Inertia-Coupled Coordinated Roll Maneuvers of Airplanes

N. Ananthkrishnan* and K. Sudhakar†
Indian Institute of Technology, Bombay 400076, India

Nomenclature

C_n	=	nondimensional yawing moment
k	=	aileron–rudder interconnect constant
n	=	yawing moment, N-m
α, β	=	respectively angle of attack and sideslip, rad
δe, δa, δr	=	respectively elevator, aileron and rudder deflection, rad

Subscript

δa, p, . . .	=	stability derivative with respect to δa, p, . . .

Introduction

RAPID rolling is an essential performance requirement for airplanes of the fighter and aerobatic categories. Large roll rates in fuselage-heavy aircraft lead to inertial coupling between the lateral-directional and longitudinal modes. Inertia coupling, also called roll coupling, has been described in detail by Hacker and Oprisiu.[1] Inertia-coupled roll maneuvers of airplanes may lead to jump phenomenon. A jump is a sudden change from one stable equilibrium state to another, the latter usually being a large roll rate, large sideslip state. Schy and Hannah[2] used the pseudo-steady-state (PSS) formulation to identify jump phenomenon with a saddle-node bifurcation of the state variables with aileron deflection as the parameter. It has been shown[3] that even when the control input (aileron deflection) is withdrawn before the roll rate builds up to the large postjump value, significant and rapid changes in sideslip may occur. While a large roll rate capability is generally desirable, the accompanying large sideslip often results in structural damage to the vertical fin and loss of pilot control.

The common solution to the problem of avoiding jump is to use an aileron–rudder interconnect (ARI). Carroll and Mehra[4] used bifurcation surfaces to suggest a nonlinear ARI relationship that would avoid regions of jump in state space. It has been shown by Ananthkrishnan and Sudhakar[5] that a linear ARI is adequate for jump prevention, and a specific methodology based on bifurcation theory has been proposed for this purpose. A linear ARI can be defined by $\delta r = k\delta a$. This alters the effective yaw generated by the aileron to $(n_{\delta a} + kn_{\delta r})\delta a$. Thus, the ARI can be seen to augment $n_{\delta a}$ which, through the yaw rate, influences the sideslip in a rolling maneuver. Essentially, $n_{\delta a}$ needs to be altered so as to balance the yaw produced due to roll rate n_p. For the aircraft model considered in Ref. 5, it was shown that positive (augmented) $n_{\delta a}$ values could be used to suppress sideslip and avoid jump. It is, therefore, of interest to study coordinated (zero sideslip) roll maneuvers in the presence of inertial coupling. Besides, the maximum roll rate achievable in a coordinated roll is a useful design parameter.

Jump Prevention

The dynamic model described in Ref. 5 is used for the present study. This model assumes linear aerodynamics, with nonlinearities arising from inertial and kinematic coupling. This corresponds to Aircraft B of Schy and Hannah,[2] for which data was borrowed from Etkin.[6] In addition, $Cn_{\delta r}$ is taken to be -0.01. The PSS solutions for the basic aircraft for a rolling pushover maneuver with $\delta e = 2$ deg are given in Refs. 2 and 7, and are not reproduced here. In short, at δa nearly -4 deg, the system shows a saddle-node bifurcation that results in a roll rate jump from about 100 deg/s to nearly 200 deg/s. The large roll rate solution also corresponds to very high sideslip. It was found[5] that the saddle-node bifurcation could be avoided and jump prevented if $n_{\delta a}$ were augmented to a value of 3.5 or more. The critical $n_{\delta a}$ of 3.48 ($k = -2.05$) was shown to correspond to the transformation of the saddle-node into a transcritical bifurcation. Thus, a specific methodology to evaluate the ARI constant becomes available.

