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Roll Control Reversal of Variable Swept Wing in Supersonic Flow

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Abstract--- Roll control reversal of a variable swept wing is investigated in the present paper. The wing model is based on the Rodden-Love forward swept wing which is modified in the present work so that it can swept forward and backward. The flexural and torsional wing flexibilities are considered in the analysis so that their influence on the aileron control effectiveness can be assessed. The influence of the vertical tail is included in the trim analysis in several flight altitudes. A parametric study by varying the wing bending and torsional stiffness is conducted. The result shows that the aileron control effectiveness of the forward swept wing performs better than the backward swept wing for the present model.

Keywords: Roll; Control reversal; Swept wing; Aileron; Wing bending; Torsional stiffness

1 INTRODUCTION

Technological advancement in aviation sector has been a key element in the development of the aircraft design program. One of the most essential discussion has been about the effect of roll control reversal towards the swept forward wing. A large view of the studies focused on effectiveness of canard and wing as well as various methods of augmenting control surface effectiveness. Therefore, many researchers are working on military aircrafts and missile designs, improvement of the control surface specifically aileron to reduce adverse rolling moment. The study conducted by Rose and Jinu [1] shows that improving roll control reversal helps the performance of high aspect ratio and flexible wings especially at the cruising stage. On the other hand, the research performed by Borzachillo [2] stated that aileron effectiveness can be reduced by relatively thin wing as well as when the aircraft are approaching transonic speed. In addition, the research done by Woods-Vedeler, et al [3] illustrated that feedback control laws can significantly reduce the torsional load to approximately 61.6% during rolling maneuver. A similar research conducted by Platanitis and Strganac [4] supports that leading-edge control law can minimize roll control reversal. Yet another discussion from the same article claims that active control methods such as leading-edge control surface (LECS) and passive methods including structural enhancement can be used to minimize the control reverse phenomena. The research by Schult [5] indicates that the main issue at supersonic is providing effective control to reduce the loads due to the control deflection. The study conducted by Irving Abel [6] proclaim that static experimental techniques are useful in determining aileron effectiveness. Another research done by T. E. Noll, Eastep and Calico [7] suggest that active law for both leading-edge and trailing-edge improves the aeroelastic stability of forward swept wing. However, the conclusion given by Weisshaar and Nam [8] is combination of the structural and control design together is intense and thus optimal optimization is required to get reasonable aileron effectiveness. Finally, greater part of control effectiveness focused on techniques used to minimize reversal issue, but more can be done to understand the aileron control reversal in detail.

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2 METHODOLOGY

2.1. Model data

In the present work, the aileron control effectiveness is investigated by considering the wing flexibility in bending and torsion as well as wing sweep angle. The basic wing planform is based on the forward swept wing model of Rodden-Love airplane model [9, 10] as shown in Figure 1. The wing is geometrically untwisted and has an aspect ratio of 4, a taper ratio of 1 and wing span length of 40 ft.

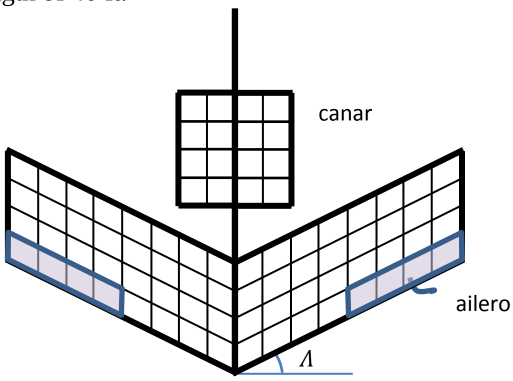

Fig. 1: Rodden-Love wing model

The aileron chord length is 2.5 ft with its span length of 10 ft as shown in Figure 1. The aileron rotational axis is at 75% of wing chord. Following [10], the wing weight is assumed to be 2,000 lb with the center of gravity at the 45% of the wing chord. The wing flexural and torsional

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stiffness are assumed to be each 0.25 x 10^9 lb-ft2 distributed uniformly along the wing span.

The fuselage length is 30 ft with the total weight of 6,000 lb per side and the center of gravity at 12.82 ft forward of the intersection of the fuselage and wing elastic axis. The centroidal moment of inertia is 892 900 lb-ft^2 and its cross sectional bending stiffness of I_y = 0.173611 ft^4 and I_z = 0.15 ft^4 and torsional stiffness of J = 0.5 ft^4 along the longitudinal fuselage axis.

The canard is a rectangular, symmetric, untwist plate planform with aspect ratio of 1. The axis of rotation is at its quarter-chord perpendicular to the fuselage longitudinal axis.

