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Engineering Notes

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Flight Dynamics of Unguided Rockets with Free-Rolling Wrap Around Tail Fins

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Introduction

THE technical relevance of wraparound fin configurations is justified by their convenient packaging characteristics for ammunitions launched from a tube or from the internal bays of aerial platforms. This note is the extension of [1] to wraparound fin configurations with free-to-roll tail arrangements.

Differential Equation of Motion

The lateral motion of the free-rolling tail rocket can be obtained by combining the vectorial equations for body and tail in their own nonrolling systems of axes at the respective center of gravity (c.g.) (Fig. 1).

The nomenclature is taken from the meeting paper version. For a wraparound fin configuration the resulting differential equation at the global c.g. in terms of the complex angle of attack ($\tilde{\xi} = \tilde{\beta} + i\tilde{\alpha}$) is

$$\tilde{\xi}'' + [H + i(I - \sigma\phi'_g)]\tilde{\xi}' - [M + U + i(N + \sigma\phi'_g T)]\tilde{\xi} = \sigma\phi'_g \frac{gD}{V^2} - F_B e^{i\phi_B} - F_T e^{i\phi_T} \tag{1}$$

where H, I, M, U, N, T, and $\sigma\phi'_g$ stand for

$$\begin{aligned} H &= C^*_{L\alpha} - C^*_D - k_t^{-2}(C^*_{Mq} + C^*_{M\dot{\alpha}}) \\ I &= C^*_{N\beta} + k_t^{-2}(C^*_{Mr} - C^*_{M\dot{\beta}}) \qquad M = k_t^{-2}C^*_{M\alpha} \\ U &= -[\sigma\phi'_g C^*_{N\beta} - k_t^{-2}\phi'_T C^*_{Mp\alpha}] \qquad N = k_t^{-2}C^*_{M\beta} \\ T &= C^*_{L\alpha} + k_a^{-2}C^*_{Mp\beta} \qquad \sigma\phi'_g = \sigma_B\phi'_B + \sigma_T\phi'_T \end{aligned} \tag{2}$$

The aerodynamic coefficients were obtained summing up the body and tail contributions, and the effect of body and tail asymmetries was introduced by two small forcing functions at body and tail roll rate frequencies. The lack of mirror symmetry of the tail introduces the aerodynamic terms: $C_{NTp\alpha}$, $C_{N\beta}$, C_{Nr}, $C_{N\dot{\beta}}$, $C_{M\beta}$, $C_{Mp\alpha}$, C_{Mr}, and $C_{M\dot{\beta}}$.

Resonance and Lock-in

The presence of two trim angles due to body and tail asymmetries makes possible the existence of two resonant conditions that for practical purposes occur when the body or the tail rate match the zero spin pitch frequency $\sqrt{-M}$. In body and tail fixed axes, respectively, the resonant trim angles are

$$\xi_{Br} = \frac{F_B}{-i[\sqrt{-M}(H - \sigma_B T) - N - \sigma_T T\phi'_T]}; \quad \xi_{Tr} = \frac{F_T}{-i[\sqrt{-M}(H - \sigma_T T) - N - \sigma_B T\phi'_B]} \tag{3}$$

The side moment term N, due to the lack of mirror symmetry of the tail, is present in the denominators of the trim angles and can result in large variations in the amplitude of trim at resonance [2].

The resonant lock-in condition appears when induced roll moments due to trim angles [3] originated by configurational asymmetries cancel the roll acceleration pushing the missile into a state of sustained resonance.

By limiting all possible configurational asymmetries to a body lateral center of mass offset, the trim angle is caused by the drag force (Fig. 2). The associated normal force yields a negative roll moment as

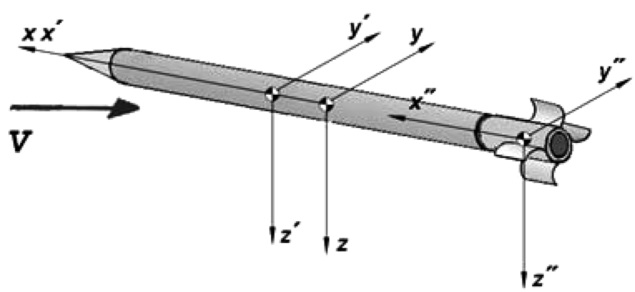

Fig. 1 Nonrolling systems of axes.