PSS solutions for the case of an augmented $n_{\delta a} = 4.0$ ($k = -2.35$) are shown in Figs. 1 and 2 by dashed lines marked with empty circles. (These figures are plotted for only negative aileron deflections since the PSS curves are symmetric with respect to δa.) The PSS roll rate in Fig. 1 begins to saturate beyond $\delta a = -10$ deg, and the solutions, in fact, become oscillatory unstable around $\delta a = -18$ deg. Thus, the useful range of δa can be taken to be (-10 deg, 10 deg). Over this range, Fig. 2 shows sideslip β to be well-limited in spite of an increasing trend. This is clearly the effect of increasing the effective $n_{\delta a}$, which has suppressed the sideslip, though not reduced it to zero. The time response for this combination of

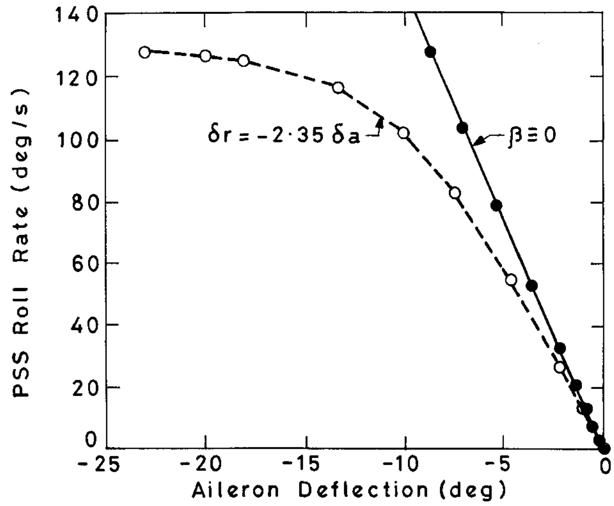

Fig. 1 PSS roll rate solution with varying aileron deflection for both linear ARI[5] and zero sideslip cases.

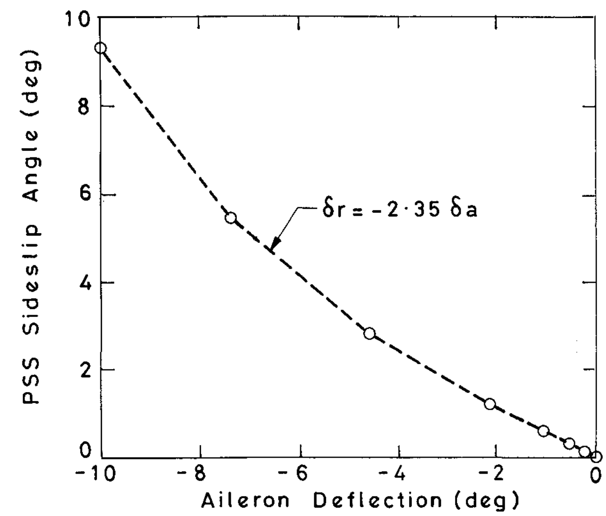

Fig. 2 PSS sideslip solution with varying aileron deflection for linear ARI[5] case.

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*Visiting Faculty Member, Department of Aerospace Engineering.
†Associate Professor, Department of Aerospace Engineering. Member AIAA.

control inputs has been confirmed to be satisfactory by numerical simulations.[5,7]

Coordinated Rolls

In a coordinated roll, sideslip is maintained equal to zero, the rudder being appropriately deflected for this purpose. PSS solutions for the previously mentioned model with an extra condition, $\beta = 0$, are solved and the required rudder deflection simultaneously determined. These are plotted in Figs. 1 and 3 by full lines marked with filled circles. In the absence of any sideslip, the roll rate shows, as expected, an ideal linear relation with aileron deflection. However, the PSS roll rate for this case in Fig. 1 is unstable for δa beyond -8 deg. This has been verified by numerical simulation for a solution point (filled circle of Figs. 1 and 3) of $\delta a = -8.6$ deg. The divergence in α and β has been recorded in Fig. 4. In any case, the maximum achievable stable roll rate is about the same for either of the curves in Fig. 1.

The $\delta r - \delta a$ curve in Fig. 3 for a coordinated roll is nonlinear with more rudder deflection being needed to maintain zero sideslip for large aileron deflections. If a linear interconnect were derived from this curve by taking the interconnect constant k to be the slope at the origin, the value of k would turn out to be much less than the critical value of -2.05 required to avoid jump.

