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INVESTIGATION OF LATERAL FLYING QUALITIES OF AIRCRAFT

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ABSTRACT

Methodology for investigation of lateral flying and handling qualities of an airplane is found based on stability analysis. The fighter aircraft (F4C) and the jet trainer aircraft are used as an example models in this investigation. Effect of changing the rolling moment due to sideslip (L_β) and the yawing moment due to sideslip (N_β) derivatives on lateral-directional motion characteristics and flying qualities is evaluated for both models. For the lateral-directional motion the MIL-F-8785C specifications were used to compare the parameters (time to double or to half amplitude in the spiral mode (T_{2s}), roll mode time constant (T_r), damping ratio (ζ_d), and undamped natural frequency (ω_{nd}) of the dutch roll mode) with the minimum or maximum required limits of flying qualities.

KEY WORDS: Flying qualities, Handling qualities, and airplane stability analysis.

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1. INTRODUCTION

Flying qualities testing involve the airplane's static and dynamic stability and its control characteristics. The handling qualities can only be assessed from pilot opinions, but the governing military standards for flying qualities offer methods of predicting the handling qualities from estimated transfer function coefficients using flight test data. To investigate the lateral flying and handling qualities of the aircraft, a fighter aircraft and a jet trainer aircraft as example model is chosen. Analysis of lateral stability for different values of the derivatives, rolling moment due to sideslip angle (L_β) and yawing moment due to sideslip angle (N_β) is performed. Evaluation of the effect of these derivatives on lateral flying qualities is performed.

2. MATHEMATICAL MODELING

The mathematical linear model used is obtained as state space equation:

$$\dot{x} = Ax + Bu \tag{1}$$

$$y = Cx \tag{2}$$

For lateral motion, the control vector, **u**, defined as:

$$u \equiv \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix}$$

where δa aileron deflection and δr rudder deflection
the state vector, **x**, is defined as:

$$x \equiv \begin{bmatrix} \beta \\ p \\ r \\ \phi \end{bmatrix}$$

Then the coefficient matrix **A** becomes:

$$A = \begin{bmatrix} y_V & 0 & -1 & \dfrac{g}{U_O} \\ L'_\beta & L'_p & L_r' & 0 \\ N_\beta' & N'_p & N'_r & 0 \\ 0 & 1 & \tan\gamma_O & 0 \end{bmatrix}$$

And the driving matrix **B** becomes:

$$B = \begin{bmatrix} 0 & Y^{*}_{\delta r} \\ L^{'}_{\delta a} & L^{'}_{\delta r} \\ N^{'}_{\delta a} & N^{'}_{\delta r} \\ 0 & 0 \end{bmatrix}$$

where $Y^{*}_{\delta r} = {Y_{\delta r}}/{U_o}$, U_o .. Aircraft forward speed

The primed lateral-directional stability derivatives are evaluated for both models and shown in table (1).

Table 1. Lateral stability derivatives

No	Derivative	F4C	SIAI-211
1	$L^{'}_{\beta}$ (s^{-2})	-19.208	-91.743
2	$L^{'}_{P}$ (s^{-1})	-1.227	-7.389
3	$L^{'}_{r}$ (s^{-1})	0.389	5.161
4	$L^{'}_{\delta a}$ (s^{-2})	9.761	88.571
5	$L^{'}_{\delta r}$ (s^{-2})	1.724	40.244
6	$N^{'}_{\beta}$ (s^{-2})	5.602	19.44
7	$N^{'}_{p}$ (s^{-1})	$-6.533*10^{-3}$	-0.022
8	$N^{'}_{r}$ (s^{-1})	-0.256	-0.559
9	$N^{'}_{\delta a}$ (s^{-2})	-0.252	2.9606
10	$N^{'}_{\delta r}$ (s^{-2})	-2.776	-14.685

3. ANALYSIS OF LATERAL-DIRECTIONAL STABILITY CHARACTERISTICS

By substitute the values of primed stability derivatives in the model equation (1), matrix A, the results of lateral-directional characteristics obtained for the F4C and SIAI-211 aircraft models is shown in table (2). As shown, all of these modes are stable except the spiral mode for SIAI-211 is found as unstable mode.

Table 2. Lateral-directional mode characteristics

VALUES	F4C	SIAI-211
Lateral modes	λ = -0.1148 ±2.3971i (dutch -roll) =-1.3361 (rolling) =-0.0132 (spiral)	λ = -0.4194 ±4.4949i =-7.4823 = 0.0170
T_S(sec)	76	58.823
T_{2S}(sec)	52.679	40.648
T_R(sec)	0.748	0.133
T_d(sec)	2.62	1.396
ω_{nd} (rad/sec)	2.395	4.52
ζ_d	0.048	0.092
$\zeta_d\omega_{nd}$	0.115	0.4158
$\left\|\varphi/\beta\right\|_{dr}$	3.0475	2.51
$\omega_{nd}^2\left\|\varphi/\beta\right\|_{dr}$	17.437	51.28

4. EFFECT OF CHANGE $C_{l\beta}$ AND $C_{n\beta}$ ON THE LATERAL STABILITY CHARACTERISTICS

To find the effect of change $C_{l\beta}$ and $C_{n\beta}$ on the lateral stability characteristics we increased and decreased the original values of these derivatives by ±20%,and ±40%. Fig.1 to Fig. 10 presents the results of these changes for both aircraft models.

If we examine the influence of these stability coefficients on the lateral roots, we observe the following; as the dihedral effect is increased, that is $C_{l\beta}$ becomes more negative, the dutch roll mode moves toward the right half-plane, which means the dutch roll root is becoming less stable. The spiral mode and the rolling modes are moving in the direction of increased stability. The frequency of the dutch roll root is increased and the damping ratio is decreased. Figs. (1 - 4) shows the effect of the airplane dihedral effect, $C_{l\beta}$ the lateral-directional characteristics, that a negative increase in $C_{l\beta}$ results in a decrease in dutch roll damping ratio (ζ_d), and an increase in spiral stability.

Also increasing directional stability of the airplane, that is, $C_{n\beta}$ becomes more positive, causes the spiral and roll modes to become less stable and the dutch roll mode to become more stable. The frequency of the dutch roll mode is increased for both models. The damping ratio of the dutch roll mode is not affected for (F4C), but it is decreasing as $C_{n\beta}$ is increasing for (SIAI-211). The effect of directional stability, $C_{n\beta}$ on the lateral-directional stability characteristics is illustrated in Figs. (6 - 10).

At low positive values of $C_{n\beta}$ it seen that there is a strong detrimental effect on all modes, this is clearly when decreased by 40 % for jet trainer aircraft (SIAI-211, $C_{n\beta}$ = 0.102) the spiral mode is converted to be stable mode.

Figs. (2, 4, 7, and 9) show the relation between the $C_{l\beta}$, and $C_{n\beta}$ derivatives and inverse of spiral time constant, inverse of spiral time to double or to half amplitude for two models, the different effect is resulted from the nature of the spiral mode for the two aircraft models used. Also the dihedral angle (Γ) effect, it's positive for F4C aircraft and negative for SIAI-211. Also the location of the wing, when the airplane has a low wing (F4C) dihedral effect is diminished by the fuselage interference while the jet trainer SIAI – 211 have mid wing .

5. EVALUATION OF LATERAL FLYING QUALITIES

According to MIL-F-8785C the evaluation of lateral flying qualities is determined by lateral-directional flying qualities criteria and due to lateral –directional stability characteristics.

