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MALTON - ONTARIO

TECHNICAL DEPARTMENT (Aircraft)

AIRCRAFT:

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ARROW 1
DIGITAL COMPUTATION AND ANALYSIS
OF ARROW LATERAL RESPONSE IN
EMERGENCY MODE

PREPARED BY M.V. Jenkins

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AVRO AIRCRAFT LIMITED
MALTON - ONTARIO

TECHNICAL DEPARTMENT

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SHEET NO. 1

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ARROW

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AVRO AIRCRAFT LIMITED MALTON - ONTARIO TECHNICAL DEPARTMENT		REPORT NO. <u>71/Stab/16</u> SHEET NO. <u>2</u>	
AIRCRAFT <u>ARROW</u>		PREPARED BY: M.V. Jenkins	DATE: Jan. /58.
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INTRODUCTION

This report is simply a record of the derivation of the equations which may be used relevant to response with Emergency Mode Lateral Damping.

A far more complete introduction to the step by step time solution of response and method of analysis of flight test records of response is given in reference 1.

NOTATION

As used in reference 1.

REFERENCE

1. Digital Computation of Response using an approximation to Lateral Damper System.

71/Stab/9

M.V. Jenkins

(Relevant to Normal Mode Lateral Damping)

$$-\beta \frac{C_{Y\beta}}{2\gamma} - p \frac{C_{Yp}}{4\mu_2} - r \frac{C_{Yr}}{4\mu_2} + \frac{a_y}{V} - \frac{\bar{X}\dot{r}}{V} + \frac{\bar{Z}\dot{p}}{V} = \frac{C_{Y\delta a}}{2\gamma} \delta a + \frac{C_{Y\delta r}}{2\gamma} \delta r$$

$$-\beta \frac{C_{L\beta}}{L_x} - p \frac{C_{Lp}}{L_x} \frac{b}{2V} - r \frac{C_{Lr}}{L_x} \frac{b}{2V} - pq \frac{K_{xz}}{K_x^2}$$

$$+ \dot{p} - \dot{r} \frac{K_{xz}}{K_x^2} + r q \frac{K_z^2 - K_y^2}{K_x^2} = \frac{C_{L\delta a}}{L_x} \delta a + \frac{C_{L\delta r}}{L_x} \delta r$$

$$-\beta \frac{C_{N\beta}}{L_z} - p \frac{C_{Np}}{L_z} \frac{b}{2V} - r \frac{C_{Nr}}{L_z} \frac{b}{2V} + pq \frac{K_y^2 - K_z^2}{K_z^2}$$

$$- \dot{p} \frac{K_{xz}}{K_z^2} + r q \frac{K_{xz}}{K_z^2} + \dot{r} = \frac{C_{N\delta a}}{L_z} \delta a + \frac{C_{N\delta r}}{L_z} \delta r$$

$$\delta r = K_6 \delta a + K_7 r - .061 K_7 p + K_8 a_y + K_{10} P_e$$

$$\begin{aligned} \frac{C_{Y\delta r}}{2\gamma} \delta r &= \frac{C_{Y\delta r} \cdot K_6 \delta a}{2\gamma} + \frac{C_{Y\delta r} \cdot K_7 r}{2\gamma} - \frac{.061 C_{Y\delta r} \cdot K_7 p}{2\gamma} \\ &\quad + \frac{C_{Y\delta r} \cdot K_8 a_y}{2\gamma} + K_{10} P_e \end{aligned}$$

$$\text{LET } K_6 C_{Y\delta r} = \Delta C_{Y\delta a} : K_7 C_{Y\delta r} \cdot \frac{2V}{b} = \Delta C_{Yr}$$

$$-.061 K_7 C_{Y\delta r} \cdot \frac{2V}{b} = \Delta C_{Yp} : K_8 C_{Y\delta r} = C_{Ya_y}$$

