A. V. ROE CANADA LIMITED

MALTON - ONTARIO

TECHNICAL DEPARTMENT (Aircraft)

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ARROW 1

DIGITAL COMPUTATION AND ANALYSIS OF ARROW LATERAL RESPONSE IN EMERGENCY MODE

PREPARED BY M.V. Jenkins DATE Jan./58.

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AVRO AIRCRAFT LIMITED
MALTON · ONTARIO
TECHNICAL DEPARTMENT

REPORT NO. 71/Stab/16
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FORM 1319A

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)

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

$$-\beta\frac{C_{l\beta}}{i_x} - p\frac{C_{lp}}{i_x}\cdot\frac{b}{2V} - r\frac{C_{lr}}{i_x}\cdot\frac{b}{2V} - pq_1\frac{K_{xz}}{K^2_x}$$

$$+\dot{p} - \dot{r}\frac{K_{xz}}{K^2_x} + rq_1\frac{K^2_z - K^2_Y}{K^2_x} = \frac{C_{l\delta a}\cdot\delta a}{i_x} + \frac{C_{l\delta r}\cdot\delta r}{i_x}$$

$$-\beta\frac{C_{n\beta}}{i_z} - p\frac{C_{np}}{i_z}\cdot\frac{b}{2V} - r\frac{C_{nr}}{i_z}\cdot\frac{b}{2V} + pq_1\frac{K^2_Y - K^2_x}{K^2_z}$$

$$-\dot{p}\frac{K_{xz}}{K^2_z} + rq_1\frac{K_{xz}}{K^2_z} + \dot{r} = \frac{C_{n\delta a}\cdot\delta a}{i_z} + \frac{C_{n\delta r}\cdot\delta r}{i_z}$$

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

$$\frac{C_{Y\delta r}\,\delta r}{2\tau} = \frac{C_{Y\delta r}\cdot K_6\,\delta a}{2\tau} + \frac{C_{Y\delta r}\cdot K_7\cdot r}{2\tau} - \frac{\cdot 061\, C_{Y\delta r}\cdot K_7\cdot p}{2\tau}$$

$$+\frac{C_{Y\delta r}\cdot K_8\cdot a_Y}{2\tau} + K_{10} P_e$$

LET $K_6 C_{Y\delta r} = \Delta C_{Y\delta a}$: $K_7 C_{Y\delta r}\cdot\frac{2V}{b} = \Delta_1 C_{Yr}$

$-\cdot 061 K_7 C_{Y\delta r}\cdot\frac{2V}{b} = \Delta_1 C_{Yp}$: $K_8 C_{Y\delta r} = C_{Ya_Y}$

CONTINUED ------

--- CONTINUATION

$$\therefore \frac{C_{Y_{\delta r}} \cdot \delta r}{2\tau} = \frac{\Delta C_{Y_{\delta a}}}{2\tau} + \frac{\Delta_1 C_{Y_r} \cdot \frac{b}{2V}}{2\tau} + \frac{\Delta_1 C_{Y_p} \cdot \frac{b}{2V}}{2\tau}$$

$$+ \frac{C_{Y_{a_y}}}{2\tau} + \frac{K_{10}\, P_e . C_{Y_{\delta r}}}{2\tau}$$

$$= \frac{\Delta C_{Y_{\delta a}}}{2\tau} + \frac{\Delta_1 C_{Y_r}}{4\mu_2} + \frac{\Delta_1 C_{Y_p}}{4\mu_2} + \frac{C_{Y_{a_y}}}{2\tau} + \frac{K_{10}\, P_e\, C_{Y_{\delta r}}}{2\tau}$$

$$\frac{C\ell_{\delta r} \cdot \delta r}{i_x} = \frac{C\ell_{\delta r} \cdot K_6\, \delta a}{i_x} + \frac{C\ell_{\delta r} \cdot K_7 \cdot r}{i_x} - \frac{\cdot 061\, C\ell_{\delta r} \cdot K_7 \cdot p}{i_x}$$

$$+ \frac{C\ell_{\delta r} \cdot K_8 \cdot a_y}{i_x} + \frac{C\ell_{\delta r} \cdot K_{10} \cdot P_e}{i_x}$$