5.1 Roll Rate Oscillation Criteria

The Dutch roll contamination occurs primarily in roll rate when $\left|\phi/\beta\right|_{dr}$ is moderate to large. For these configurations, the dutch roll contamination can be quantified in the time domain by the ratio (p_{osc} / p_{avg}), a measure of the ratio of the oscillatory component of roll rate to the average component of roll rate following a yaw- control-free step roll control command. This ratio can be expressed as a function of, $\left|\phi/\beta\right|_{dr}$ Oscillatory phi/beta ratio of the dutch roll mode, $(\beta/P)_{roll}$ Sideslip angle to roll rate ratio of the rolling mode and ($N'_{\delta a}/L'_{\delta a}$) yawing and rolling moments due an aileron deflection ratio by defining it in terms of the system residues. This is explained as follows:

The roll rate due to a unit step input in lateral stick expressed in terms of system residues and eigenvalues is given by (note that: there is only one input, the third subscript on the *R* 's has been omitted)

$$p(t) = \frac{R_{p,sprl}}{\lambda_{sprl}} e^{\lambda_{sprl} t} + \frac{R_{p,roll}}{\lambda_{roll}} e^{\lambda_{roll} t} + 2\left|\frac{R_{p,dr}}{\lambda_{dr}}\right| e^{-\zeta_{dr}\omega_{dr} t} \cos(\omega_{dr}\sqrt{1-\zeta_{dr}^2}\, t + \angle \frac{R_{p,dr}}{\lambda_{dr}}) \tag{3}$$

where:

$$R_{p,roll} = \frac{L_{\delta}\lambda_{roll}(\lambda_{roll} - z_{\phi})(\lambda_{roll} - \bar{z}_{\phi})}{(\lambda_{roll} - \lambda_{sprl})(\lambda_{roll} - \lambda_{dr})(\lambda_{roll} - \bar{\lambda}_{dr})} \tag{4}$$

$$R_{p,sprl} = \frac{L_{\delta}\lambda_{sprl}(\lambda_{sprl} - z_{\phi})(\lambda_{sprl} - \bar{z}_{\phi})}{(\lambda_{sprl} - \lambda_{roll})(\lambda_{sprl} - \lambda_{dr})(\lambda_{sprl} - \bar{\lambda}_{dr})} \tag{5}$$

$$R_{p,dr} = \frac{L_{\delta}\lambda_{dr}(\lambda_{dr} - z_{\phi})(\lambda_{dr} - \bar{z}_{\phi})}{(\lambda_{dr} - \lambda_{sprl})(\lambda_{dr} - \lambda_{roll})(\lambda_{dr} - \bar{\lambda}_{dr})} \tag{6}$$

and $z_{\phi} = -\omega_{\phi}\zeta_{\phi} + j\omega_{\phi}\sqrt{1-\zeta_{\phi}^2}$, $\bar{x}$ denotes the complex conjugate of x .

Where ζ_{ϕ} is the damping ratio of the roll mode, and ω_{ϕ} the undamped natural frequency of the roll mode (rad/sec)

The p-to-δ_{stk} transfer function numerators z_{ϕ} can be expressed in terms of system eigenvalues, $|\phi/\beta|_{dr}$, $(\beta/P)_{roll}$ and $(N'_{\delta a}/L'_{\delta a})$ as:

$$z_{\phi} \cong \tilde{z}_{\phi} = -\tilde{\omega}_{\phi}\tilde{\zeta}_{\phi} + j\tilde{\omega}_{\phi}\sqrt{1-\tilde{\zeta}_{\phi}^2} \tag{7}$$

Where:

$$\omega_{\phi}^2 \cong \tilde{\omega}_{\phi}^2 = \omega_{dr}^2\left\{1 + \left(\frac{N'_{\delta}}{L'_{\delta}}\right)\left(\frac{\phi}{\beta}\right)_{dr}\right\} \tag{8}$$

$$2\omega_{\phi}\zeta_{\phi} \cong 2\tilde{\omega}_{\phi}\tilde{\zeta}_{\phi} = 2\omega_{dr}\zeta_{dr} + \left(\frac{\phi}{\beta}\right)_{dr}\left\{\begin{array}{l}\left(\frac{N'_{\delta}}{L'_{\delta}}\right)\left(\lambda_{roll} + 2\omega_{dr}\zeta_{dr}\right) \\ +\left(\frac{\beta}{p}\right)_{roll}\dfrac{\left(\lambda_{roll}^2 + 2\lambda_{roll}\zeta_{dr}\omega_{dr} + \omega_{dr}^2\right)}{\left(1-\lambda_{roll}\left(\frac{\beta}{p}\right)_{roll}\left(\frac{\phi}{\beta}\right)_{dr}\right)}\left(1 + \left(\frac{\phi}{\beta}\right)_{dr}\left(\frac{N'_{\delta}}{L'_{\delta}}\right)\right)\end{array}\right\} \tag{9}$$

Where $\bar{x}$ denotes an approximation to x. an approximation to p(t) expressed in terms of $\tilde{z}_{\phi}$ is given by:

$$\tilde{p}(t)=\frac{\tilde{R}_{p,sprl}}{\lambda_{sprl}}e^{\lambda_{sprl}t}+\frac{\tilde{R}_{p,roll}}{\lambda_{roll}}e^{\lambda_{roll}t}+ 2\left|\frac{\tilde{R}_{p,dr}}{\lambda_{dr}}\right|e^{-\zeta_{dr}\omega_{dr}t}\cos(\omega_{dr}\sqrt{1-\zeta_{dr}^{2}}\,t+\angle\frac{\tilde{R}_{p,dr}}{\lambda_{dr}}) \tag{10}$$

Where:

$$\tilde{R}_{p,roll}=\frac{L_{\delta}\lambda_{roll}(\lambda_{roll}-\tilde{z}_{\phi})(\lambda_{roll}-\bar{\tilde{z}}_{\phi})}{(\lambda_{roll}-\lambda_{sprl})(\lambda_{roll}-\lambda_{dr})(\lambda_{roll}-\bar{\lambda}_{dr})} \tag{11}$$

$$\tilde{R}_{p,sprl}=\frac{L_{\delta}\lambda_{sprl}(\lambda_{sprl}-\tilde{z}_{\phi})(\lambda_{sprl}-\bar{\tilde{z}}_{\phi})}{(\lambda_{sprl}-\lambda_{roll})(\lambda_{sprl}-\lambda_{dr})(\lambda_{sprl}-\bar{\lambda}_{dr})} \tag{12}$$

$$\tilde{R}_{p,dr}=\frac{L_{\delta}\lambda_{dr}(\lambda_{dr}-\tilde{z}_{\phi})(\lambda_{dr}-\bar{\tilde{z}}_{\phi})}{(\lambda_{dr}-\lambda_{sprl})(\lambda_{dr}-\lambda_{roll})(\lambda_{dr}-\bar{\lambda}_{dr})} \tag{13}$$

The ratio (P_{osc}/P_{avg}) can be expressed as function of $\tilde{p}$ (t) by:

$$\frac{p_{osc}}{p_{avg}}\cong\frac{\tilde{p}_{osc}}{\tilde{p}_{avg}}=\frac{\tilde{p}_{1}+\tilde{p}_{3}-2\tilde{p}_{2}}{\tilde{p}_{1}+\tilde{p}_{3}+2\tilde{p}_{2}} \tag{14}$$

For ζ_{dr} less than or equal to 0.2.

Using these equations ($\tilde{p}_{osc}$ / $\tilde{p}_{avg}$) can be calculated in the following way:

(1) Choose system eigenvalues and values of $|\phi/\beta|_{dr}$, $(\beta/P)_{roll}$ and ($N'_{\delta a}$ / $L'_{\delta a}$).That the development requires (1+ ($N'_{\delta a}$ / $L'_{\delta a}$) $|\phi/\beta|_{dr}$)>0.