CONTINUED -----

--- CONTINUATION

$$\begin{aligned}\therefore \frac{C_{y_{\delta r}} \cdot \delta r}{2T} &= \frac{\Delta C_{y_{\delta a}}}{2T} + \frac{\Delta C_{y_r} \cdot \frac{b}{2V}}{2T} + \frac{\Delta C_{y_p} \cdot \frac{b}{2V}}{2T} \\ &\quad + \frac{C_{y_{ay}}}{2T} + \frac{K_{10} P_e \cdot C_{y_{\delta r}}}{2T} \\ &= \frac{\Delta C_{y_{\delta a}}}{2T} + \frac{\Delta C_{y_r}}{4\mu_2} + \frac{\Delta C_{y_p}}{4\mu_2} + \frac{C_{y_{ay}}}{2T} + \frac{K_{10} P_e C_{y_{\delta r}}}{2T}\end{aligned}$$

$$\begin{aligned}\frac{Cl_{\delta r} \cdot \delta r}{l_x} &= \frac{Cl_{\delta r} \cdot K_6 \delta a}{l_x} + \frac{Cl_{\delta r} \cdot K_7 \cdot r}{l_x} - \frac{.061 Cl_{\delta r} \cdot K_7 \cdot p}{l_x} \\ &\quad + \frac{Cl_{\delta r} \cdot K_8 \cdot a_r}{l_x} + \frac{Cl_{\delta r} \cdot K_{10} \cdot P_e}{l_x}\end{aligned}$$

$$\text{LET } K_6 Cl_{\delta r} = \Delta Cl_{\delta a} : K_7 \cdot \frac{2V}{b} \cdot Cl_{\delta r} = \Delta_1 Cl_r$$

$$-.061 K_7 \cdot \frac{2V}{b} \cdot Cl_{\delta r} = \Delta_1 Cl_p : K_8 Cl_{\delta r} = Cl_{a_r}$$

$$\begin{aligned}\therefore \frac{Cl_{\delta r} \cdot \delta r}{l_x} &= \frac{\Delta Cl_{\delta a} \cdot \delta a}{l_x} + \frac{\Delta_1 Cl_r \cdot \frac{b}{2V} \cdot r}{l_x} + \frac{\Delta_1 Cl_p \cdot \frac{b}{2V} \cdot p}{l_x} \\ &\quad + \frac{Cl_{a_r} \cdot a_r}{l_x} + \frac{Cl_{\delta r} \cdot K_{10} \cdot P_e}{l_x}\end{aligned}$$

CONTINUED

--- CONTINUATION

SIMILARLY :

$$\text{LET } K_6 C_{n_{\delta r}} = \Delta C_{n_{\delta a}} \quad ; \quad K_7 \frac{2V}{b} \cdot C_{n_{\delta r}} = \Delta C_{n_r}$$

$$- .061 K_7 \cdot \frac{2V}{b} \cdot C_{n_{\delta r}} = \Delta C_{n_p} \quad ; \quad K_8 C_{n_{\delta r}} = C_{n_{a_1}}$$

$$\therefore \frac{C_{n_{\delta r}} \cdot \delta r}{I_z} = \frac{\Delta C_{n_{\delta a}} \cdot \delta a}{I_z} + \frac{\Delta C_{n_r} \cdot b \cdot r}{I_z \cdot 2V} + \frac{\Delta C_{n_p} \cdot b \cdot p}{I_z \cdot 2V}$$

$$+ \frac{C_{n_{a_1}} \cdot a_1}{I_z} + \frac{C_{n_{\delta r}} \cdot K_{10} P_e}{I_z}$$

$$\text{LET } C_{Y_{\delta a}} + \Delta C_{Y_{\delta a}} = C_{Y'_{\delta a}}$$

$$C_{Y_r} + \Delta C_{Y_r} = C_{Y'_r}$$

$$C_{Y_p} + \Delta C_{Y_p} = C_{Y'_p}$$

$$C_{l_{\delta a}} + \Delta C_{l_{\delta a}} = C_{l'_{\delta a}}$$

$$C_{l_r} + \Delta C_{l_r} = C_{l'_r}$$

$$C_{l_p} + \Delta C_{l_p} = C_{l'_p}$$

$$C_{n_{\delta a}} + \Delta C_{n_{\delta a}} = C_{n'_{\delta a}}$$

$$C_{n_r} + \Delta C_{n_r} = C_{n'_r}$$

$$C_{n_p} + \Delta C_{n_p} = C_{n'_p}$$

AS A CONSEQUENCE THE EQUATIONS OF MOTION

ON PAGE 3 NOW BECOME

CONTINUED --

$$-\beta \frac{C_{y\beta}}{2T} - p \frac{C_{yP}}{4\mu_2} - r \frac{C_{yT}}{4\mu_2} + a_v \left(\frac{1}{V} - \frac{C_{yay}}{2T} \right)$$

