at the voltage doubler. If this variation became great enough it could cause the discharge current from the rate capacitor (C_6), through the transistor (TR_2), to be sufficient to cause a continuous skid signal. To set the voltage variation allowable, we must give consideration to the voltage change required to pull in step 1 skid control. Laboratory tests have established this value must be at least 1.3 volts. To provide adequate safety against malfunction due to eccentricity, let

$$de_{max} = 1/3 \times 1.3 = .41 \text{ volts.}$$

To accomplish this, the voltage variation (de_2), due to eccentricity shall not exceed,

$$de_2 = .41 - .3075 = .1025 \text{ volts.}$$

$$de_2 = de_{max} - de_1$$

The equation for de_2 is obtained by subtracting de_1 from the equation derived for de shown above i.e.,

$$de_2 = \frac{.123 \dfrac{\frac{dR}{R}}{1 - (\frac{dR}{R})^2}}{RC \cdot \varepsilon \frac{5}{N \cdot RC}}$$

also

$$de_2 = 2\, de_1 \frac{\frac{dR}{R}}{1 - (\frac{dR}{R})^2}$$

Then to determine the amount of eccentricity allowable, transpose;

$$\frac{\frac{dR}{R}}{1 - (\frac{dR}{R})^2} = \frac{de_2}{2\, de_1} = \frac{.1025}{2 \times .3075} = .167$$

Solving for $\frac{dR}{R}$

$$6 \frac{dR}{R} = 1 - (\frac{dR}{R})^2$$

$$(\frac{dR}{R} - .163)\ (\frac{dR}{R} + 6.163) = 0$$

$$\frac{dR}{R} = .163$$

The amount of eccentricity for a one inch radius drive arm could be 0.163 inch, but this is more than would be necessary for even loose machine tolerance. Good shop practice could easily keep the eccentricity at one-fourth the above value, so eccentricity will cause no problem of malfunction within the electrical system.