(2) Calculate $\tilde{\omega}_{\varphi}$ and $\tilde{\zeta}_{\varphi}$ using equations (1.8 & 1.9) and form $\tilde{z}_{\varphi}$.

(3) Calculate $\tilde{R}_{p,sprl}$, $\tilde{R}_{p,roll}$,and $\tilde{R}_{p,dr}$ using equations(1.11-1.13) and form $\tilde{p}$(t).

(4) Generate step time response using $\tilde{p}$(t). (Equation (1.10)). See Figs. (11, 13).

(5) Pick off peaks from $\tilde{p}$(t) step time response ($\tilde{P}_1$, $\tilde{P}_2$,and $\tilde{P}_3$).

(6) Calculate ($\tilde{p}_{osc}$ / $\tilde{p}_{avg}$) using equation (1.14).

5.2 Sideslip Deviation Criteria

The sideslip due to a step input in lateral stick expressed in terms of system residues and eigenvalues is given by

$$\tilde{\beta}(t) = \tilde{\beta}_0 + \frac{\tilde{R}_{\beta,roll}}{\lambda_{roll}} e^{\lambda_{roll} t} + 2\left|\frac{\tilde{R}_{\beta,dr}}{\lambda_{dr}}\right| e^{-\zeta_{dr}\omega_{dr} t} \cos(\omega_{dr}\sqrt{1-\zeta_{dr}^2}\, t + \angle \frac{\tilde{R}_{\beta,dr}}{\lambda_{dr}}) \tag{15}$$

where:

$$\tilde{\beta}_0 = -\left(\frac{\tilde{R}_{\beta,roll}}{\lambda_{roll}} + 2\left|\frac{\tilde{R}_{\beta,dr}}{\lambda_{dr}}\right| \cos(\angle \frac{\tilde{R}_{\beta,dr}}{\lambda_{dr}}) \right) \tag{16}$$

$$\tilde{R}_{\beta,roll} = \frac{L'_\delta \left(1 + \frac{N'_\delta}{L'_\delta}\left(\frac{\phi}{\beta}\right)_{dr}\right)\left(\frac{\beta}{p}\right)_{roll}}{\left(1 - \lambda_{roll}\left(\frac{\beta}{p}\right)_{roll}\left(\frac{\phi}{\beta}\right)_{dr}\right)} \tag{17}$$

And:

$$\tilde{R}_{\beta,dr} = \frac{-L'_\delta \left(\frac{N'_\delta}{L'_\delta} + \left(\lambda_{roll} - \bar{\lambda}_{dr}\right) \frac{\left(1 + \frac{N'_\delta}{L'_\delta}\left(\frac{\phi}{\beta}\right)_{dr}\left(\frac{\beta}{p}\right)_{roll}\right)}{\left(1 - \lambda_{roll}\left(\frac{\beta}{p}\right)_{roll}\left(\frac{\phi}{\beta}\right)_{dr}\right)} \right)}{\left(\lambda_{dr} - \bar{\lambda}_{dr}\right)} \tag{18}$$

And $\tilde{x}$ denotes an approximation to *x*. The ratio ($\Delta\beta_{max} / k_\beta$) can be expressed as a function $\tilde{\phi}(t)$ by:

$$\frac{\Delta\beta_{max}}{k_\beta} \cong \frac{\Delta\tilde{\beta}_{max}}{\tilde{k}_\beta} \tag{19}$$

where:

$$\Delta\beta_{max} \cong \Delta\tilde{\beta}_{max} = \max(\tilde{\beta}(t)) - \min(\tilde{\beta}(t)) \qquad \text{For} \quad 0 < t < t_\beta \tag{20}$$

$\Delta\beta$ Maximum change in sideslip occurring within 2 seconds or one half period of the dutch roll t_β, whichever is greater, for step roll-control Command

and:

$$k_\beta \cong \tilde{k}_\beta = \left|\frac{\tilde{\phi}(t)}{60}\right|_{t=1\sec} \tag{21}$$

k_β is the ratio of 'command roll performance' to 'applicable roll performance requirement'

that:

$$\tilde{\phi}(t) = \tilde{\phi}_0 + \frac{\tilde{R}_{\phi,sprl}}{\lambda_{sprl}} e^{\lambda_{sprl} t} + \frac{\tilde{R}_{\phi,roll}}{\lambda_{roll}} e^{\lambda_{roll} t} + 2\left|\frac{\tilde{R}_{\phi,dr}}{\lambda_{dr}}\right| e^{-\zeta_{dr}\omega_{dr} t} \cos(\omega_{dr}\sqrt{1-\zeta_{dr}^2}\, t + \angle \frac{\tilde{R}_{\phi,dr}}{\lambda_{dr}}) \tag{22}$$

where ϕ is the bank angle of the aircraft (deg)

with:

$$\tilde{\phi}_0 = -\left(\frac{\tilde{R}_{\phi,sprl}}{\lambda_{sprl}} + \frac{\tilde{R}_{\phi,roll}}{\lambda_{roll}} + 2\left|\frac{\tilde{R}_{\phi,dr}}{\lambda_{dr}}\right| \cos(\angle \frac{\tilde{R}_{\phi,dr}}{\lambda_{dr}})\right) \tag{23}$$

$$\tilde{R}_{\phi,sprl} = \frac{\tilde{R}_{p,sprl}}{\lambda_{sprl}}; \tilde{R}_{\phi,roll} = \frac{\tilde{R}_{p,roll}}{\lambda_{roll}}; \tilde{R}_{\phi,dr} = \frac{\tilde{R}_{p,dr}}{\lambda_{dr}} \tag{24}$$

Using these equations ($\Delta\tilde{\beta}_{max} / \tilde{k}_\beta$) can be calculated in the following way:

(1) Choose system eigenvalues and values of $|\phi/\beta|_{dr}$, $(\beta/P)_{roll}$ and ($N'_{\delta a} / L'_{\delta a}$).This development requires (1 + $N'_{\delta a} / L'_{\delta a}$) $|\phi/\beta|_{dr}$)>0.

(2) Calculate $\tilde{\beta}_0$, $\tilde{R}_{\beta,roll}$, and $\tilde{R}_{\beta,dr}$ and form $\tilde{\beta}$(t).

(3) Generate step time response using $\tilde{\beta}$(t). (Equation (1.15)).See Figs. (12, 14)

(4) Calculate $\Delta\tilde{\beta}_{max}$ (Equation (1.20)) from $\tilde{\beta}$(t) step time response.

(5) Calculate $\tilde{\phi}_o$, $\tilde{R}_{\phi,sprl}$, $\tilde{R}_{\phi,roll}$,and $\tilde{R}_{\phi,dr}$ (equations (1.23 &1.24))and form $\tilde{\phi}(t)$.

(6) Calculate $\tilde{k}_\beta$ (Equation (1.21)) from $\tilde{\phi}(t)$.

(7) Calculate ($\Delta\tilde{\beta}_{max} / \tilde{k}_\beta$) using equation (1.19).