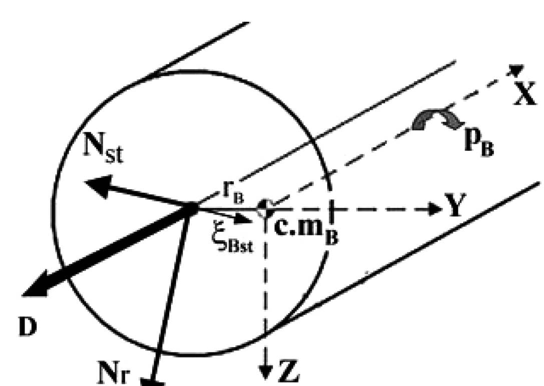

Fig. 2 Laterally offset body c.g. and trim response for static and resonance conditions.

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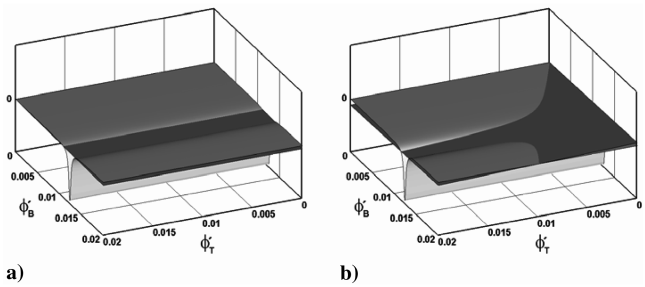

Fig. 3 Body plane and induced roll moment intersection.

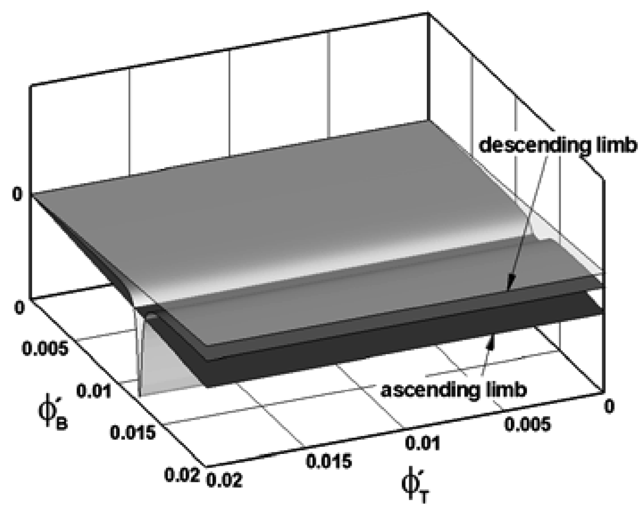

Fig. 4 Gravity effect on K_{pB}.

shifting occurs with the exception of a small range at low body rates due to the wraparound fin side moment. Steady-state solutions for body roll, including sustained resonance, occur at the intersecting points of the plane of the left-hand side and the induced roll surface of the right hand in the body roll equation:

$$\phi'_B\left(K_{pB} + \frac{V_{fB}}{V}\right) - \frac{V_{fB}}{V}\phi'_T = K_{iB} \tag{4}$$

where:

$$K_{pB} = -(C_D^* + k_{aB}^{-2}C_{lpB}^*) \qquad V_{fB} = k_{aB}^{-2}\frac{\kappa}{m_B D} \qquad K_{iB} = k_{aB}^{-2}C_{liB}^* \tag{5}$$

The intersection between the plane and the surface is shown in Fig. 3a, in which where the frictional term (V_{fB}/V) was neglected. The effect of the body-tail friction is depicted in Fig. 3b where the steady solutions are seen to be tail-rate dependent.

The slope of the plane for negligible friction (Fig. 3a) given by K_{pB} is, for most configurations, a small negative value. If the curvature of the trajectory is introduced, K_{pB} presents an additional term due to gravity [4]:

$$K_{pB} = -(C_D^* + k_{aB}^{-2}C_{lpB}^* + g\sin\Theta D/V^2) \tag{6}$$

On the descending limb of a trajectory positive values of K_{pB} can be attained (Fig. 4). Therefore by assuming that lateral center of mass offsets are the only usual body configurational asymmetries, the associated negative roll moments prevent body lock-in conditions to develop when K_{pB} is positive.

Conclusion

A free-rolling tail fall store may elude body lock-in onset because of its one way descending path and hence the chance of sustained resonance reduces greatly. This feature may explain the reported [5] good behavior of free fall stores equipped with spinning stabilizers compared to the same stores with fixed stabilizers. Free-rolling tail configurations with wraparound fins can take full advantage of this characteristic while retaining their packaging expediency to be launched from the internal bays of aerial platforms.

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