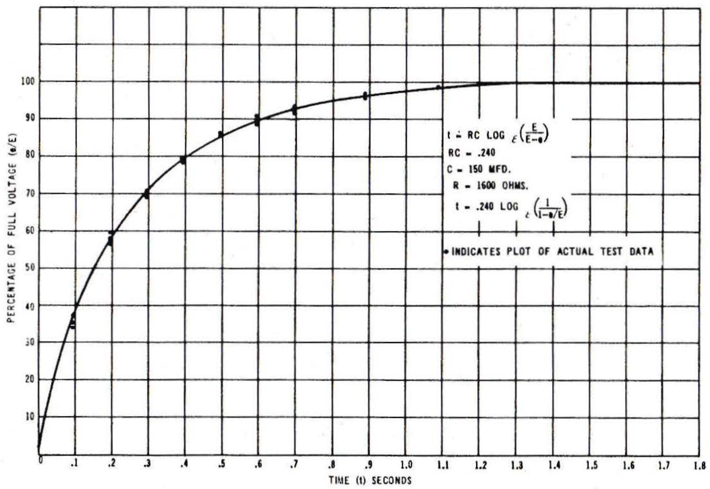

Figure A-15 Rise Time Characteristics of Voltage Doubler and Rate Circuits

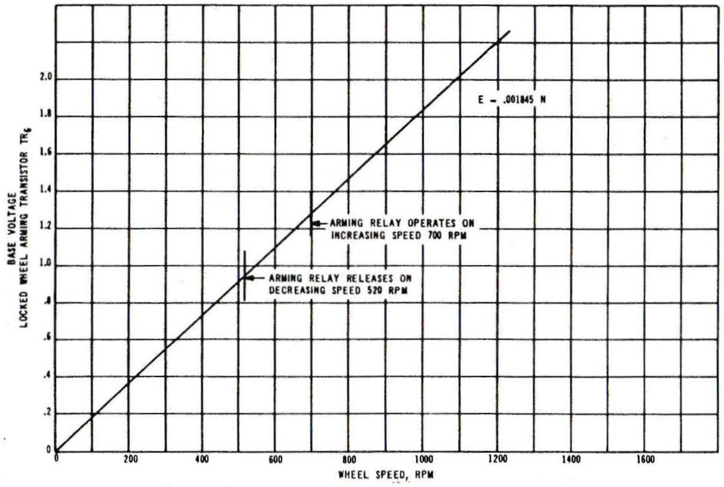

Figure A-16 Voltage Applied to Base of Locked Wheel Arming Transistor TR6

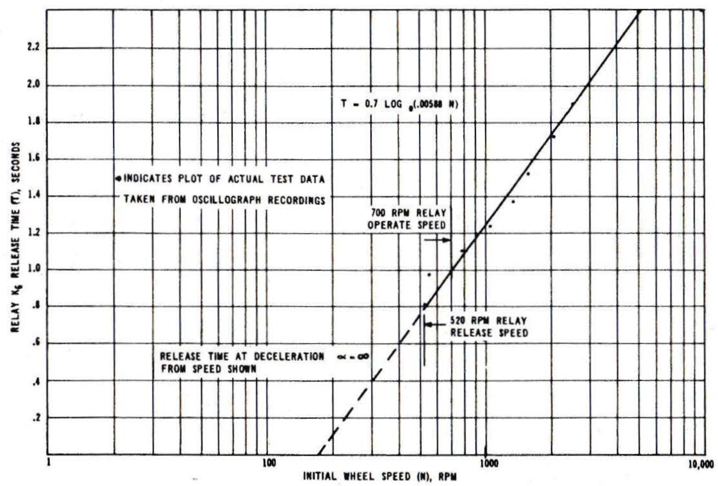

Figure A-17 Time Delay of Locked Wheel Arming Relay at Various Wheel Speeds

3.8 SKID SIGNAL TIME VS WHEEL SPEED

The length of skid signal time compared with wheel speed at the start of the signal is shown in figure A-8. This gives the length of time a step 1 signal will continue if the wheel has stopped rotating and is not restored to rotation before the skid signal ends. There are two equations that express this time in relation to wheel speed.

For low speed up to approximately 600 RPM, the first step skid control signal time can last as long as

$$t = 0.707 \log_{\mathcal{E}} \; 0.00456N$$

which gives a maximum time of about one second.

For wheel speed above 600 RPM, the first step skid control signal can last as long as

$$t = 0.56 \log_{\mathcal{E}} \; 0.00456N$$

At 2100 RPM, the skid signal time will last for longer than 1.6 seconds if the wheel has not been restored to rotation.

At the end of the skid signals, brake release is continued through action of the locked wheel control circuit if wheel rotation has not been restored. (The development of the basic equations is made in paragraph 3.2. The curves shown in figure A-8 are closely substantiated by test data.)

3.9 VOLTAGE RISE DURING ACCELERATION

Voltage rise during acceleration is shown in figure A-15. From actual voltage rise data for various speeds, it was determined that the time to come from zero to 95% of full voltage was less than one second for all speeds. The equation for the rise time can be developed as follows:

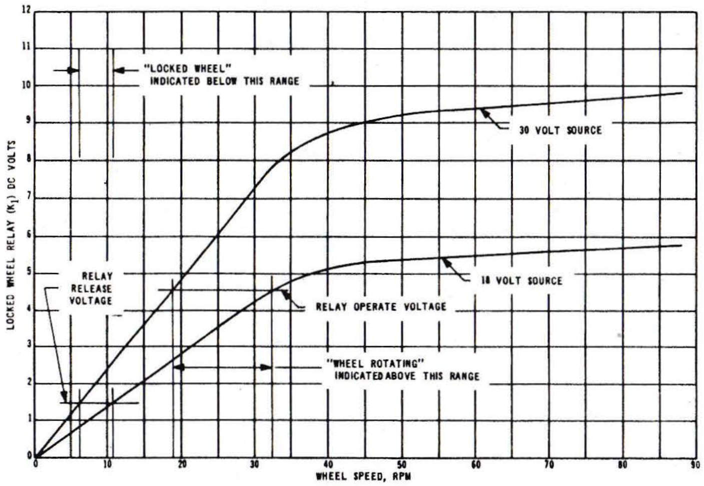

Figure A-18 Locked Wheel Sensing Circuit Characteristics

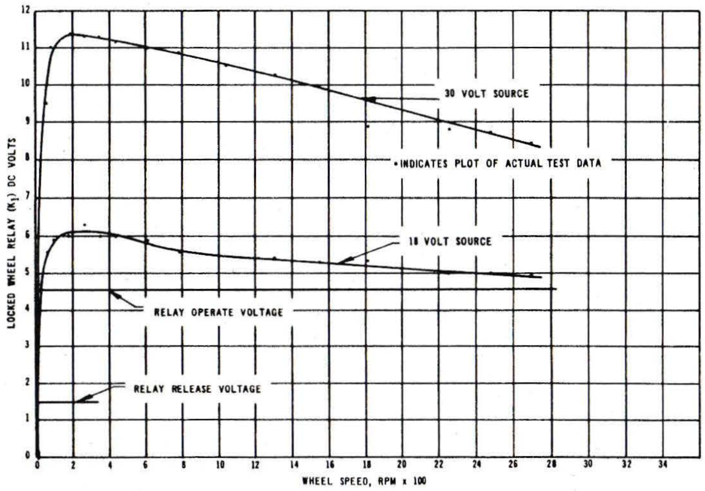

Figure A-19 Voltage Applied to Locked Wheel Relay K1

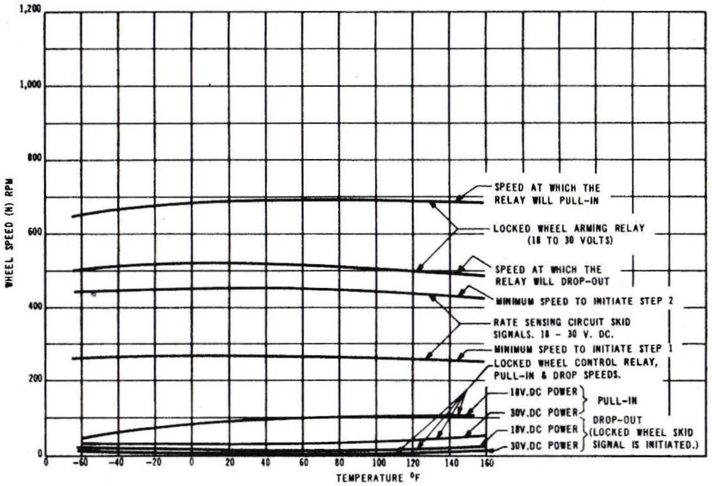

Figure A-20 Effect of Temperature on Skid Control Performance

Let e = instantaneous voltage

E = final voltage

$e' = E - e$

Then $e' = E\,\varepsilon^{-t/RC}$

$$\varepsilon^{-t/RC} = \frac{E}{e'}$$

$$t = RC \log_{\varepsilon} \frac{E}{e'} = RC \log_{\varepsilon} \frac{E}{E - e}$$

$$t = RC \log_{\varepsilon} \left(\frac{1}{1 - e/E} \right)$$

By plotting of data, the value of RC was determined using T = RC when e = 63.2% E

$RC = 0.24$

Since $C \doteq 150$ mfd

Then $R = 1600$ ohms

and $t = 0.24 \log_{\varepsilon} \cdot \left(\frac{1}{1 - e/E} \right)$

Thus the voltage rise time characteristic is sufficiently short to allow the rate circuit voltage to be nearly porportional to wheel speed very soon after the wheel has accelerated to full speed.

3.10 LOCKED WHEEL CONTROL

3.10.1. Locked Wheel Arming Relay

Speed required to actuate relay = 700 RPM
Speed relay releases = 520 RPM
Arming is accomplished in flight before touchdown by the oleo switches.