5.3 Phase Angle of Dutch Roll Component of Sideslip

An approximation to Ψ_β Phase angle of the dutch roll component of sideslip (deg) expressed in terms of system eigenvalues $|\phi/\beta|_{dr}$, $(\beta/P)_{roll}$ and $(N'_{\delta a}/L'_{\delta a})$, is given by:

$$\Psi_\beta \cong \tilde{\Psi}_\beta = \tan^{-1}\left(\frac{\omega_{dr}\sqrt{1-\zeta_{dr}^2} - \tilde{\omega}_\phi\sqrt{1-\tilde{\zeta}_\phi^2}}{-\zeta_{dr}\omega_{dr} + \tilde{\zeta}_\phi\tilde{\omega}_\phi}\right) - 270 \qquad (25)$$

5.4 Generating Flying Qualities Guidelines

Eigenspace flying qualities guidelines for choosing $(\beta/P)_{roll}$ and $(N'_{\delta a}/L'_{\delta a})$ for a given value of $|\phi/\beta|_{dr}$ are determined in the following way:

(1) Choose value of $|\phi/\beta|_{dr}$ and desired eigenvalues.

(2) Evaluate $(\tilde{p}_{osc}/\tilde{p}_{avg})$, $(\Delta\tilde{\beta}_{max}/\tilde{k}_\beta)$, and $\tilde{\Psi}_\beta$ over desired range of $(\beta/P)_{roll}$ and $(N'_{\delta a}/L'_{\delta a})$, table (3).

(3) The eigenspace roll rate oscillation guideline is based on the military standard roll rate oscillation criteria. This guideline can be determined by overlaying the $(\tilde{p}_{osc}/\tilde{p}_{avg})$ and $\tilde{\Psi}_\beta$ data in Fig. (15).

(4) The eigenspace sideslip deviation guideline is based on the Military Standard sideslip deviation criteria. This guideline can be determined by overlaying the $(\Delta\tilde{\beta}_{max}/\tilde{k}_\beta)$ and $\tilde{\Psi}_\beta$ data in Fig. (16).

For intermediate values of $|\phi/\beta|_{dr}$, both guidelines must be satisfied to meet level one flying qualities, therefore the two models used here evaluated by both guidelines and overlaying to meet level one flying qualities (Figs. 15, 16).

Table 3. Result data for two airplanes

Airplane	[illegible] (rad/sec)	[illegible]	[illegible] . deg)	(p_{osc}/p_{avg})	([illegible]max/ k[illegible]) (deg)
SIAI-211	4.7083	0.0636	-210.46	0.0452	0.755
F4C	2.299	0.094	-224.36	0.0362	1.6995

6. LATERAL-DIRECTIONAL FLYING QUALITIES

The Military Specification, Flying qualities of piloted airplanes or the MIL-F-8785C is used to evaluate the flying qualities of Lateral-directional mode characteristics for the two aircraft models used. The following result is obtained:

The frequency, ω_{nd}, and damping ratio, ζ_d, of the dutch roll mode shall exceed the minimum values.

For the jet trainer aircraft SIAI – 211 for category B and level one, the values:

$\zeta_d = 0.092 > 0.08$
$\omega_{nd} = 4.52$ rad/sec > 0.4
$\zeta_d * \omega_{nd} = 0.4158 > 0.15$

So that the values of ζ_d, ω_{nd}, and $\zeta_d\ \omega_{nd}$ are satisfied the required values.

The value $\omega_{nd}^2 * \left|\frac{\phi}{\beta}\right|_d = 51.28(\text{rad}/\sec)^2 > 20$, therefore the minimum $\zeta_d\omega_{nd}$ shall be increased above the $\zeta_d\omega_{nd}$ minimum above by:

$\Delta\zeta_d\omega_{nd} = 0.014(\omega_{nd}^2 \left|\phi/\beta\right|_d - 20)$

So that: $\zeta_d\omega_{nd} = 0.4158 < 0.588$, not satisfied the needed requirement

For the fighter aircraft F4C, for category B and level one, the values:

$\zeta_d = 0.048 < 0.08$ (not satisfied)
$\omega_{nd} = 2.395$ rad/sec > 0.4 (satisfied)
$\zeta_d\omega_{nd} = 0.115 < 0.15$ (not satisfied)

The value $\omega_n^2 * \left|\frac{\phi}{\beta}\right| = 17.437(\text{rad}/\sec)^2 < 20$, therefore the minimum $\zeta_d\omega_{nd}$ shall not be modified.

The roll-mode time constant, T_r, shall be no greater than the appropriate value, for category B, level one:

For the jet trainer aircraft SIAI – S 211; $T_r = 0.133$ sec
For the fighter aircraft F4C; $T_r = 0.748$ sec

Thus the two models satisfied the needed requirement.

The spiral-mode time to double amplitude, T_{2s}, shall be not than the appropriate value for category B, level one.

For the jet trainer aircraft SIAI – S 211, time to double or half amplitude, $T_{2s} = 40.648$ sec
For the fighter aircraft F4C, time to double amplitude, $T_{2s} = 52.679$ sec

Thus the two models satisfied the needed requirement

7. CONCLUSIONS

The lateral-directional motion characteristics is evaluated for different values of the derivatives $C_{l\beta}$ and $C_{n\beta}$, and analyzed by root locus plots. A tie-in with handling qualities is provided by referring to a military specification MIL-F-8785C. It is shown the handling qualities requirements are given in terms of upper and lower bounds of frequency, damping and other modal characteristics of the airplane. The jet trainer aircraft satisfied the desired lateral-directional requirements and the fighter aircraft did not.

A lateral-directional eigenvalues flying qualities guidelines were used to predict the level of flying qualities of the aircraft models used in this thesis, the fighter aircraft (F4C) and the jet trainer aircraft (SIAI -211) are predicted to have level 1 by using roll rate oscillation and sideslip deviation criteria since they have intermediate values of $|\phi/\beta|_{dr}$, both guidelines satisfied to meet desired flying qualities.

The difference of the results for the two example models comes from the configuration and the nature of lateral stability modes for each model, specially for the jet trainer aircraft (spiral mode).

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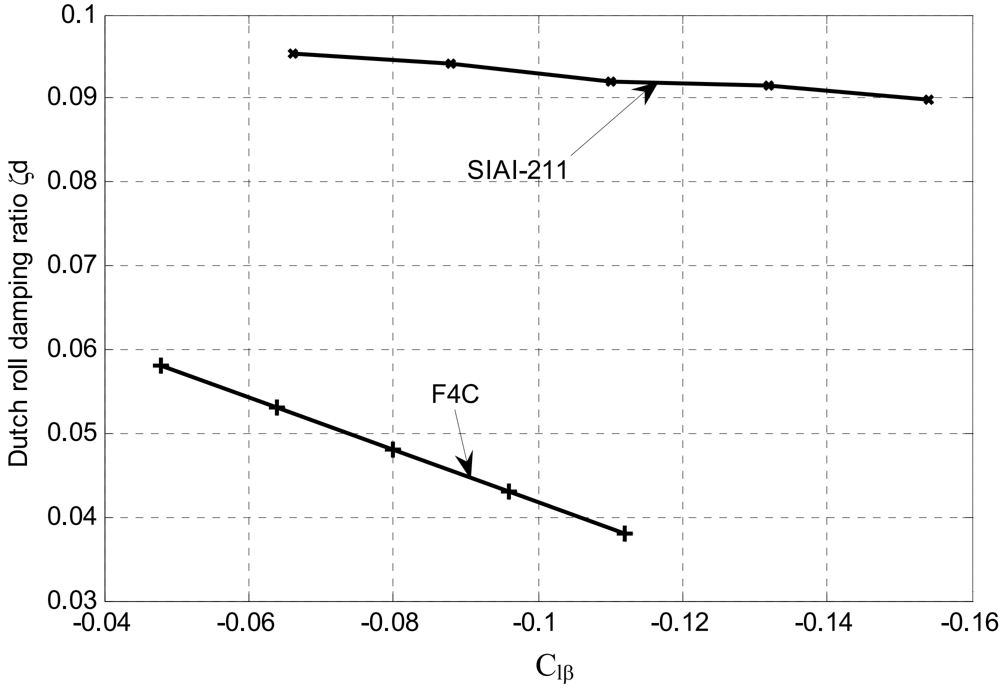

