Engineering Notes

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National Aerospace Plane Longitudinal Long-Period Dynamics

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Introduction

OVER the years many papers have been published on the longitudinal dynamics of lifting hypersonic vehicles, for example those by Etkin and Porter.[1,2] These authors used linear analysis of hypersonic lifting vehicles in equilibrium flight to analyze the characteristic longitudinal long-period modes. These modes consisted of the aperiodic height mode (caused by the variation of atmospheric density with altitude) and the more conventional oscillatory phugoid mode. These authors also investigated the sensitivity of the longitudinal long-period modes to the variation of thrust with Mach number M and altitude. However, vehicles currently proposed for the National Aerospace Plane Program (NASP) will have different operating conditions and propulsion systems than those considered by Etkin and Porter. This Note extends some of the results of Etkin and Porter to propulsion system characteristics and flight conditions more typical of a NASP vehicle. Linear analyses using mass and aerodynamic data from Etkin were used.[1] Results are presented in terms of phugoid damping and height-mode stability. Some basic feedback control strategies are also considered.

Results and Discussion

Propulsion System Influences

Figure 1 illustrates the trend of phugoid damping ratio and height-mode root with Mach number as influenced by dynamic pressure for a simple airbreathing propulsion system thrust law. The thrust law approximates a turbojet; that is, the thrust is assumed to be unaffected by Mach number but proportional to atmospheric density. It can be seen that the phugoid damping ratio deteriorates as Mach number increases. The height-mode roots also become less stable. The influence of dynamic pressure is not great for the range investigated, as indicated by the shaded region. Advanced airbreathing propulsion systems proposed for hypersonic flight are more complicated than the simple thrust law just discussed. Figure 2 presents a typical thrust variation for an advanced propulsion system at constant dynamic pressure. It can be seen that there are significant variations in thrust throughout the Mach number range. These variations are associated with traversing the transonic region and changes in engine cycles in the $M=3.0$ and $M=6.0$ regions.

The slope of the thrust variation with Mach number can significantly affect long-period dynamics. From Fig. 2 it can be seen that at high Mach number, the slopes are relatively shallow and these influences are not expected to be significant. The most rapid thrust changes occur in two regions roughly corresponding to the engine cycle changes. Regions *a*, *b*, and *c* are regions of maximum positive slope, zero slope, and maximum negative slope, respectively. These regions will be referred to in the subsequent discussion.

The thrust level can also strongly affect the stability of long-period modes. Care must be taken in interpreting thrust level effects, however, in that for thrust-to-drag ratios greater than 1, the vehicle is accelerating. The analysis is adequate, however, for assessing initial tendencies and trends, particularly for large mass vehicles in which the accelerations are lower.

The influence of thrust slope and thrust-to-drag ratio on the phugoid damping ratio and height-mode root was investigated from $M=3.0$ to $M=18.0$. Thrust slope influences were found to be significant only in the $M=3.0$ range, as a result of the rapid reduction in thrust slope as Mach number increases (Fig.

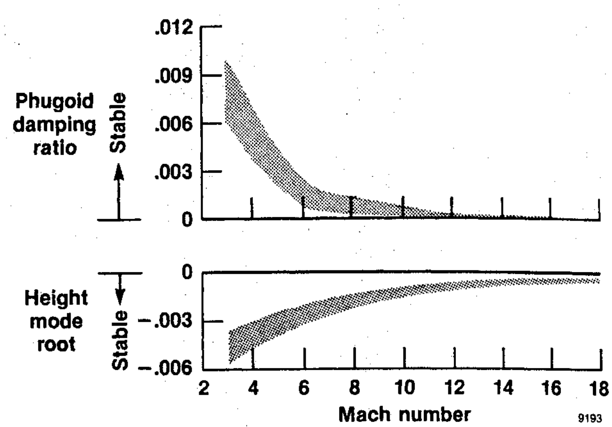

Fig. 1 Variation of phugoid damping ratio and height-mode root for a simple air breather; dynamic pressure 500 to 2000 lb/ft².

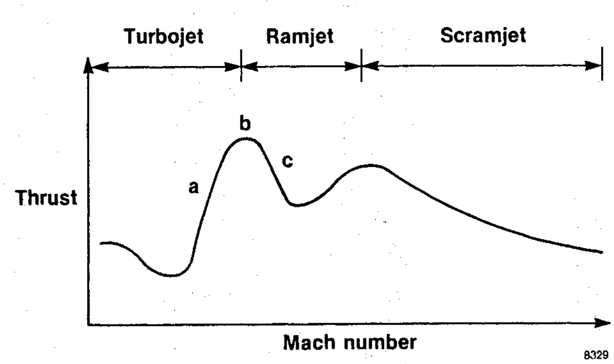

Fig. 2 Typical thrust variation of an advanced air breather.

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Table 1 Combined effects of thrust slope and thrust level at $M = 3.0$

Thrust slope	Thrust-to-drag ratio	Phugoid damping ratio	Height-mode root
a	1	-0.04[a]	0.04[a]
b	1	0.01	-0.005
a	4	-0.27[a]	0.02[a]
b	4	-0.16[a]	-0.02

[a]Unstable.