LET $K_6 C\ell_{\delta r} = \Delta C\ell_{\delta a}$: $K_7 \cdot \frac{2V}{b} \cdot C\ell_{\delta r} = \Delta_1 C\ell_r$

$-\cdot 061\, K_7 \cdot \frac{2V}{b} \cdot C\ell_{\delta r} = \Delta_1 C\ell_p$: $K_8\, C\ell_{\delta r} = C\ell_{a_y}$

$$\therefore \frac{C\ell_{\delta r} \cdot \delta r}{i_x} = \frac{\Delta C\ell_{\delta a} \cdot \delta a}{i_x} + \frac{\Delta_1 C\ell_r \cdot \frac{b}{2V} \cdot r}{i_x} + \frac{\Delta_1 C\ell_p}{i_x} \frac{b}{2V} \cdot p$$

$$+ \frac{C\ell_{a_y} \cdot a_y}{i_x} + \frac{C\ell_{\delta r} \cdot K_{10} \cdot P_e}{i_x}$$

CONTINUED

--- CONTINUATION

SIMILARLY :

LET $K_6 C_{n_{\delta r}} = \Delta C_{n_{\delta a}}$: $K_7 \frac{2V}{b} . C_{n_{\delta r}} = \Delta_1 C_{n_r}$

$-.061 K_7 . \frac{2V}{b} . C_{n_{\delta r}} = \Delta_1 C_{n_p}$: $K_8 C_{n_{\delta r}} = C_{n_{a_y}}$

$$\therefore \frac{C_{n_{\delta r}} . \delta r}{i_z} = \frac{\Delta C_{n_{\delta a}} . \delta a}{i_z} + \frac{\Delta_1 C_{n_r}}{i_z} . \frac{b . r}{2V} + \frac{\Delta_1 C_{n_p}}{i_z} . \frac{b . p}{2V}$$

$$+ \frac{C_{n_{a_y}} . a_y}{i_z} + \frac{C_{n_{\delta r}} . K_{10} P_e}{i_z}$$

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

$C_{Y_r} + \Delta_1 C_{Y_r} = C'_{Y_r}$

$C_{Y_p} + \Delta_1 C_{Y_p} = C'_{Y_p}$

$C_{\ell_{\delta a}} + \Delta C_{\ell_{\delta a}} = C'_{\ell_{\delta a}}$

$C_{\ell_r} + \Delta_1 C_{\ell_r} = C'_{\ell_r}$

$C_{\ell_p} + \Delta_1 C_{\ell_p} = C'_{\ell_p}$

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

$C_{n_r} + \Delta_1 C_{n_r} = C'_{n_r}$

$C_{n_p} + \Delta_1 C_{n_p} = C'_{n_p}$

AS A CONSEQUENCE THE EQUATIONS OF MOTION ON PAGE 3 NOW BECOME

CONTINUED ---

$$-\beta \frac{C_{Y_\beta}}{2\tau} - p\frac{C_{Y_p}'}{4\mu_2} - r\frac{C_{Y_r}'}{4\mu_2} + a_Y\left(\frac{1}{V} - \frac{C_{Y_{a_Y}}}{2\tau}\right)$$

$$-\frac{\bar{X}\dot{r}}{V} + \frac{\bar{Z}\dot{p}}{V} \qquad = \frac{C_{Y_{\delta a}}'\cdot\delta a}{2\tau} + \frac{C_{Y_{\delta r}}}{2\tau}\cdot K_{10}P_e$$

$$-\beta\frac{C\ell_\beta}{i_x} - p\frac{C\ell_p'}{i_x}\cdot\frac{b}{2V} - r\frac{C\ell_r'}{i_x}\cdot\frac{b}{2V} - \frac{C\ell_{a_Y}}{i_x}\cdot a_Y$$

$$+\dot{p} - pq_1\frac{K_{xz}}{K_x^2} + rq_1\frac{K_z^2-K_Y^2}{K_x^2} - \dot{r}\frac{K_{xz}}{K_x^2} \qquad = \frac{C\ell_{\delta a}'}{i_x}\cdot\delta a + \frac{C\ell_{\delta r}\cdot K_{10}\cdot P_e}{i_x}$$

$$-\beta\frac{Cn_\beta}{i_z} - p\frac{Cn_p'}{i_z}\cdot\frac{b}{2V} - r\frac{Cn_r'}{i_z}\cdot\frac{b}{2V} - \frac{Cn_{a_Y}\cdot a_Y}{i_z}$$

$$+pq_1\frac{K_Y^2-K_x^2}{K_z^2} - \bar{p}\frac{K_{xz}}{K_z^2} + rq_1\frac{K_{xz}}{K_z^2} + \dot{r} = \frac{Cn_{\delta a}'}{i_z}\cdot\delta a + \frac{Cn_{\delta r}}{i_z}\cdot K_{10}P_e$$