Fig.1. Effect of $C_{l\beta}$ on the dutch roll damping

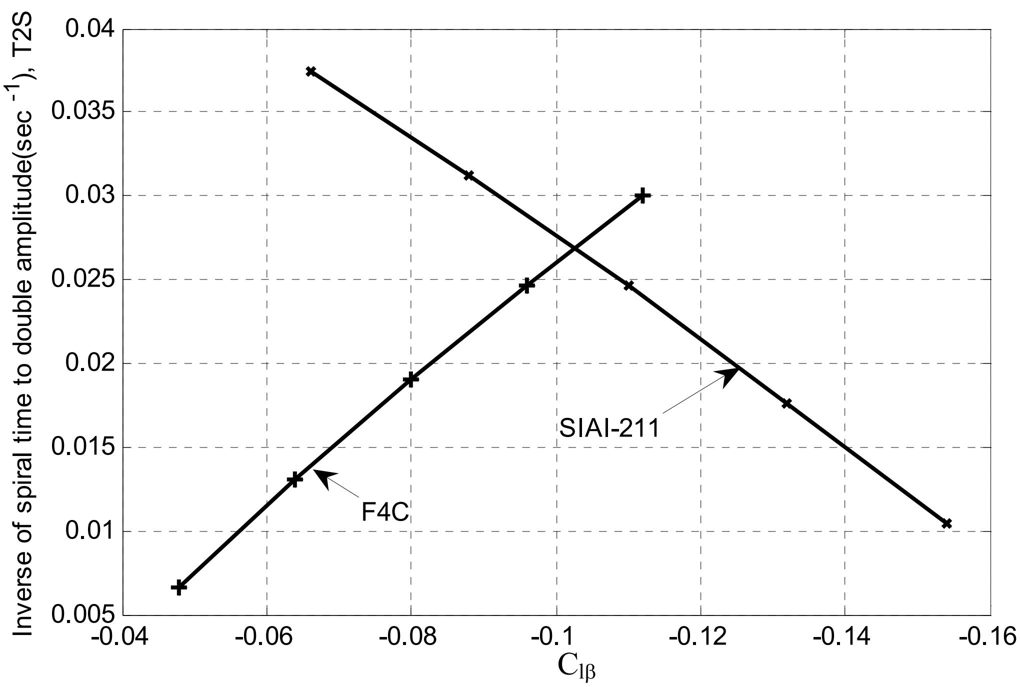

Fig.2. Effect of $C_{l\beta}$ on the inverse of spiral time to double or to half amplitude