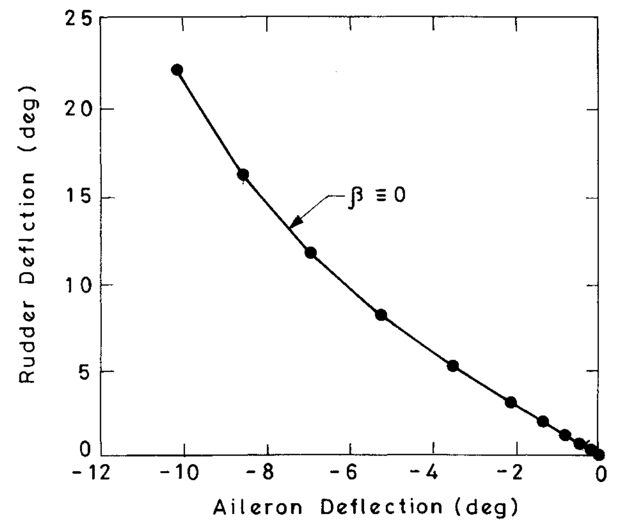

Fig. 3 Rudder deflection solution with varying aileron deflection for zero sideslip case.

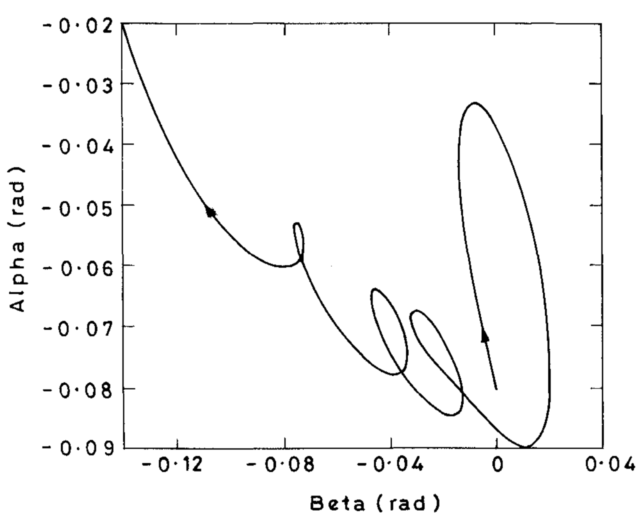

Fig. 4 Trajectory illustrating unstable PSS solution for zero sideslip case with $\delta e = 2$ deg, $\delta a = -8.6$ deg, and $\delta r = 16.3$ deg.

Discussion

Coordinated rolling gives an ideal linear $p - \delta a$ curve, and ensures zero β for all conditions; however, this requires a nonlinear ARI relationship. The PSS solutions for a coordinated roll are unstable beyond $\delta a = -8$ deg. Although, the maximum achievable stable roll rate is comparable to that obtained in the previous study,[5] the onset of instability is sudden.

On the other hand, the PSS solutions obtained from a linear ARI using $k = -2.35$ reported in Ref. 5 show a gradual saturation of the roll rate. The eventual instability around $\delta a = -18$ deg is oscillatory. This solution also gives a larger range of usable δa values, though there is no significant advantage in terms of roll rate. Also, the sideslip in this case (Fig. 2) is not exactly zero, but well-restricted over the required range of aileron deflections.

Conclusions

The present study has shown that the condition for nonexistence of jump based on bifurcation theory cannot be routinely replaced by one derived from the requirement of a coordinated roll, even when the formulation contains inertial coupling terms.

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Effects of Spanwise Blowing on a Delta Wing with Vortex Flaps

Lance W. Traub*
University of the Witwatersrand, Johannesburg, South Africa

Introduction

SEVERAL concepts to enhance and control the formation of leading-edge vortices on slender swept wings have been studied. Typically, concepts that significantly increase per-

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*Graduate Student, School of Mechanical Engineering, Branch of Aeronautical Engineering, 1 Jan Smuts Ave., PO Wits, 2050; currently at Texas A&M University, College Station, Texas.