$$-\frac{\bar{X}\dot{r}}{V} + \frac{\bar{Z}\dot{p}}{V}$$

$$= \frac{C_{y\delta a} \cdot \delta a}{2T} + \frac{C_{y\delta r} \cdot K_{10} P_e}{2T}$$

$$-\beta \frac{Cl_{\beta}}{l_x} - p \frac{Cl'_{\beta} \cdot b}{l_x \cdot 2V} - r \frac{Cl'_{\beta} \cdot b}{l_x \cdot 2V} - \frac{Cl_{ay} \cdot a_v}{l_x}$$

$$+ \dot{p} - p q_1 \frac{K_{xz}}{K_x^2} + r q_1 \frac{K_z^2 - K_y^2}{K_x^2} - \dot{r} \frac{K_{xz}}{K_x^2} = \frac{Cl'_{\delta a} \cdot \delta a}{l_x} + \frac{Cl_{\delta r} \cdot K_{10} P_e}{l_x}$$

$$-\beta \frac{C_{n\beta}}{l_z} - p \frac{C_{nP} \cdot b}{l_z \cdot 2V} - r \frac{C_{nT} \cdot b}{l_z \cdot 2V} - \frac{C_{nay} \cdot a_v}{l_z}$$

$$+ p q_1 \frac{K_y^2 - K_x^2}{K_z^2} - \dot{p} \frac{K_{xz}}{K_z^2} + r q_1 \frac{K_{xz}}{K_z^2} + \dot{r} = \frac{C_{n\delta a} \cdot \delta a}{l_z} + \frac{C_{n\delta r} \cdot K_{10} P_e}{l_z}$$

$$\text{LET } F = \left(\frac{1}{V} - \frac{C_{va}}{2\tau} \right)$$

$$-a_v = -\beta \frac{C_{vp}}{2\tau F} - p \frac{C_{vp}'}{4\mu_2 F} - \tau \frac{C_{vt}'}{4\mu_2 F} - \frac{\bar{X}\dot{\tau}}{VF} + \frac{\bar{Z}\dot{p}}{VF}$$

$$- \frac{C_{v\delta a}' \cdot \delta a}{2\tau F} - \frac{C_{v\delta r} \cdot K_{10} \cdot P_e}{2\tau F}$$

$$-C_{va} \cdot a_v = -\beta \frac{C_{va} \cdot C_{vp}}{2\tau F} - p \frac{C_{va} \cdot C_{vp}'}{4\mu_2 F} - \tau \frac{C_{va} \cdot C_{vt}'}{4\mu_2 F}$$

$$- \frac{\dot{\tau} C_{va} \cdot \bar{X}}{VF} + \frac{\dot{p} C_{va} \cdot \bar{Z}}{VF} - \frac{C_{v\delta a}' \cdot C_{va} \cdot \delta a}{2\tau F} - \frac{C_{v\delta r} \cdot C_{va} \cdot K_{10} \cdot P_e}{2\tau F}$$

$$\text{LET } \Delta C_{vp} = \frac{C_{va} \cdot C_{vp}}{2\tau F} : \Delta_2 C_{vp} = \frac{C_{va} \cdot C_{vp}'}{2\tau F} : \Delta_2 C_{vt} = \frac{C_{va} \cdot C_{vt}'}{2\tau F}$$

$$\therefore -\frac{C_{va} \cdot a_v}{2\tau} = -\beta \frac{\Delta C_{vp}}{2\tau} - p \frac{\Delta_2 C_{vp}}{4\mu_2} - \tau \frac{\Delta_2 C_{vt}}{4\mu_2}$$

$$- \frac{\dot{\tau} C_{va} \bar{X}}{2\tau VF} + \frac{\dot{p} C_{va} \bar{Z}}{2\tau VF}$$

$$- \frac{C_{v\delta a}' \cdot C_{va} \delta a}{4\tau^2 F} - \frac{C_{v\delta r} \cdot C_{va} \cdot K_{10} \cdot P_e}{4\tau^2 F}$$