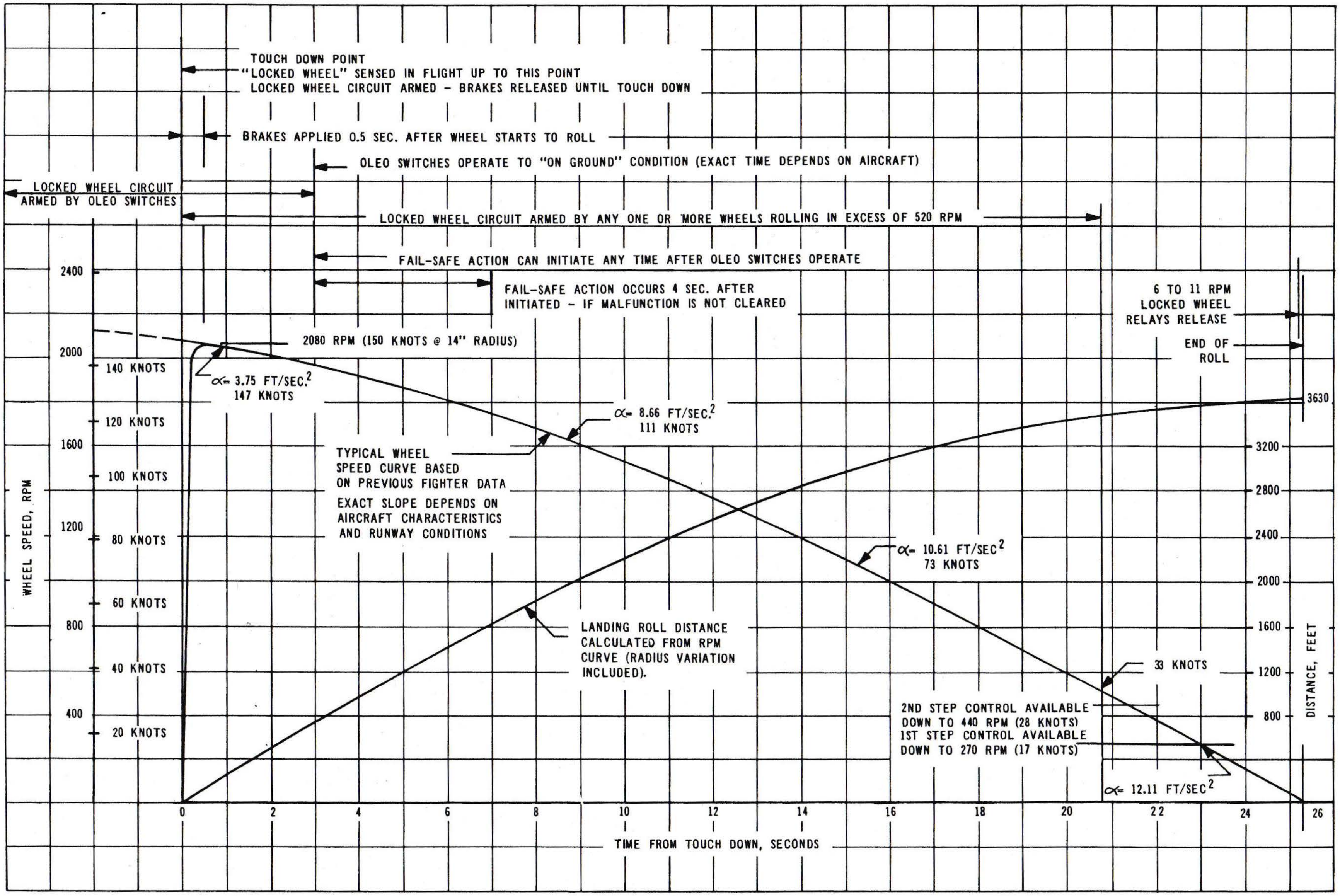

Figure A-21 Skid Control System Sequence of Events

Release time delay at $\alpha = \infty$ ranges from 0.8 seconds to 1.7 seconds as shown in figure A-16.

Since its time delay is based on the discharge of an RC circuit, the basic equation can be developed as described in paragraph 2.8. Actual test data shows that

$$t = 0.7 \log_{\varepsilon} (0.00588N)$$

This represents the time available for control if all wheels lock simultaneously.

This relay is actuated through transistor TR6 from the rate voltage doubler circuit. The characteristics of the transistor base voltage are shown by figure A-17. Since this is a linear voltage-speed curve, no points of marginal operation are encountered. The voltage is expressed by:

$$E = 0.001845N$$

3.10.2 Locked Wheel Sensing Relay (see figure A-18)

Speed to actuate relay = 19 to 32 RPM
Speed to release relay = 6 to 11 RPM

Voltage applied to the relay over the full wheel speed range is shown in figure A-19. The voltage to the relay comes to a maximum value at about 200 RPM and remains adequate to hold the relay in throughout the speed range.

3.11 TEMPERATURE EFFECTS

Effects of temperature are shown by figure A-20. The variations determined in test were so small that no measurable effect on performance was encountered.

3.12 PERFORMANCE SUMMARY

The sequence of events in skid control performance during a landing roll is shown in figure A-21.

Study of this figure shows that there is first step incipient skid protection from touchdown to about 17 knots or to less than 2.5 seconds before the airplane stops.

Second step incipient skid control extends down to about 28 knots and locked wheel control down to about 33 knots.

This can be approximately 4.5 seconds before the airplane is stopped and within 150 feet of the stopping point. Second step control continues until within 120 feet of the stopping point and first step control until within about 50 feet of the stopping point.

The locked wheel control relays do not drop out to give a brake release until the wheel speed has dropped to less than 11 RPM. This allows the airplane to be completely stopped before a malfunction of the locked wheel arming system could permit undesirable brake release. At this point, if there is a malfunction of the skid control system, the skid control system can be switched off to instantly restore braking.