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

$$-a_Y = -\beta\frac{C_{Y_\beta}}{2\tau F} - p\frac{C'_{Y_p}}{4\mu_2 F} - r.\frac{C'_{Y_r}}{4\mu_2 F} - \frac{\bar{X}\dot{r}}{VF} + \frac{\bar{Z}.\dot{p}}{VF}$$

$$-\frac{C'_{Y_{\delta a}}.\delta a}{2\tau F} - \frac{C_{Y_{\delta r}}.K_{10}.P_e}{2\tau F}$$

$$-C_{Y_{a_Y}}.a_Y = -\beta.\frac{C_{Y_{a_Y}}.C_{Y_\beta}}{2\tau F} - p.\frac{C_{Y_{a_Y}}.C'_{Y_p}}{4\mu_2 F} - r.\frac{C_{Y_{a_Y}}.C'_{Y_r}}{4\mu_2 F}$$

$$-\frac{\dot{r}\,C_{Y_{a_Y}}.\bar{X}}{VF} + \dot{p}\frac{C_{Y_{a_Y}}.\bar{Z}}{VF} - \frac{C'_{Y_{\delta a}}.C_{Y_{a_Y}}.\delta a}{2\tau F} - \frac{C_{Y_{\delta r}}.C_{Y_{a_Y}}.K_{10}.P_e}{2\tau F}$$

LET $\Delta C_{Y_\beta} = \dfrac{C_{Y_{a_Y}}.C_{Y_\beta}}{2\tau F}$: $\Delta_2 C_{Y_p} = \dfrac{C_{Y_{a_Y}}.C'_{Y_p}}{2\tau F}$: $\Delta_2 C_{Y_r} = \dfrac{C_{Y_{a_Y}}.C'_{Y_r}}{2\tau F}$

$$\therefore -\frac{C_{Y_{a_Y}}.a_Y}{2\tau} = -\beta\frac{\Delta C_{Y_\beta}}{2\tau} - p\frac{\Delta_2 C_{Y_p}}{4\mu_2} - r\frac{\Delta_2 C_{Y_r}}{4\mu_2}$$

$$-\frac{\dot{r}\,C_{Y_{a_Y}}\bar{X}}{2\tau VF} + \dot{p}\frac{C_{Y_{a_Y}}.\bar{Z}}{2\tau VF}$$

$$-\frac{C'_{Y_{\delta a}}.C_{Y_{a_Y}}\delta a}{4\tau^2 F} - \frac{C_{Y_{\delta r}}.C_{Y_{a_Y}}.K_{10}.P_e}{4\tau^2 F}$$

CONTINUED

$$-a_Y \cdot Cl_{a_Y} = -\beta \frac{Cl_{a_Y} \cdot C_{Y_\beta}}{2\Upsilon F} - p \cdot \frac{Cl_{a_Y} \cdot C'_{Y_p}}{4\mu_2 F} - r \cdot \frac{Cl_{a_Y} \cdot C'_{Y_r}}{4\mu_2 F}$$

$$-\dot{r} \frac{Cl_{a_Y} \cdot \bar{X}}{VF} + \dot{p} \frac{Cl_{a_Y} \cdot \bar{Z}}{VF}$$

$$-\frac{C'_{Y_{\delta a}} \cdot Cl_{a_Y} \cdot \delta a}{2\Upsilon F} - \frac{C_{Y_{\delta T}} \cdot Cl_{a_Y} \cdot K_{10} \cdot P_e}{2\Upsilon F}$$