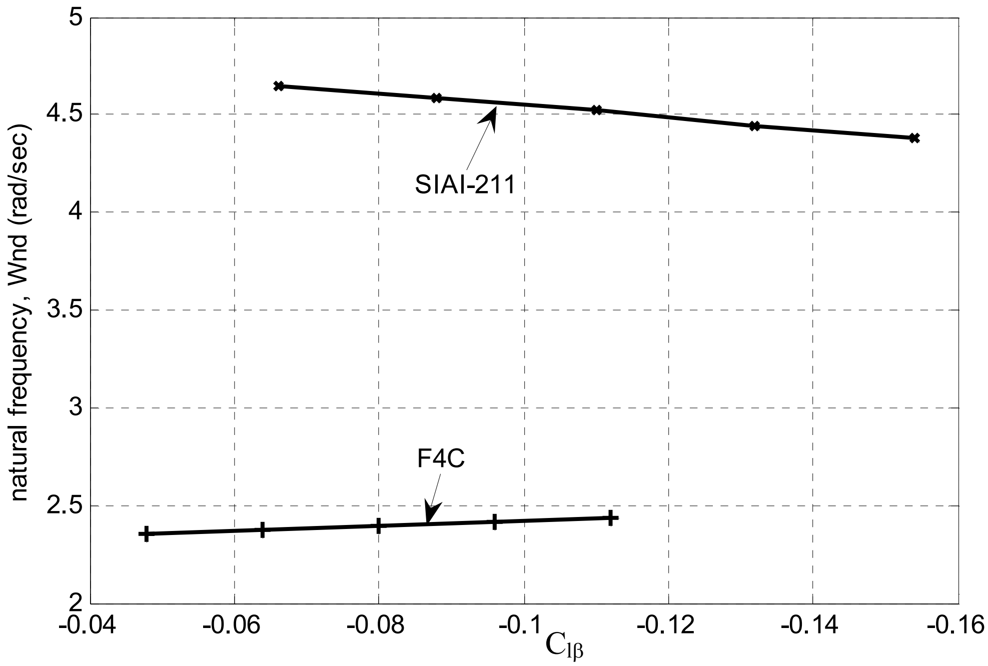

Fig.3. Effect of $C_{l\beta}$ on the natural frequency

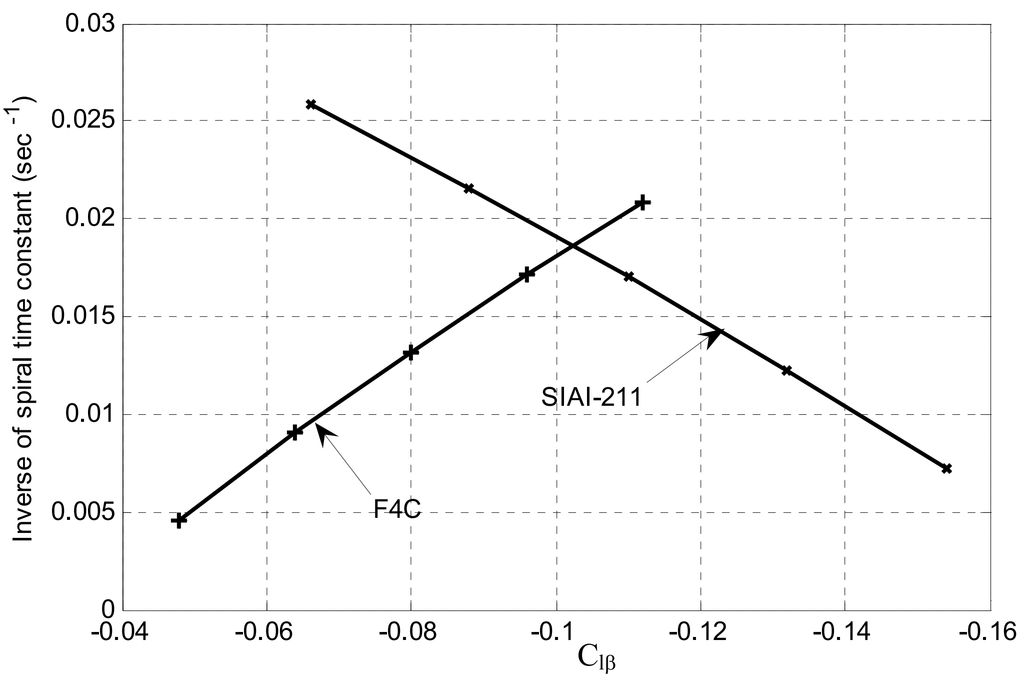

Fig.4. Effect of $C_{l\beta}$ on the inverse of spiral time Constant

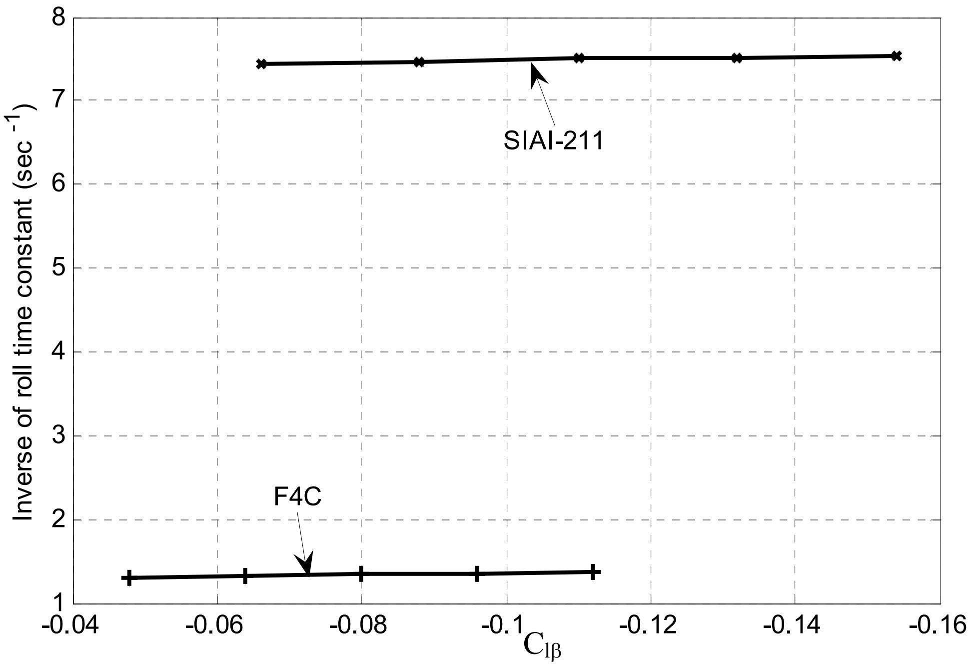

Fig.5. Effect of $C_{l\beta}$ on the inverse of roll time constant

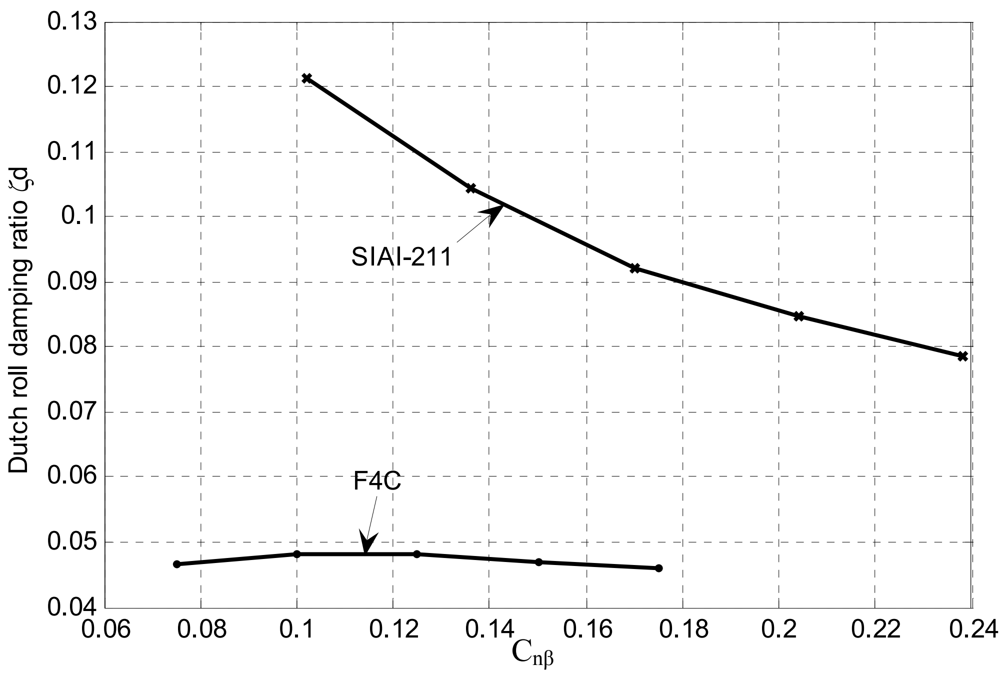

Fig.6. Effect of $C_{n\beta}$ on the dutch roll damping

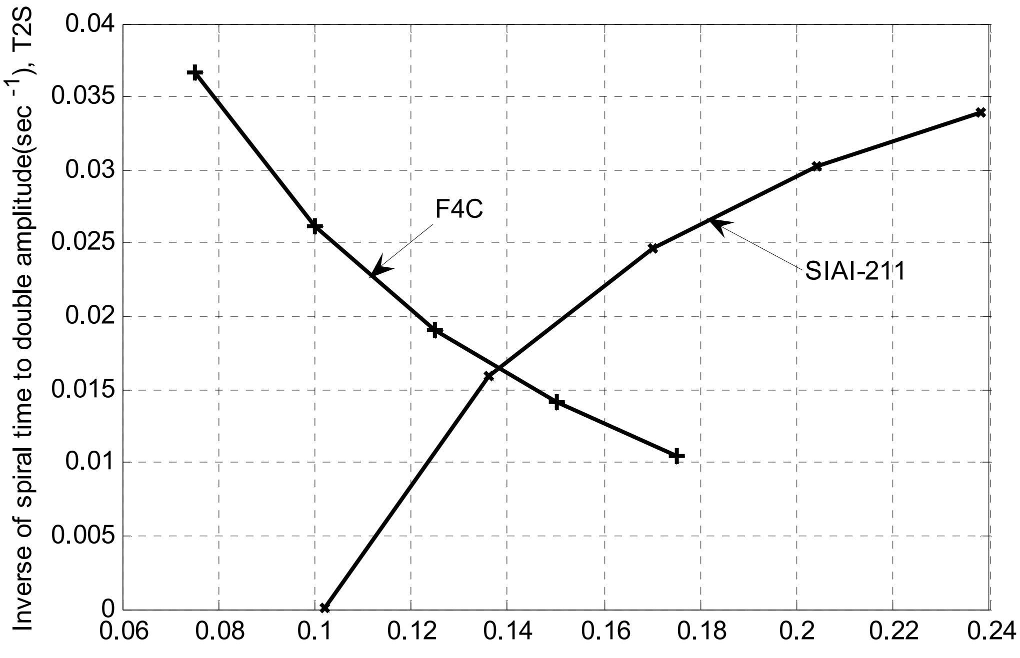

Fig.7. Effect of $C_{n\beta}$ on the inverse of spiral time to double or to half amplitude