False brake release caused by flexibility of the landing gear is prevented by the metered control of brake pressure in the skid control valve. The landing gear, oscillating at 9 cps will have a half-cycle time of 0.0555 second while the skid control system is designed to give a complete brake release in not less than 0.06 seconds under the worst wheel deceleration conditions. This condition is further improved by the metered control of brake pressure which will prevent excessive wheel deceleration and keep the brake release response time in the range of 0.3 to 0.5 seconds. Thus the skid control system avoids increasing the amplitude of landing gear oscillation.

All the values of the system characteristics pertinent to the skid control system are tabulated in the pages following.

SECTION 4

SYSTEM CHARACTERISTICS

Characteristics	Value	Symbol	Formula	Reference Paragraph	Reference Figure
Airplane Speed	150 knots max. ground speed 20 knots min. skid control speed	V		2.7	A-1
Wheel Speed	2080 RPM max. 320 RPM min. skid control	N	N = 13.86V N = 16.0 V	2.7 2.7	A-1
Tire Rolling Radius	At touchdown = 14 in (or 1.166 ft) At rest = 12.5 in (or 1.041 ft)	--		2.7	A-1
Landing Gear Natural	9.0 cps, Period = 0.111 sec. 1/2 Period = 0.0555 sec.	--		2.8	
Wheel Mass Moment of Inertia	2.2 slug-ft^2	I		2.7	
Ground Coefficient of Friction	0.55 (max. steady state condition)	u		2.8	
Airplane Deceleration	17.7 ft/sec^2 max.	a	a = ug	2.8	
Wheel Deceleration	17.0 rad/sec^2 max. without incipient skid	α	$\alpha = a/R$	2.8	
DC Voltage Output	26 volts at max. wheel speed	E	E = 0.0123N	2.8	A-3 A-7
Voltage at Rate Capacitor vs Load Resistance	E_C = 0.0123N with 4000 ohms load resistance. The relationship of E_C to N was held regardless of capacitance change in doubler and rate circuit. (50 to 400 mfd)		$E_C/N = 0.000272\,(R3)^{.46}$	2.8	A-4

SYSTEM CHARACTERISTICS (Continued)

Characteristics	Value	Symbol	Formula	Reference Paragraph	Reference Figure
Skid Signal Voltage vs rate of voltage change	0.7 volt, 1st step signal strength 0.9 volt, 2nd step signal strength	E_R	$E_R = K_1(de/_{dt})^{.41}$ $[K_1 = 3.6 \text{ to } 4.0]$	2.8	A-5
To determine optimum values for load resistance and total capacitance in the rate sensing circuit.			Nomograph		A-6
Rate Sensing Circuit Voltage vs Wheel Speed	R3 = 4000 ohms	E_C	$E_C = 0.0123N$	3.1	A-7
Skid Signal Time vs wheel speed at start of signal	t = 1.70 sec when stopping wheel from 2080 RPM t = 0.35 sec when stopping wheel from 320 RPM	t	$t = 0.56 \log_{\varepsilon} 0.000456N$ $t = 0.707 \log_{\varepsilon} 0.000456N$	3.2	A-8
Skid signal Voltage (E_R) vs wheel speed (N) with $\alpha = \infty$	270 RPM E_R = 0.7 volt, 1st step signal min. speed. Provides skid control below 20 knots. 440 RPM E_R = 0.9 volt, 2nd step signal min. speed. Provides skid control below 30 knots.	E_R	$E_R = 0.043(N)^{.5}$ for $\alpha = \infty$	3.3	A-9
Skid Signal strength vs Deceleration	31 rad/sec^2, 1st step sensistivity good 60 rad/sec^2, 2nd step good signal above max. non-skid condition	E_R	$E_R = 0.174 (\alpha)^{.41}$	3.4 3.4	A-10 A-10
Response Time Step 1 at $\alpha = \infty$ (Min. possible without metered brake control)	0.015 to 0.20 sec over speed range.	dt	$dt = \frac{-deRC}{E} \varepsilon^{dt/RC}$	3.5	A-11

SYSTEM CHARACTERISTICS (Continued)