2.2. Aerodynamic model

For the supersonic flow, the boundary element lifting surface method of ZONA51 of MSc.Nastran is used [10]. The wing planform is divided into a number of trapezoidal panels with its sides parallel to the flow as shown in Figure 1. Each of the trapezoidal panel has a constant aerodynamic pressure represented at the center of the panel and has a control point at 0.85 of the panel chord. Since only roll maneuver is of the interest of the present study, it is possible to consider to model only half of the wing i.e by assuming the wing deformation follows the anti-symmetric modes.

The canard is modelled similarly with the wing. However, the aerodynamic of fuselage is not modelled as due to its small influence to the roll control reversal.

2.3. Aerodynamic-structural model interpolation

The structural finite element (FEM) data is connected to the aerodynamic boundary element (BEM) data through the use of the so called Spline interpolation in MSC.Nastran. For the present study the beam SPLINE2 model is used to specify a linear interpolation function between the FEM structural node deformations and the BEM aerodynamic panel loads.

2.4. Static aeroelasticity analysis

When the airplane is in rolling maneuver, the aileron is deflected in anti-symmetric mode. The aileron deflection creates torsional load to the wing such that it may twist the wing. This twist angle can be large for a flexible wing that may reduce the net of lift required to roll the airplane. Since the torsional load is related to the dynamic pressure and hence the flight speed, the effectiveness of the roll maneuver is related directly to the flight speed for a flexible wing.

Consider the roll coefficient C_l as the function of its related lateral stability derivatives as follow:

$$\boldsymbol{C_l = C_{l\,\delta a}\,\delta a + C_{lp}\,\frac{p\,b}{2V} + C_{l\dot{p}}\,\frac{\dot{p}b}{2g}} \tag{1}$$

where δa is aileron deflection angle, p is the angular roll speed and $\dot{p}$ is the angular roll rate. In the present study, only steady roll case is considered such that the last term in (1) can be ignored. If the stability derivatives $C_{l\,\delta a}$ and C_{lp} can be calculated from trim analysis, then the rolling helix angle can be obtained as

$$\boldsymbol{\frac{p\,b}{2V} = -\,C_{l\,\delta a}\,\delta a\,/\,C_{lp}} \tag{2}$$

where b is the wing span length. The helix angle shows that the roll speed p performance is a function of the stability derivatives. Since $C_{l\,\delta a}$ and C_{lp} is functions of flight speed, the helix angle in (2) can be plotted as function of speed, dynamic pressure or Mach number. The control reversal occurs when the helix angle above is equal to zero.

In the present study, the influence of the wing sweep angle on the roll control reversal effectiveness is investigated. There are three sweep angles Λ are considered: Forward swept wing (FSW) Λ = -30˚, straight wing (SW) Λ = 0˚ and backward swept wing (BSW) Λ = 30˚ where Λ is the angle of the quarter chord line and the fuselage lateral axis. To analyse the roll control effectiveness the helix angle in (2) is computed where the stability derivatives for flexible wing is calculated by using SOL 144 of MSC.Nastran. The air density and speed of sound is based on the US Atmospheric Standard of [15].

3 RESULTS AND DISCUSSION

3.1. Validation

By using Rodden-Love forward swept wind model described above by Figure 1, trim analysis is conducted by using case SOL 144 of MSC Nastran. The result presented in Table 1 shows the results are precisely comparable to Ref.10 hence giving excellent agreement. Therefore, this partly validates the procedures for the calculation of the roll control effectiveness.

Table 1: Comparing with Ref. 10 for M=0.9 at Sea Level.

	$cl_{\delta a}$	c_{lp}	δ_a(rad)	pb/2vδa
Present result	0.262	-0.445	1	0.589
Ref. 10	0.262	-0.445	1	0.590

3.2. Variations

The effect of flight altitude is mandatory in assessing the performance of the aircraft [12, 13] as it may affect its static and dynamic stability.

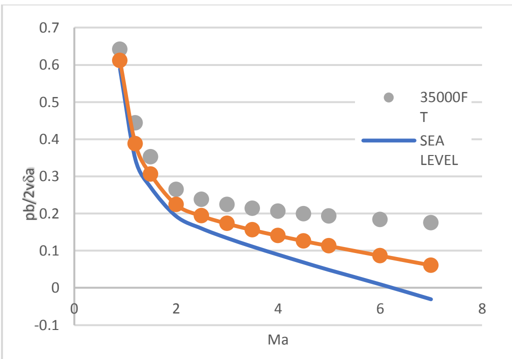

Fig. 2: Variation in altitude

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Following Figure 2 above, it has vividly indicated that sea level case is the most critical compared to higher altitudes. The density of the air at sea level is almost twice that of 10,000ft altitude, and the sound speed at sea level is also higher. This affects a bigger wing deformation which in turn decreases the critical control reversal speed.