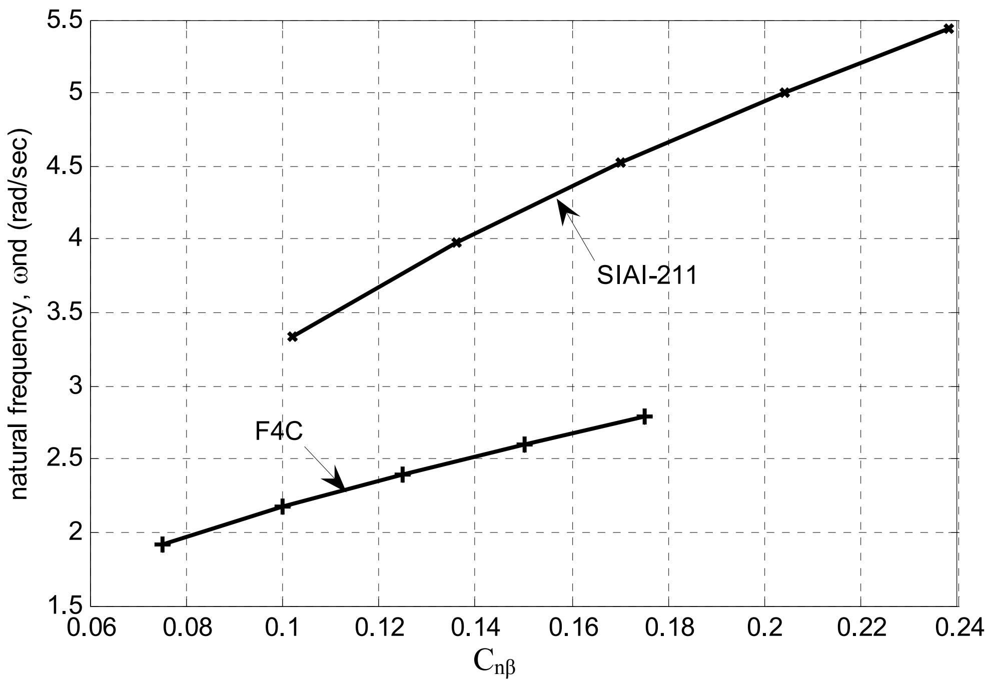

Fig.8. Effect of $C_{n\beta}$ on the natural frequency

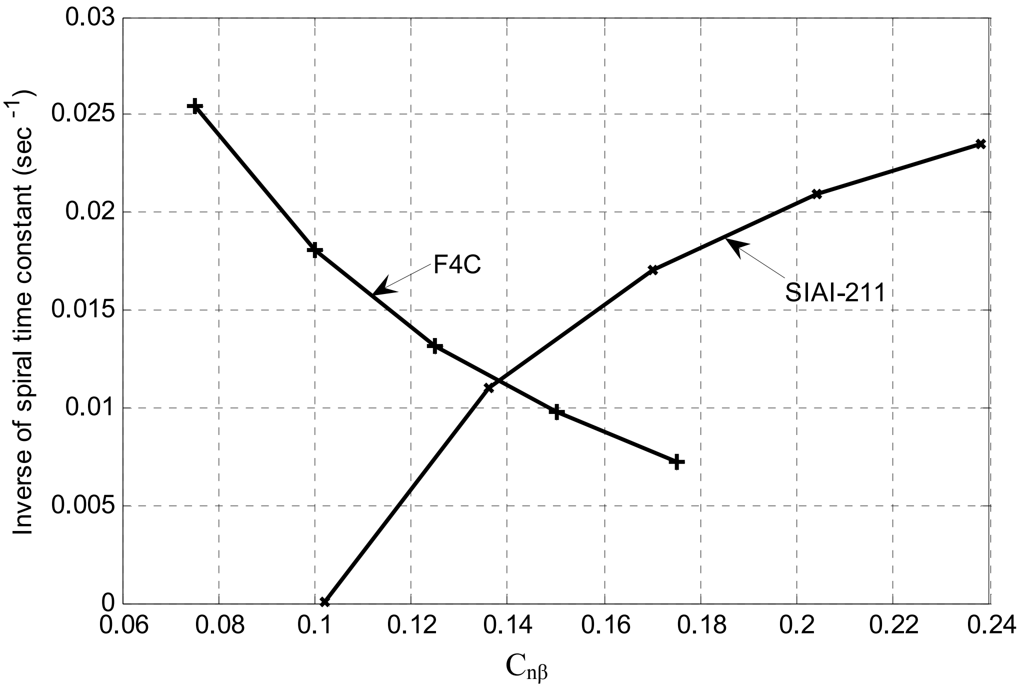

Fig.9. Effect of $C_{n\beta}$ on the inverse of spiral time constant

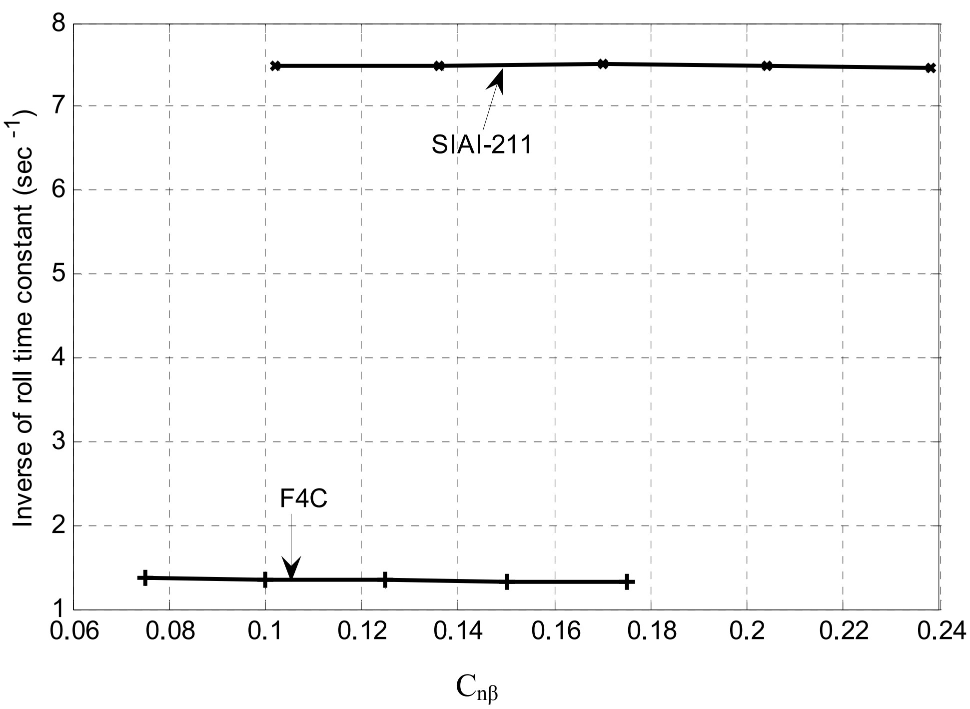

Fig.10. Effect of $C_{n\beta}$ on the inverse of roll time constant

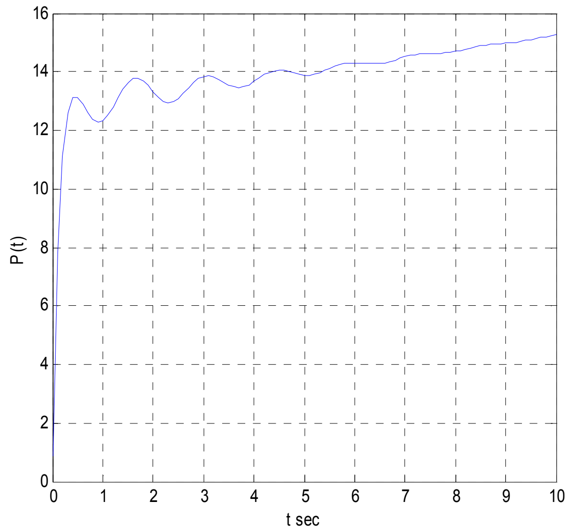

Fig.11. The roll rate due to a unit input in lateral stick for SIAI-211

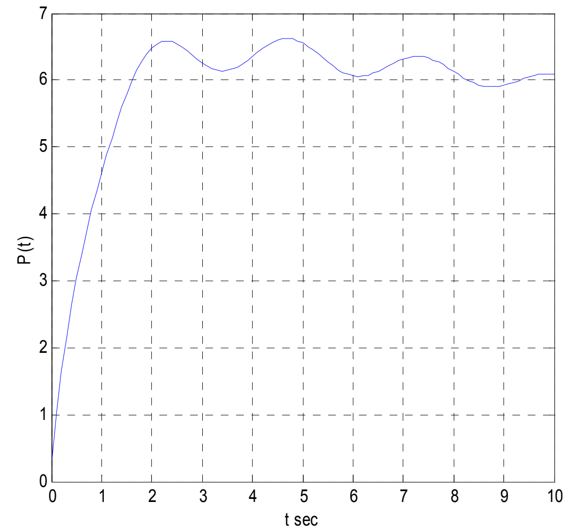