Characteristics	Value	Symbol	Formula	Reference Paragraph	Reference Figure
Response Time Step 2 at $\alpha = \infty$	0.055 to 0.21 sec over speed range	dt	$dt = \frac{-deRC}{E} \quad \varepsilon^{dt/RC}$	3.5	A-11
Step 1 Response Time relative to Deceleration rate	0.56 to 0.017 sec over 30 to 1000 rad/sec^2 range	dt	$dt = 17/\alpha$	3.5	A-12
Step 2 Response Time relative to Deceleration rate	0.56 to 0.055 sec over 60 to 1000 rad/sec^2 range	dt	$dt = 34/\alpha$	3.5	A-12
Maximum brake press. rise time rate	2250 psi/sec max.	dp/dt		3.6	A-13
Maximum wheel Deceleration at maximum pressure rise during 1/2 cycle of landing gear frequency.	174.5 rad/sec^2	α	$\alpha_{max} = \frac{To\ max}{I}$	3.6	
Average wheel deceleration at maximum pressure rise during 1/2 cycle of landing gear frequency.	100.7 rad/sec^2		$\alpha_{av} = \frac{\alpha\ max + 17}{2}$	3.6	
Effect of landing gear natural frequency.	No release in Step 1 or Step 2			3.6	A-12
Wheel deceleration due to landing gear displacement at natural frequency.	300 rad/sec^2 Just at step 1 release and well above step 2 release			3.6	A-12

SYSTEM CHARACTERISTICS (Continued)

Characteristics	Value	Symbol	Formula	Reference Paragraph	Reference Figure
Wheel deceleration and effect of landing gear displacement during controlled pressure rise	1.39 rad/sec^2 No release in Step 1 or Step 2			3.6	A-12
Change of detector speed due to drive eccentricity.		dn	$dn = \frac{2N \frac{dR}{R}}{1 - \left(\frac{dR}{R}\right)^2}$	3.7	A-14
Change of generated voltage due to eccentricity.	0.3	de	$de = \pm 0.0246N \frac{\frac{dR}{R}}{1 + \frac{dR}{R}}$	3.7	A-14
Allowable eccentricity	dR/R = 0.163	dR/R		3.7	A-14
Dwell time of 1st step skid signal up to 600 RPM.	1 sec approximately max.	t	$t = 0.707 \log_{\varepsilon} 0.00456N$	3.8	A-8
Dwell time of 1st step skid signal at over 600 RPM.	Over 1.6 sec at 2100 RPM.	t	$t = 0.56 \log_{\varepsilon} 0.00456N$	3.8	A-8
Voltage rise time during acceleration	0.5 sec to 85% full voltage. 1.0 sec to 97.5% full voltage.	t	$t = 0.24 \log_{\varepsilon} \left(\frac{1}{1 - e/E}\right)$		A-15

SYSTEM CHARACTERISTICS (Continued)

Characteristics	Value	Symbol	Formula	Reference Paragraph	Reference Figure
Locked wheel arming.					
Relay pull-in wheel speed.	Armed at over 700 RPM			3.10	A-16
Relay drop-out wheel speed.	Unarmed under 520 RPM			3.10	A-16
	Armed in flight			3.10	A-16
Locked wheel arming release, time delay	0.8 to 1.75 sec over landing speed range	t	$t = 0.7 \log_{\epsilon} (0.00588N)$	3.10	A-17
Locked wheel sensing	Rotation sensed at speeds over 19-32 RPM			3.10	A-18
	Locked wheel sensed at speeds under 6-11 RPM			3.10	A-18
Locked wheel relay voltage				3.10	A-19
Effects of temperature	No measurable effects to the control of skids			3.11	A-20

SECTION 5

FAIL-SAFE ANALYSIS OF ELECTRICAL SYSTEM

Operation of the fail-safe circuitry (see figure 6) of the skid control system is as follows: When relays K2 or K3 are operated, the line voltage is applied to transistor TR5 through diode CR11 and resistor R9 or diode CR7 and resistor R10. The voltage level at the collector terminal of transistor TR5 is held very constant by the Zener diode Z1. Upon application of this voltage, resistor R11 starts to charge capacitor C8. When C8 has been charged to a level sufficient to cause TR5 to conduct, relay K4 is operated. Once K4 has been operated, it is held in the operated position by resistor R12. Thus any continuous brake release signal of more than 4 seconds will cause power to be removed from the control circuit and automatically restores manual braking. After the cause of failure has been removed, relay K4 can be restored to its normal unenergized position by opening and closing the pilot's switch.

The effects of failure of the individual electrical and electro-mechanical components of the system are tabulated below.

Component	Condition of Failure	Effect on System	Effect on Braking
Rotation Generator	Shorted	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.
Rotation Generator	Open	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.
TR1	Shorted	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.
TR1	Open	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.

Component	Condition of Failure	Effect on System	Effect on Braking
R1	Shorted	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.
R1	Open	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.
C1	Open	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.
C1	Shorted	Locked wheel operation with increased sensitivity.	Skid control available.
B1	Any diode shorted	Locked wheel operation with reduced sensitivity.	Skid control available.
B1	Any diode open	Locked wheel operation with reduced sensitivity.	Skid control available.
C2	Shorted	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.
C2	Open	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.

