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Stability of Asymmetric Equilibrium Flight States

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Abstract

CONTROLS-FIXED dynamic stability of asymmetric trim states of a large, multiengine jet transport which are dictated by engine failure at low speed is considered. Eigenvalue (root) loci obtained from coupled equations of motion for a range of sideslip angles are presented. These loci indicate that as long as the equilibrium sideslip angle is kept small in magnitude there is little difference in the stability characteristics for symmetric and asymmetric thrust conditions. However, when a large magnitude sideslip angle is present in the equilibrium state the coupling effects due to sideslip result in appreciable differences in the coupled motion counterparts of phugoid, spiral, and Dutch roll modes. In particular, under a condition of left outboard engine out and large positive sideslip, the "phugoid" mode becomes unstable. The "spiral" mode, under the same engine-out condition, is unstable for both positive and negative sideslip angles.

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Introduction

Failure of an engine of a multiengine aircraft during takeoff, or climbout, produces a critical situation since asymmetric thrust effects are prominent and aerodynamic control effectiveness is limited.[1] If an engine failure occurs when the aircraft is either already airborne or if takeoff cannot be aborted, the aircraft must be controllable. Although not conclusive on the question of controllability, the controls-fixed, dynamic stability characteristics of asymmetric equilibrium flight states which are achievable under engine-out conditions are important since they determine to what extent feedback control by the pilot may be necessary.

Stability characteristics of asymmetric flight states of high performance aircraft has been an area of considerable interest.[2-5] However, although the significance of the effects of large equilibrium sideslip on the stability of large multiengine aircraft has been investigated,[6] the combined effects of asymmetric thrust and sideslip apparently have not been considered.

Mathematical Model

The model consists of coupled (longitudinal and lateral) equations of motion for a large, four-engine jet transport (KC-135A). The stability of motion near equilibrium states in which the controls are deflected to counteract effects of asymmetric thrust and/or sideslip was studied using standard techniques. The linear system which yields the stability information is eighth order and consists of equations for perturbations in airspeed, V, angle of attack, α, pitch rate, q, flight-path angle, γ, velocity roll angle, ϕ_w, roll rate, p, yaw rate, r, and sideslip angle, β. Coupling terms of three types are present in the equations. First, because the lateral control coefficients are functions of angle of attack, when the equilibrium control deflections are not zero the perturbation in angle of attack, $\Delta\alpha$, appears in the "lateral" equations. Second, when β_e (the equilibrium value of β) is nonzero, coupling arises from kinematic terms in both the "lateral" and the "longitudinal" equations. Third, also when $\beta_e \neq 0$, certain coupling terms are present because many lateral stability derivatives, for example, C_{l_β}, are functions of angle of attack.

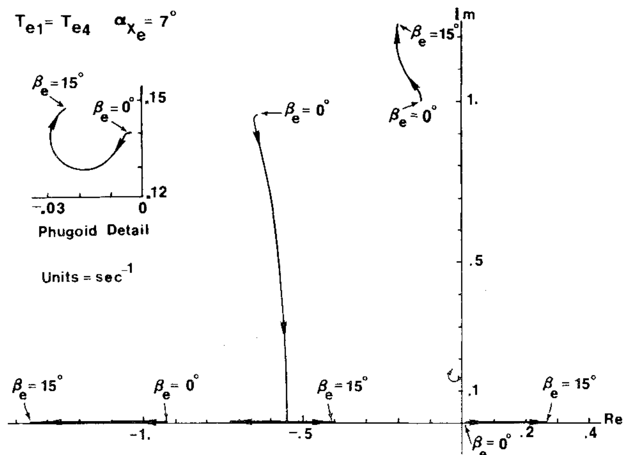

Fig. 1 Eigenvalue loci for $\alpha_{x_e} = 7$ deg and symmetric thrust.