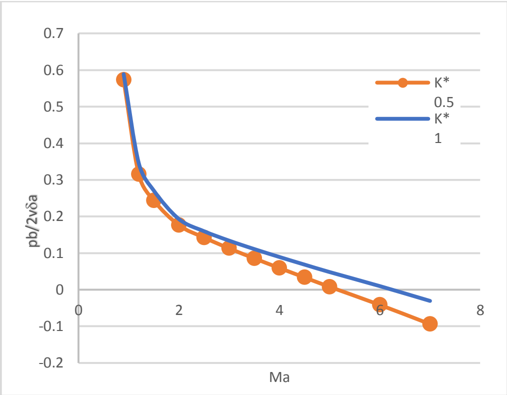

Fig. 3: Parametric study on the wing bending stiffness at sea level

From figure 2 above, the result show that the wing bending stiffness affects the control reversal. As expected, the reduction of the bending stiffness will reduce the efficiency of the aileron control surface.

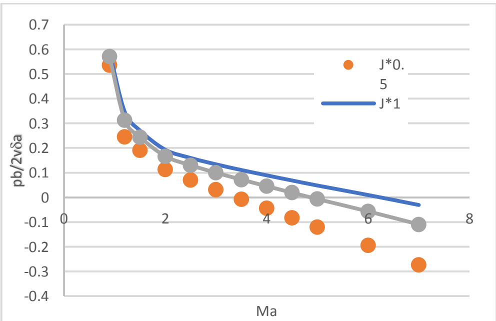

Fig. 4: Parametric study on the wing torsional stiffness at sea level

The figure 3 above as well shows that wing torsional stiffness affects the control reversal. Similarly, reducing the torsional makes the aileron surface more critical.

3.5. Influence of wing swept angle due torsional stiffness reduction

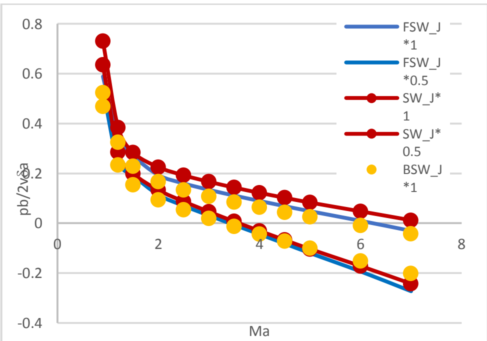

Fig. 5: Influence of wing swept angle due torsional stiffness reduction

The above diagram illustrates that back swept wings are more critical than the forward and straight wings. Moreover, back swept wings are more prone to aileron control reversal even after reducing the torsional stiffness of the wing.

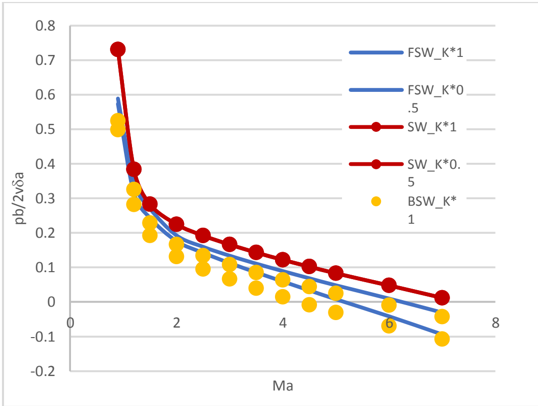

Fig. 6: Influence of wing swept angle due bending stiffness reduction

Furthermore, similar results are obtained, back swept wings are seen to be more critical before and after reducing the bending stiffness of the wing.

4 CONCLUSION

In general both the flexural and torsional stiffness affect the aileron roll control effectiveness. The higher the stiffness the higher also the control reversal speed. This conclusion is however not applicable for a straight wing. For a straight wing, the wing bending stiffness does not contribute to the wing angle of attack deformation and therefore does not have an effect on the roll control effectiveness. For swept wing, the forward swept wing roll control effectiveness is better than that of the backward swept wing. This is due to the fact that the forward swept bending deflection contributes to twist upwash, and the backward swept bending induces downwash deflection. The upwash will increase the angle of attack, and therefore increase the lift force different between left and right wing better. The altitude affects the air density and speed of sound such that in general the lowest the altitude the lowest also the control speed reversal speed.

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