Component	Condition of Failure	Effect on System	Effect on Braking
K1	Shorted coil	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.
K1	Open coil	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.
K1	N.C. contacts welded	Fail-safe circuit operates after oleo switch actuates to "on ground". Brake is released on associated wheel until fail-safe occurs.	Manual braking available.
R2	Shorted	Reduced time delay for locked wheel recovery.	Skid control available.
R2	Open	Reduced time delay for locked wheel recovery.	Skid control available.
C3	Shorted	Fail-safe circuit will operate.	Manual braking available.
C3	Open	Reduced time delay for locked wheel recovery.	Skid control available.
CR4	Shorted	Step one signal can operate step two.	Skid control available.
CR4	Open	Step one will not operate on locked wheel signal.	Skid control available.
CR5	Shorted	Step two signal can operate step one.	Skid control available.
CR5	Open	Step two will not operate on locked wheel signal.	Skid control available.

Component	Condition of Failure	Effect on System	Effect on Braking
CR12	Shorted	One short duration brake release on associated wheel then reduced sensitivity.	Skid control available.
CR12	Open	TR6 base voltage will be supplied by other wheel or wheels.	Skid control available.
R18	Shorted	No effect on system.	Skid control available.
R18	Open	Locked wheel control not available after oleo switches actuates to "on ground" condition.	Skid control available.
TR6	Shorted	Locked wheel brake release occurs after stop. Fail-safe circuit will restore brakes for parking.	Skid control available.
TR6	Open	Locked wheel control not available after oleo switches actuate to "on ground" condition.	Skid control available.
C10	Shorted	Arming circuit time delay and sensitivity reduced.	Skid control available.
C10	Open	Arming circuit time delay reduced.	Skid control available.
R19	Shorted	Arming circuit time delay reduced.	Skid control available.
R19	Open	Arming circuit time delay reduced.	Skid control available.
K6	Coil shorted.	Locked wheel circuit unarmed after oleo switch actuates to "on ground" position.	Skid control available.
K6	Coil open	Locked wheel circuit unarmed after oleo switch actuates to "on ground" position.	Skid control available.
K6	N.O. contacts welded	Brake release after stop. Fail-safe circuit will restore brakes for parking.	Skid control available.
R20	Shorted	Increased sensitivity of arming circuit.	Skid control available.

Component	Condition of Failure	Effect on System	Effect on Braking
R20	Open	Locked wheel circuit unarmed after oleo switch actuates to "on ground" position.	Skid control available.
CR8	Shorted	Prevents fail-safe circuit operation while K6 relay is energized.	Skid control available.
CR8	Shorted	No effect after K6 relay is de-energized.	Skid control available.
CR8	Open	K2 and K3 relay not operated in flight. No brake release before touch down, normal after touch down.	Skid control available.
CR9	Shorted	Reduces fail-safe circuit time delay.	Skid control available.
CR9	Open	Fail-safe circuit will operate in flight.	Manual braking available.
CR10	Shorted	Circuit normal except no protection against reversed aircraft polarity.	Skid control available.
CR10	Open	Circuit inoperative.	Manual braking available.
R16	Shorted	Fail-safe circuit inoperative but circuit breaker will trip if fail-safe action is called for.	Skid control available.
R16	Open	K5 inoperative and skid control inoperative.	Manual braking available.
K5	Coil shorted	Skid control inoperative.	Manual braking available.
K5	Coil open	Skid control inoperative.	Manual braking available.
K5	Contacts welded	Fail-safe circuit inoperative. Manual switch off is required if malfunction is suspected.	Skid control available.

Component	Condition of Failure	Effect on System	Effect on Braking
Rate Generator	Shorted	One brake release if failure occurs while operating. No brake release if failure occurs before operation.	Manual braking available.
Rate Generator	Open	One brake release if failure occurs while operating. No brake release if failure occurs before operation.	Manual braking available.
CR1 or CR2	Shorted	One brake release then sensitivity reduced to approximately 50%.	Skid control available.
CR1 or CR2	Open	One brake release then sensitivity reduced to approximately 50%.	Skid control available.
C4 or C5	Shorted	One brake release then sensitivity reduced to approximately 50%.	Skid control available.
C4 or C5	Open	One brake release then sensitivity reduced to approximately 50%.	Skid control available.
R3	Shorted	One brake release, then control circuit becomes inoperative.	Manual braking available.
R3	Open	No brake release and circuit inoperative.	Manual braking available.
CR3	Shorted	No brake release and circuit inoperative.	Manual braking available.
CR3	Open	Circuit operative approximately 50% sensitivity.	Skid control available.
R15	Shorted	No brake release. Circuit becomes inoperative.	Manual braking available.
R5	Open	Circuit operative, sensitivity increased by approximately 20%.	Skid control available.
R4	Shorted	Circuit operative, will function normally.	Skid control available.
R4	Open	Circuit inoperative.	Manual braking available.

