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Effects of Dynamic Aeroelasticity on Aircraft Handling Qualities

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Introduction

THE subject of handling qualities requirements and criteria for highly elastic airplanes in turbulent and high dynamic pressure environments has been largely ignored by researchers. Much of the research on handling qualities has been concerned with relatively rigid, tactical military aircraft. The handling qualities parameters, such as phugoid, short-period, and dutch-roll frequencies and damping ratios, which have been determined pertinent for such airplanes, are considerably less meaningful for a flexible airplane with elastic mode frequencies close to the rigid body frequencies. When multiple frequencies are in close proximity, the pilot cannot easily discern individual modes of motion; rather, his opinion of the transient dynamics will likely be based on the time histories of the total motion.

No useful discussion of aeroelastic effects is included in the 1969 revision of the military aircraft handling qualities specification.[1] It contains only the following statement: "Since aeroelasticity, control equipment, and structural dynamics may exert an important influence on the airplane flying qualities, such effects should not be overlooked in calculations or analyses directed toward investigation of compliance with the requirements of this specification."

The specification is concerned mainly with desirable ranges of values on rigid body static and dynamic response parameters. There are methods available for estimating static aeroelastic corrections to rigid body aerodynamic stability derivatives; however, these are then used in rigid aircraft equations of motion. It seems quite possible that the desirable ranges of parameter values could be significantly affected by elastic mode degrees of freedom—particularly when some of the modes have natural frequencies of the same order of magnitude as the frequencies of the rigid body alone. It is not clear at all that the handling qualities should be specified by rigid body dynamic parameters when such mode interaction is present. In fact, the pilot would find it difficult to tell, for example, how much of a given pitch angle response to command input is due to rigid body and how much to low-frequency elastic modes.

Simplified Example

The total pitch angle time history that the pilot feels and sees, either on the outside horizon or the attitude indicator display, is given by:

$$\theta_i(x_p,t) = \theta(t) - \sum_{j=1}^{n} \phi_j'(x_p)\xi_j(t) = \theta(t) - \theta_e(t) \tag{1}$$

where x_p indicates pilot fuselage station, $\phi_j'(x_p)$ the slope of the jth symmetric elastic mode at that station, $\xi_j(t)$ the generalized displacement, $\theta(t)$ the rigid body pitch angle, and $\theta_e(t)$ the elastic contribution to total pitch angle (see Fig. 1). The relative contribution of the elastic terms to the total pitch angle increases as the natural frequencies of the elastic modes decrease. This can readily be seen by the following simplified example.

Equation (2) is the Laplace transformed longitudinal dynamics for a large flexible aircraft at a Mach 0.85, sea-level flight condition and includes the short-period, two-degree-of-freedom approximation plus the lowest frequency symmetric elastic mode. Equation (3) is the total pitch angle the pilot sees. The slope of the elastic mode is 0.025 at the cockpit.

$$\begin{bmatrix} s+1.21 & 0.94s & 0 \\ 0.48s+7.65 & s^2+1.57s & 0 \\ -2.26s+735.00 & 135.00s & s^2+1.14s+177.00 \end{bmatrix}$$
$$\times \begin{bmatrix} \alpha(s) \\ \theta(s) \\ \xi_I(s) \end{bmatrix} = \begin{bmatrix} -0.29 \\ -15.18 \\ -2228.00 \end{bmatrix} \delta_e(s) \tag{2}$$

$$\theta_i(t) = \theta(t) - 0.025\xi_I(t) \tag{3}$$

The characteristic equation is:

$$s(s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2)(s^2+2\zeta_{Ie}\omega_{Ie}s+\omega_{Ie}^2) = 0 \tag{4}$$

where the short-period, undamped natural frequency and damping ratio are $\omega_{sp} = 3.017$ rad/s and $\zeta_{sp} = 0.535$. The coupled elastic mode, undamped natural frequency, and damping ratio are $\omega_{Ie} = 13.304$ rad/s and $\zeta_{Ie} = 0.0428$. The in-vacuum, undamped natural frequency of the elastic mode is $\omega_I = 13.59$ rad/s with structural damping of $\zeta_I = 0.01$.

Figure 2 shows the rigid $\theta(t)$ and total $\theta_i(t)$ pitch angle responses to the up-elevator pulse shown in the figure. Notice

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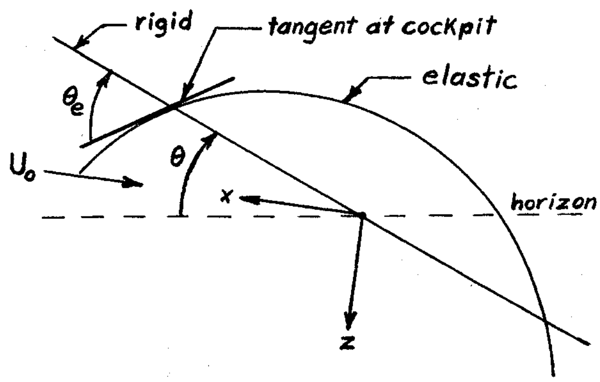

Fig. 1 Pitch angles at cockpit.