CONTINUED

$$\begin{aligned}
 -a_r \cdot Cl_{a_r} &= -\rho \frac{Cl_{a_r} \cdot C_{\gamma \beta}}{2\gamma F} - p \cdot \frac{Cl_{a_r} \cdot C_{\gamma \rho}}{4\mu_2 F} - \tau \cdot \frac{Cl_{a_r} \cdot C_{\gamma \tau}}{4\mu_2 F} \\
 &\quad - \dot{\tau} \frac{Cl_{a_r} \cdot \bar{X}}{VF} + \dot{p} \frac{Cl_{a_r} \cdot \bar{Z}}{VF} \\
 &\quad - \frac{C_{\gamma \delta a} \cdot Cl_{a_r} \cdot \delta a}{2\gamma F} - \frac{C_{\gamma \delta \tau} \cdot Cl_{a_r} \cdot K_{10} \cdot Pe}{2\gamma F}
 \end{aligned}$$

$$\text{LET } \Delta Cl_{\beta} = \frac{Cl_{a_r} \cdot C_{\gamma \beta}}{2\gamma F} \quad : \Delta_2 Cl_p = \frac{Cl_{a_r} \cdot C_{\gamma \rho}}{2\gamma F}$$

$$\Delta_2 Cl_{\tau} = \frac{Cl_{a_r} \cdot C_{\gamma \tau}}{2\gamma F}$$

$$\begin{aligned}
 -\frac{a_r \cdot Cl_{a_r}}{l_x} &= -\rho \frac{\Delta Cl_{\beta}}{l_x} - p \cdot \frac{\Delta_2 Cl_p}{l_x} \cdot \frac{b}{2v} \\
 &\quad - \tau \frac{\Delta_2 Cl_{\tau} \cdot \frac{b}{2v}}{l_x} - \dot{\tau} \frac{Cl_{a_r} \cdot \bar{X}}{l_x \cdot VF} + \dot{p} \frac{Cl_{a_r} \cdot \bar{Z}}{l_x \cdot VF} \\
 &\quad - \frac{C_{\gamma \delta a} \cdot Cl_{a_r} \cdot \delta a}{2\gamma F l_x} - \frac{C_{\gamma \delta \tau} \cdot Cl_{a_r} \cdot K_{10} \cdot Pe}{2\gamma F l_x}
 \end{aligned}$$

CONTINUED

$$\frac{a_y}{V} = -\frac{\bar{Z}\dot{p}}{V} + \frac{\bar{X}\dot{r}}{V} - p\alpha_1 - \phi \frac{g}{V} \cos \phi_1 \cos \beta_1 \cos \Theta + \beta + r \cos \alpha_1$$