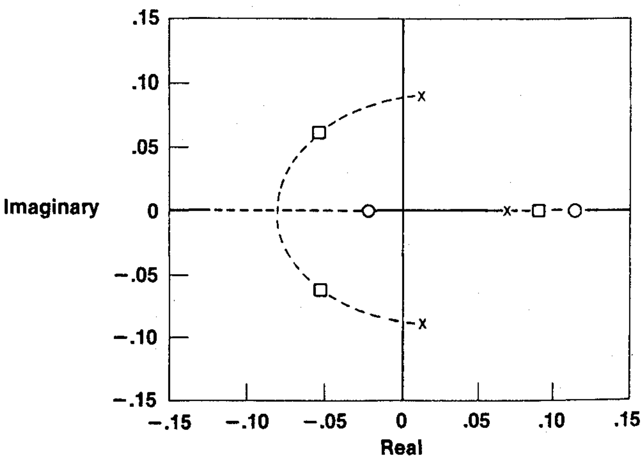

Fig. 3 Root locus of advanced air breather with pitch attitude feedback (long period).

2). As noted by Stengel, positive thrust slopes were destabilizing to both the phugoid and height mode.[3] On the other hand, thrust level primarily influenced phugoid damping. Increases in thrust-to-drag ratio were destabilizing and these effects were not grossly affected by Mach number. Consequently, the most critical combination of thrust slope and thrust level occurred at $M = 3.0$. A summary of $M = 3.0$ results is presented in Table 1.

Note that thrust slope b equals zero and corresponds to a simple air breather. It can be seen that the advanced air breather (thrust slope a) has more unstable long-period modes than the simple air breather (thrust slope b) at low and high thrust-to-drag ratios (1 and 4). Increasing the thrust-to-drag ratio significantly destabilizes the phugoid, resulting in a much more negative damping ratio for both thrust slope cases. Increasing the thrust level stabilizes the height mode. However, for thrust slope a, the height mode is still unstable, whereas for thrust slope b, a nearly neutral mode becomes significantly stable. The difference between a simple air breather (b) with no thrust level effects ($T/D = 1$) and an advanced air breather (a) at a $T/D = 4$ is especially noteworthy. It can be seen that the former has a slightly stable phugoid damping ratio of 0.01 and a slightly stable height-mode root of -0.005. The latter (advanced air breather) has a significantly unstable phugoid damping ratio of -0.27 and a significantly unstable height-mode root of 0.02. This illustrates the strong influence the propulsion system can have on the long-period dynamics.

Basic Feedback Control

Pitch attitude feedback to the pitch control surface is a common means of improving phugoid damping of conventional aircraft. Even at high speeds, in the absence of propulsion system effects, aircraft tend to be relatively conventional since the height mode has a pole and zero near the origin that tend to cancel each other. An advanced air breather, however, has a height-mode pole and zero in the right-half plane, and attempts to improve phugoid damping with attitude feedback make the height mode more unstable. This is illustrated in Fig. 3. However, as shown by Stengel and others, velocity and altitude feedback loops can be used to alter the phugoid and height-mode characteristics.[3] This avoids the problems presented by the use of attitude feedback.

Concluding Remarks

The propulsion system is a dominant influence on the stability of aerospace vehicle longitudinal long-period modes. These effects are most significant in the $M = 3.0$ range caused by the large changes in thrust with Mach number associated with engine cycle changes. The modes cannot be simultaneously stabilized with pitch attitude feedback but can be stabilized with velocity and attitude feedback loops.

References

[1]Etkin, B., "Longitudinal Dynamics of a Lifting Vehicle in Orbital Flight," Inst. of Aeronautical Sciences National Summer Meeting, Los Angeles, CA, June 28–July 1, 1960, IAS Paper 60-82.

[2]Porter, R. F., "The Linearized Long-Period Longitudinal Modes of Aerospace Vehicles in Equilibrium Flight," AFFTC-TN-61-2, 1961.

[3]Stengel, R. F., "Altitude Stability in Supersonic Cruising Flight," *Journal of Aircraft,* Vol. 7, No. 5, 1970.

Stability Tests of Spin-Stabilized Spacecraft in the Presence of Thrust

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Nomenclature

a_s	= space vehicle acceleration
Fr	= Froude number [Eq. (4)]
$I_x = I_y, I_z$	= moments of inertia
ℓ_s, ℓ_m	= characteristic lengths of spacecraft and model, respectively
m_s	= spacecraft mass
n	= z component of angular velocity
R	= center-of-mass radial position (Fig. 1)
r	= sensor array radial position (Fig. 1)
s	= vertical distance from center of mass to sensor array (Fig. 1)
T	= thrust
(X,Y,Z)	= laboratory (inertial) reference frame
(X',Y',Z')	= nonrotating frame attached to center of mass (accelerating)
(x,y,z)	= body-fixed frame
θ	= nutation angle
λ	= precession rate
ξ,η	= coordinates defining excursion of light beam from array center
σ	= inertia ratio
ψ	= turntable position
ω_{xy}	= transverse angular velocity

Subscripts

0	= mass center
m	= model
s	= spacecraft

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