Component	Condition of Failure	Effect on System	Effect on Braking
TR2	Shorted	Fail-safe circuit will operate.	Manual braking available.
TR2	Open	Circuit inoperative.	Manual braking available.
R5	Shorted	Circuit inoperative.	Manual braking available.
R5	Open	Circuit operative. Sensitivity increased.	Skid control available.
TR3	Shorted	Fail-safe circuit will operate.	Manual braking available.
TR3	Open	Circuit inoperative.	Manual braking available.
R6	Shorted	1st step normal, no 2nd step.	Skid control available.
R6	Open	1st step insensitive, 2nd step more sensitive.	Skid control available.
K2	Shorted Coil	1st step inoperative, 2nd step can operate.	Manual braking available.
K2	Open Coil	1st step inoperative, 2nd step can operate.	Manual braking available.
K2	Contacts welded	Fail-safe will operate.	Manual braking available.
C9	Shorted	1st step inoperative. 2nd step operative.	Manual braking available.
C9	Open	Circuit operative.	Skid control available.
R8	Shorted	2nd step more sensitive.	Skid control available.
R8	Open	2nd step inoperative.	Skid control available.
C7	Shorted	2nd step inoperative.	Skid control available.
C7	Open	2nd step more sensitive.	Skid control available.
TR4	Shorted	Fail-safe relay will operate.	Manual braking available.
TR4	Open	2nd step inoperative.	Skid control available.
K3	Shorted coil	2nd step inoperative.	Skid control available.
K3	Open coil	2nd step inoperative.	Skid control available.
K3	Contacts welded	Fail-safe relay will operate.	Manual braking available.

Component	Condition of Failure	Effect on System	Effect on Braking
CR7 Left or Right	Shorted	No effect on circuit unless both shorted.	Skid control available.
CR7 Left or Right	Open	K1 relay will not operate fail-safe relay.	Skid control available.
CR11 Left or Right	Shorted	K1 relay will not operate fail-safe relay.	Skid control available.
CR11 Left or Right	Open	K2 relay will not operate fail-safe relay.	Skid control available.
R10 Left or Right	Shorted	Will overload Zener diode. Will not cause malfunction of fail-safe circuit except to shorten time constant.	Skid control available.
R10 Left or Right	Open	K1 relay will not operate fail-safe circuit.	Skid control available.
R9 Left or Right	Shorted	Will overload Zener diode. Will not cause malfunction of fail-safe circuit except to shorten time constant.	Skid control available.
R9 Left or Right	Open	K2 relay will not operate fail-safe relay.	Skid control available.
Z1 Left or Right	Shorted	Fail-safe relay will not operate.	Skid control available.
Z1 Left or Right	Open	Will shorten time constant, but fail-safe relay can operate.	Skid control available.
R11 Left or Right	Shorted	Fail-safe relay will operate rapidly.	Manual braking available.
R11 Left or Right	Open	Fail-safe relay will not operate.	Skid control available.

Component	Condition of Failure	Effect on System	Effect on Braking
C8 Left or Right	Shorted	Fail-safe relay will not operate.	Skid control available.
C8 Left or Right	Open	Fail-safe relay will operate rapidly.	Manual braking available.
TR5	Shorted	Fail-safe relay will operate rapidly.	Manual braking available.
TR5	Open	Fail-safe relay will not operate.	Skid control available.
K4	Shorted coil	Fail-safe relay will not operate.	Skid control available.
K4	Open coil	Fail-safe relay will not operate.	Skid control available.
R12	Shorted	Will not affect circuit.	Skid control available.
R12	Open	Fail-safe relay will not latch.	Skid control available.
1st Step Solenoid	Shorted	May weld K1 contacts. Will open circuit breaker.	Manual braking available.
1st Step Solenoid	Open	No first step action.	Manual braking available.
2nd Step Solenoid	Shorted	May weld K2 contacts. Will open circuit breaker.	Manual braking available.
2nd Step Solenoid	Open	No second step action.	Skid control available.