Results

An iterative method was first used to obtain equilibrium flight conditions for symmetric thrust (44,500 N per engine) and specified angle of attack and sideslip angle. Eigenvalues of the corresponding linear system were computed. By varying the sideslip angle, the eigenvalue loci shown in Fig. 1 were obtained. Only results for positive values of β_e are shown, because results for the same *magnitude* of β_e are identical. The trim conditions are given in Table 1. Notable characteristics of the loci are that increasingly larger equilibrium sideslip results in an increasingly unstable spiral mode.‡ The phugoid mode becomes more stable as β_e is increased until $\beta_e \simeq 14$ deg. Sideslip results in a more stable Dutch roll mode and a less oscillatory short-period mode. The damping in the rolling mode is increased by sideslip. As expected, there is also significant coupling of modes (see Ref. 7 for eigenvectors) when β_e is large.

Trim states were next found for the case of asymmetric thrust which exists after the left outboard engine has failed (see Table 1). There are only minor differences in equilibrium flight speed, flight-path angle, and velocity roll angle.

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‡The classical phugoid, short-period, spiral, roll, and Dutch roll modes are defined for symmetric equilibrium flight. The terms as used here refer to the modes which evolve from the classical modes of the same name when asymmetric factors are introduced.

Table 1 Equilibrium conditions, $\alpha_{x_e} = 7$ deg

	β_e[a]	V_e	γ_e	ϕ_{w_e}	δ_{e_e}	δ_{w_e}[b]	δ_{r_e}
Symmetric thrust	0	86.12	4	0	−2.19	0	0
	10	90.85	4	6.25	−3.18	65.3	14.4
	15	93.71	4.6	10.03	−9.07	89.7	21.3
Asymmetric thrust	−10	91.0	1.54	−3.73	−3.31	60.5	−22.2
	−5	88.4	1.34	−6.09	−1.86	29.3	−15.6
	0	86.8	1.41	2.05	−2.01	6.2	−8.5
	5	89.0	1.24	4.76	−1.55	40.2	−0.7
	10	91.4	1.46	7.95	−3.04	70.0	6.8
	15	94.2	2.07	11.80	−8.95	93.7	14.0

[a] All angles in degrees. [b] The aircraft has ailerons and spoilers. Maximum aileron deflection is achieved when $\delta_w = 100$ deg.

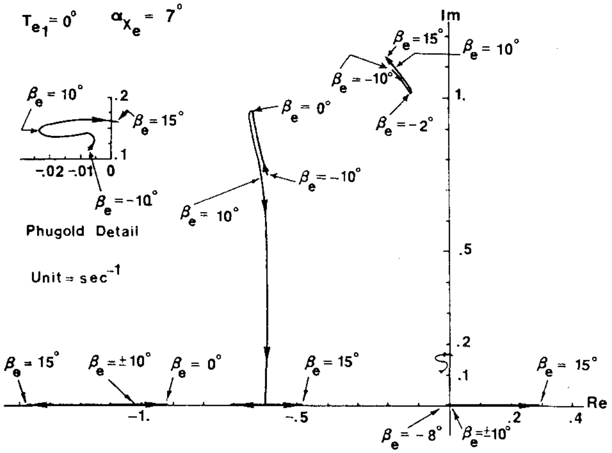

Fig. 2 Eigenvalue loci for $\alpha_{x_e} = 7$ deg and asymmetric thrust.

However, there are some differences in the eigenvalue loci (see Fig. 2). Since negative sideslip acts to counteract the torque due to asymmetric thrust, while positive sideslip produces an additional negative yawing moment, such differences are not unexpected. The principal ones appear in the phugoid and Dutch roll loci. First, eigenvalues for β_e's of the same magnitude, but different signs, are not identical when asymmetric thrust exists. Second, negative sideslip produces more stable spiral and Dutch roll modes. Third, positive sideslip of significant magnitude results in an unstable phugoid mode.

Conclusions

As long as zero equilibrium sideslip is maintained, the effect of trimming the subject aircraft in an asymmetric thrust condition is small. That is, the times to half-amplitude in all except the rolling mode are only slightly increased. Trim states in which $\beta_e \neq 0$ are generally less stable if asymmetric thrust is present. The potentially most serious effects combining asymmetric thrust and sideslip are the coupling of modes and the loss of damping in the phugoid mode. Of the two, the coupling of modes, due primarily to $\beta_e \neq 0$ as opposed to asymmetric thrust, appears to be the biggest problem. If, however, adverse sideslip builds up rapidly immediately following an engine failure, an unstable phugoid mode may exist for a period of time.

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