LET $\Delta Cl_\beta = \dfrac{Cl_{a_Y} \cdot C_{Y_\beta}}{2\Upsilon F}$ $: \Delta_2 Cl_p = \dfrac{Cl_{a_Y} \cdot C'_{Y_p}}{2\Upsilon F}$

$$\Delta_2 Cl_r = \frac{Cl_{a_Y} \cdot C'_{Y_r}}{2\Upsilon F}$$

$$-\frac{a_Y \cdot Cl_{a_Y}}{i_x} = -\beta \frac{\Delta Cl_\beta}{i_x} - p \cdot \frac{\Delta_2 Cl_p}{i_x} \cdot \frac{b}{2V}$$

$$-r \frac{\Delta_2 Cl_r \cdot \frac{b}{2V}}{i_x} - \dot{r} \frac{Cl_{a_Y} \cdot \bar{X}}{i_x \cdot V \cdot F} + \dot{p} \frac{Cl_{a_Y} \cdot \bar{Z}}{i_x \cdot V \cdot F}$$

$$-\frac{C'_{Y_{\delta a}} \cdot Cl_{a_Y} \cdot \delta a}{2\Upsilon F i_x} - \frac{C_{Y_{\delta T}} \cdot Cl_{a_Y} \cdot K_{10} \cdot P_e}{2\Upsilon F i_x}$$

CONTINUED

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

USING THE FOLLOWING NOTATION

$$C_{\bar{Y}_\beta} = C_{Y_\beta} + \Delta C_{Y_\beta}$$

$$C_{l_{\bar{\beta}}} = C_{l_\beta} + \Delta C_{l_\beta}$$

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

$$C_{\bar{Y}_p} = C'_{Y_p} + \Delta_2 C_{Y_p}$$

$$C_{l_{\bar{p}}} = C'_{l_p} + \Delta_2 C_{l_p}$$

$$C_{n_{\bar{p}}} = C'_{n_p} + \Delta_2 C_{n_p}$$

$$C_{\bar{Y}_r} = C'_{Y_r} + \Delta_2 C_{Y_r}$$

$$C_{l_{\bar{r}}} = C'_{l_r} + \Delta_2 C_{l_r}$$

$$C_{n_{\bar{r}}} = C'_{n_r} + \Delta_2 C_{n_r}$$

$$C_{\bar{Y}_{\delta a}} = C'_{Y_{\delta a}}$$

$$C_{l_{\bar{\delta a}}} = C'_{l_{\delta a}}$$

$$C_{n_{\bar{\delta a}}} = C'_{n_{\delta a}}$$

THE EQUATIONS NOW BECOME

$$-\beta\frac{C_{Y_{\bar\beta}}}{2\Upsilon} - p\cdot\frac{C_{Y_{\bar p}}}{4\mu_2} - r\cdot\frac{C_{Y_{\bar r}}}{4\mu_2} - \frac{\dot r K_8 C_{Y_{\delta r}}\bar X}{2\Upsilon V F} + \frac{\dot p K_8 C_{Y_{\delta r}}\bar Z}{2\Upsilon V F}$$

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

$$= \delta a\cdot\frac{C_{Y_{\bar{\delta a}}}}{2\Upsilon}\left[1 + \frac{K_8 C_{Y_{\delta r}}}{2\Upsilon F}\right] + K_{10}\cdot Pe\cdot\frac{C_{Y_{\delta r}}}{2\Upsilon}\left[1 + \frac{K_8\cdot C_{Y_{\delta r}}}{2\Upsilon F}\right]$$

$$-\beta\frac{C_{l_{\bar\beta}}}{i_x} - p\cdot\frac{C_{l_{\bar p}}}{i_x}\cdot\frac{b}{2V} - r\cdot\frac{C_{l_{\bar r}}}{i_x}\cdot\frac{b}{2V} - \dot r\frac{K_8 C_{l_{\delta r}}\cdot\bar X}{i_x V F}$$

$$+ \dot p\frac{K_8 C_{l_{\delta r}}\cdot\bar Z}{i_x V F} + \dot p - pq_1\frac{K_{xz}}{K_x^2} \mp rq_1\frac{K_z^2 - K_y^2}{K_x^2} - \dot r\frac{K_{xz}}{K_x^2}$$