Fig.13. The roll rate due to a unit input in lateral stick for F4C

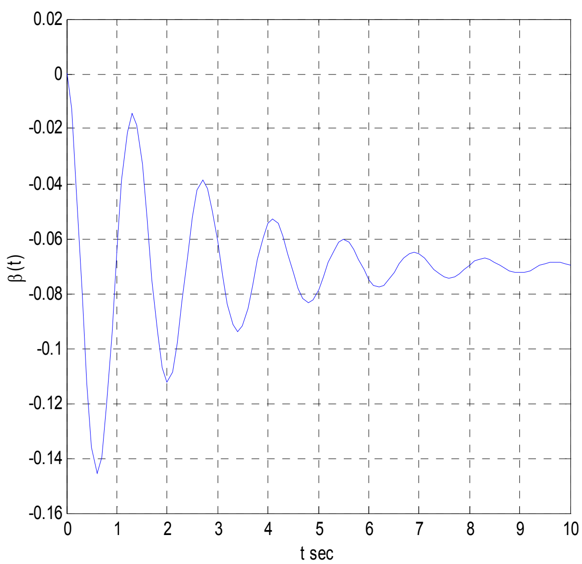

Fig.12. The sideslip due to a step input in lateral stick for SIAI- 211

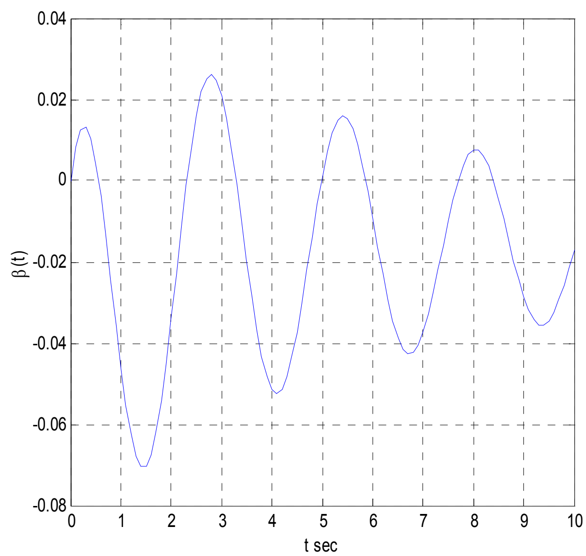

Fig.14. The sideslip due to a step input in lateral stick for F4C

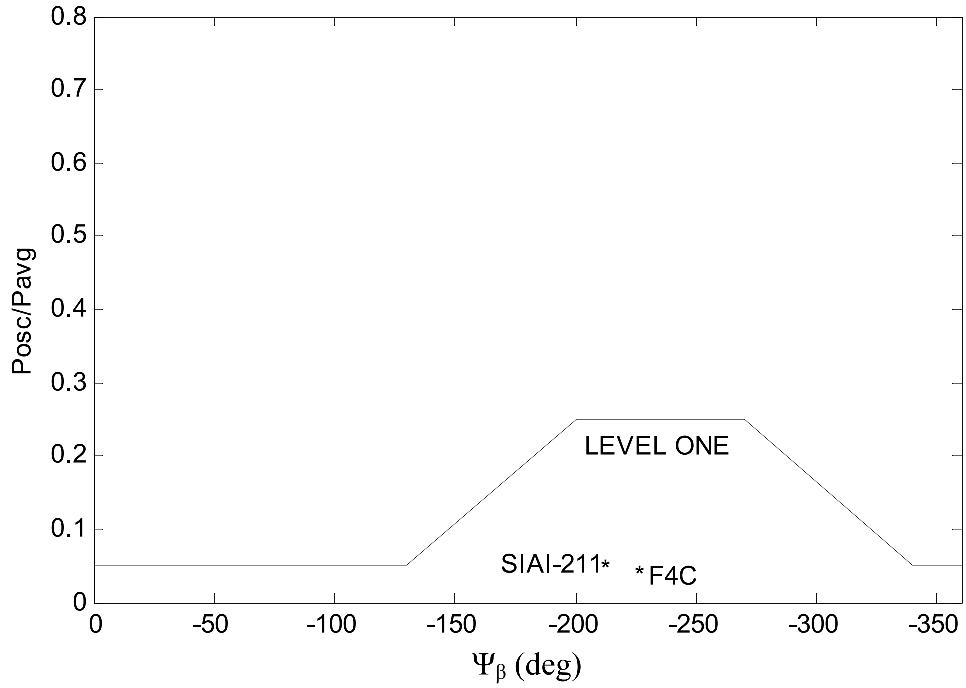

Fig.15. (p_{osc} / p_{avg}) Roll oscillation criteria limitation

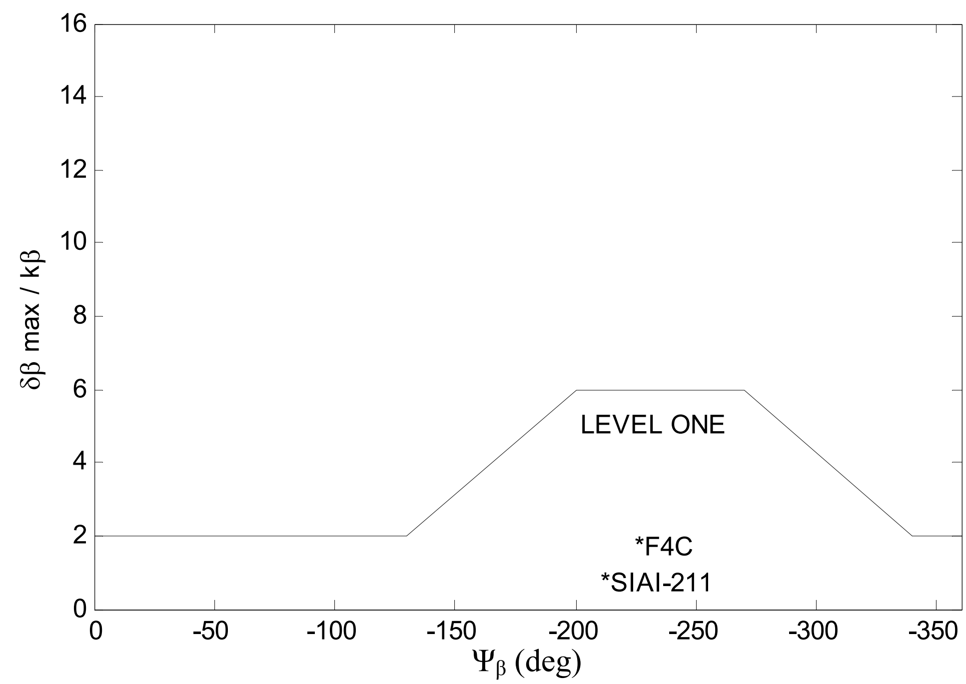

Fig.16. ($\Delta\beta_{max}$/ k_β) Sideslip deviation criteria limitations