USING THE FOLLOWING NOTATION

$$C_{\bar{y}_\beta} = C_{y_\beta} + \Delta C_{y_\beta}$$

$$C_{\bar{y}_{\delta a}} = C_{y'_{\delta a}}$$

$$Cl_{\bar{\beta}} = Cl_{\beta} + \Delta Cl_{\beta}$$

$$Cl_{\bar{\delta a}} = Cl'_{\delta a}$$

$$C_{\bar{n}_\beta} = C_{n_\beta} + \Delta C_{n_\beta}$$

$$C_{\bar{n}_{\delta a}} = C_{n'_{\delta a}}$$

$$C_{\bar{y}_p} = C_{y'_p} + \Delta_2 C_{y_p}$$

$$Cl_{\bar{p}} = Cl'_p + \Delta_2 Cl_p$$

$$C_{\bar{n}_p} = C_{n'_p} + \Delta_2 C_{n_p}$$

$$C_{\bar{y}_r} = C_{y'_r} + \Delta_2 C_{y_r}$$

$$Cl_{\bar{r}} = Cl'_r + \Delta_2 Cl_r$$

$$C_{\bar{n}_r} = C_{n'_r} + \Delta_2 C_{n_r}$$

THE EQUATIONS NOW BECOME

$$-\beta \frac{C_{Y\beta}}{2T} - p \frac{C_{Yp}}{4\mu_2} - r \frac{C_{Yr}}{4\mu_2} - \dot{r} K_8 \frac{C_{Y\delta r}}{2TVF} + \dot{p} K_8 \frac{C_{Y\delta r}}{2TVF} \bar{Z}$$

$$-p\alpha_1 - \phi \frac{g}{V} \cos \phi_1 \cos \beta_1 \cos \Theta + \dot{\beta} + r \cos \alpha_1$$

$$= \delta a \cdot \frac{C_{Y\delta a}}{2T} \left[1 + \frac{K_8 C_{Y\delta r}}{2TVF} \right] + K_{10} P_e \frac{C_{Y\delta r}}{2T} \left[1 + \frac{K_8 C_{Y\delta r}}{2TVF} \right]$$

$$-\beta \frac{Cl_{\beta}}{l_x} - p \frac{Cl_p}{l_x} \frac{b}{2V} - r \frac{Cl_r}{l_x} \frac{b}{2V} - \dot{r} K_8 \frac{Cl_{\delta r}}{l_x VF} \bar{X}$$

$$+ \dot{p} K_8 \frac{Cl_{\delta r}}{l_x VF} \bar{Z} + \dot{p} - p q_1 \frac{K_{xz}}{K_x^2} + r q_1 \frac{K_z^2 - K_y^2}{K_x^2} - \dot{r} \frac{K_{xz}}{K_x^2}$$

$$= \delta a \left[\frac{Cl_{\delta a}}{l_x} + \frac{C_{Y\delta a} \cdot K_8 Cl_{\delta r}}{2TVF l_x} \right] + K_{10} P_e \left[\frac{Cl_{\delta r}}{l_x} + \frac{C_{Y\delta r} \cdot K_8 Cl_{\delta r}}{2TVF l_x} \right]$$

$$-\beta \frac{C_{n\beta}}{l_z} - p \frac{C_{np}}{l_z} \frac{b}{2V} - r \frac{C_{nr}}{l_z} \frac{b}{2V} - \dot{r} K_8 \frac{C_{n\delta r}}{l_z VF} \bar{X}$$

$$+ \dot{p} K_8 \frac{C_{n\delta r}}{l_z VF} \bar{Z} + p q_1 \frac{K_y^2 - K_x^2}{K_z^2} - \dot{p} \frac{K_{xz}}{K_z^2} + r q_1 \frac{K_{xz}}{K_z^2} + \dot{r}$$

$$= \delta a \left[\frac{C_{n\delta a}}{l_z} + \frac{C_{Y\delta a} \cdot K_8 C_{n\delta r}}{2TVF l_z} \right] + K_{10} P_e \left[\frac{C_{n\delta r}}{l_z} + \frac{C_{Y\delta r} \cdot K_8 C_{n\delta r}}{2TVF l_z} \right]$$

CONTINUATION

$$C_{\gamma\beta}^- = C_{\gamma\beta} \left[1 + \frac{K_8 C_{\gamma\delta\tau}}{2\gamma F} \right] : Cl_{\beta}^- = Cl_{\beta} + \frac{K_8 Cl_{\delta\tau} \cdot C_{\gamma\beta}}{2\gamma F} : Cn_{\beta}^- = Cn_{\beta} + \frac{K_8 Cn_{\delta\tau} \cdot C_{\gamma\beta}}{2\gamma F}$$

$$C_{\gamma p}^- = \left[C_{\gamma p} - .061 K_7 C_{\gamma\delta\tau} \cdot \frac{2V}{b} \right] \left[1 + \frac{K_8 \cdot C_{\gamma\delta\tau}}{2\gamma F} \right]$$