$$= \delta a\left[\frac{C_{l_{\bar{\delta a}}}}{i_x} + \frac{C_{Y_{\bar{\delta a}}}\cdot K_8 C_{l_{\delta r}}}{2\Upsilon F i_x}\right] + K_{10}Pe\cdot\left[\frac{C_{l_{\delta r}}}{i_x} + \frac{C_{Y_{\delta r}}\cdot K_8\cdot C_{l_{\delta r}}}{2\Upsilon F i_x}\right]$$

$$-\beta\frac{C_{n_{\bar\beta}}}{i_z} - p\cdot\frac{C_{n_{\bar p}}}{i_z}\cdot\frac{b}{2V} - r\frac{C_{n_{\bar r}}}{i_z}\cdot\frac{b}{2V} - \dot r\frac{K_8\cdot C_{n_{\delta r}}\cdot\bar X}{i_z\cdot V\cdot F}$$

$$+ \dot p\frac{K_8 C_{n_{\delta r}}\bar Z}{i_z V F} + \frac{pq_1 (K_y^2 - K_x^2)}{K_z^2} - \dot p\frac{K_{xz}}{K_z^2} + rq_1\frac{K_{xz}}{K_z^2} + \dot r$$

$$= \delta a\left[\frac{C_{n_{\bar{\delta a}}}}{i_z} + \frac{C_{Y_{\bar{\delta a}}}\cdot K_8 C_{n_{\delta r}}}{2\Upsilon F i_z}\right] + K_{10}\cdot Pe\left[\frac{C_{n_{\delta r}}}{i_z} + \frac{C_{Y_{\delta r}}\cdot K_8\cdot C_{n_{\delta r}}}{2\Upsilon F i_z}\right]$$

CONTINUED ---

CONTINUATION

$$C_{Y\bar{\beta}} = C_{Y\beta}\left[1+\frac{K_8 C_{Y\delta r}}{2\tau F}\right] : Cl_{\bar{\beta}} = Cl_{\beta} + \frac{K_8 Cl_{\delta r}\cdot C_{Y\beta}}{2\tau F} : Cn_{\bar{\beta}} = Cn_{\beta} + \frac{K_8 Cn_{\delta r}\cdot C_{Y\beta}}{2\tau F}$$

$$C_{Y\bar{p}} = \left[C_{Yp} - \cdot 061 K_7 C_{Y\delta r}\cdot\frac{2V}{b}\right]\left[1+\frac{K_8\cdot C_{Y\delta r}}{2\tau F}\right]$$

$$Cl_{\bar{p}} = Cl_p - G' Cl_{\delta r} \quad : Cn_{\bar{p}} = Cn_p - G' Cn_{\delta r}$$

$$C_{Y\bar{r}} = \left[1+\frac{K_8 C_{Y\delta r}}{2\tau F}\right]\left[C_{Yr} + K_7 C_{Y\delta r}\cdot\frac{2V}{b}\right]$$

$$Cl_{\bar{r}} = Cl_r + H Cl_{\delta r} \quad : Cn_{\bar{r}} = Cn_r + H Cn_{\delta r}.$$

$$C_{Y\overline{\delta a}} = C_{Y\delta a} + K_6 C_{Y\delta r} : Cl_{\overline{\delta a}} = Cl_{\delta a} + K_6 Cl_{\delta r} : Cn_{\overline{\delta a}} = Cn_{\delta a} + K_6 Cn_{\delta r}$$

$$G' = \frac{2V}{b}\left\{\cdot 061 K_7 - \frac{K_8}{F 4\mu_2}\left[C_{Yp} - \cdot 061 K_7 C_{Y\delta r}\cdot\frac{2V}{b}\right]\right\}$$

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

$$K_8 = \delta r / a_r$$

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

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

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

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

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

HENCE $K_6, K_7, G', H', C_{Y_{\bar{p}}}, C_{l_{\bar{p}}}, C_{n_{\bar{p}}}$, $C_{Y_{\bar{r}}}, C_{l_{\bar{r}}}, C_{n_{\bar{r}}}$, $C_{Y_{\bar{\delta a}}}, C_{l_{\bar{\delta a}}}, C_{n_{\bar{\delta a}}}$ 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 δa IS A FUNCTION OF LATERAL STICK FORCE ONLY

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 δ_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.