$$Cl_p^- = Cl_p - G' Cl_{\delta\tau} : Cn_p^- = Cn_p - G' Cn_{\delta\tau}$$

$$C_{\gamma\tau}^- = \left[1 + \frac{K_8 C_{\gamma\delta\tau}}{2\gamma F} \right] \left[C_{\gamma\tau} + K_7 C_{\gamma\delta\tau} \cdot \frac{2V}{b} \right]$$

$$Cl_{\tau}^- = Cl_{\tau} + H Cl_{\delta\tau} : Cn_{\tau}^- = Cn_{\tau} + H Cn_{\delta\tau}$$

$$C_{\gamma\delta a}^- = C_{\gamma\delta a} + K_6 C_{\gamma\delta\tau} : Cl_{\delta a}^- = Cl_{\delta a} + K_6 Cl_{\delta\tau} : Cn_{\delta a}^- = Cn_{\delta a} + K_6 Cn_{\delta\tau}$$

$$G' = \frac{2V}{b} \left\{ .061 K_7 - \frac{K_8}{F 4\mu_2} \left[C_{\gamma p} - .061 K_7 C_{\gamma\delta\tau} \cdot \frac{2V}{b} \right] \right\}$$

$$H' = \frac{2V}{b} \left\{ K_7 + \frac{K_8}{4\mu_2 F} \left(C_{\gamma\tau} + K_7 C_{\gamma\delta\tau} \cdot \frac{2V}{b} \right) \right\} : F = \left(\frac{1}{V} - \frac{C_{\gamma av}}{2\gamma} \right)$$

$$K_8 = \delta_{\tau} / a_{\tau}$$

FOR DEFINITIONS OF K_6, K_7, K_{10} SEE NEXT PAGE

$$\delta_r = \delta_{r_6} + \delta_{r_7} + \delta_{r_8} + \delta_{r_{10}}$$

$$\text{or } \delta_r = K_6 \delta_a + K_7(r - .061p) + K_8 a_y + K_{10} P_e$$

$$K_6 = \frac{\delta_{r_6}}{\delta_a} = K'_6 + K''_6 : K'_6 = K_{6(t=0+)} : K''_6 = - \frac{.5}{\delta_a} \int_{t=0}^{t=t} \delta_{r_6} \cdot dt$$

$$K_7 = \frac{\delta_{r_7}}{r - .061p} = K'_7 + K''_7 : K'_7 = K_{7(t=0+)} : K''_7 = - \frac{.5}{r - .061p} \int_{t=0}^{t=t} \delta_{r_7} \cdot dt$$

Hence $K_6, K_7, G', H', C_{\bar{r}_p}, C_{\bar{l}_p}, C_{\bar{n}_p}$
 $C_{\bar{r}_r}, C_{\bar{l}_r}, C_{\bar{n}_r}$
 $C_{\bar{r}_{\delta a}}, C_{\bar{l}_{\delta a}}, C_{\bar{n}_{\delta a}}$ ARE FUNCTIONS OF TIME

FOR ANY GIVEN PEDAL FORCE K_{10} GIVES THE RELATIONSHIP
 BETWEEN PEDAL FORCE AND RUDDER MOVEMENT DUE TO
 PEDAL FORCE $\delta_{r_{10}}$

IN THE EMERGENCY MODE δ_a IS A FUNCTION OF LATERAL
 STICK FORCE ONLY.



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DETERMINATION OF DERIVATIVES WITH EMERGENCY LATERAL DAMPER ENGAGED

The principles of the method involved in determining the derivatives which produce a given recorded lateral response, are so similar to those given in reference 1, a description of them in this issue of this report is not worthwhile.

It is possible that some difficulties if dealt with in a certain manner may ease computing programming. At the time of writing the method of reference 1 although believed to be sound in principle, has not been tested.

CONCLUSIONS

If in the equations of reference, 1 (which are relevant to Normal Mode Lateral Damping) K_4, K_4, K_5, K_5', K_9 are put to zero and ξ_a is substituted for $\left\{ K_4' \int P dt - K_4 \int p dt + K_5' P \right\}$

then the equations become completely relevant to Emergency Mode Lateral Damping.