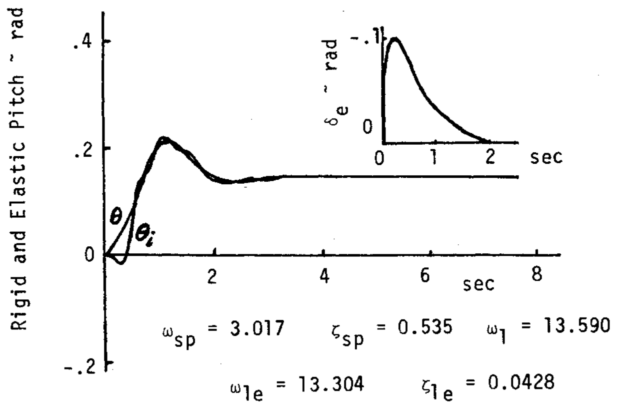

Fig. 2 Response to elevator input for original dynamics.

the elastic mode contribution appears as a ripple on the rigid response. It could be discerned by the pilot and probably would not significantly degrade his opinion of the airplane dynamics. However, the nonminimum phase character of the θ_i reponse would lower his rating somewhat.

Now, suppose the elastic mode frequency ω_l was much closer to the short-period frequency, say $\omega_l = 4.417$ rad/s. With just that change to the appropriate terms in the equations of motion, ω_{sp} and ζ_{sp} remain the same, but $\omega_{le} = 3.5$ rad/s and $\zeta_{le} = 0.149$. The responses to the same elevator pulse as before are shown in Fig. 3. $\theta(t)$ is exactly the same, but the elastic mode contribution to $\theta_i(t)$ is tremendously larger than in Fig. 2. In fact, the pilot could not possibly tell by viewing the total pitch response θ_i what portion was rigid body. This would be highly unacceptable handling qualities. If he were trying to follow a flight director commanded rigid body profile $\theta_c(t)$ by nulling the error given by $\theta_i - \theta_c$ instead of the desired $\theta - \theta_c$, pilot-induced oscillations (PIO) might result.

Even though this is a simplified example, it retains the essence of the problem and certainly points out the serious handling quality implications for highly elastic airplanes of the future. Any further delay in starting research on this untouched area could have severe impact on the design of the next generation of large military and civil aircraft.

Simulation Results

The only research of which we are aware that is directly relevant to the subject is documented in Refs. 2 and 3.

The results of North American Rockwell in Ref. 2 were for an early version of the B-1 aircraft and included piloted simulator evaluations of tracking performance in turbulence. They concluded that the structural dynamics appear essentially as a nuisance oscillation to the pilots and did not significantly affect tracking performance. However, the longitudinal dynamics of their configuration were very close

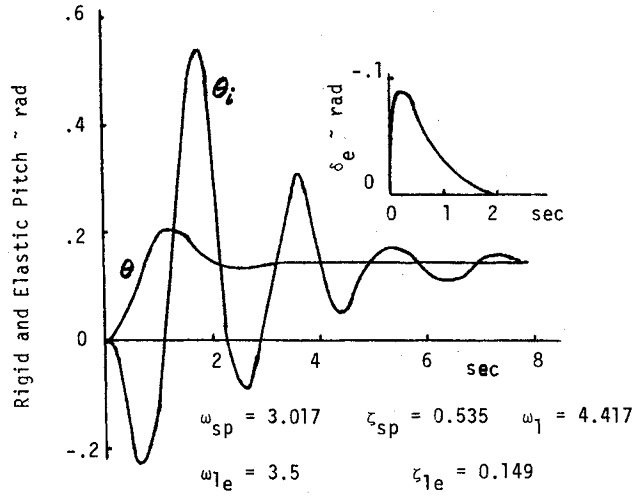

Fig. 3 Response to elevator input for altered dynamics.

to those of our simplified example in Fig. 2 as far as short-period and first symmetric elastic mode frequencies are concerned. Thus, it is not surprising that the elasticity did not significantly degrade pilot opinion; it was merely a ripple on the rigid body response.

In the work of Ref. 3, we investigated the effects of lowering the undamped natural frequencies of the first two symmetric elastic modes of a large flexible aircraft at a Mach 0.85 sea-level flight condition. A pitch tracking task, which included phugoid and short-period dynamics, was programmed on a fixed-base simulator with a CRT display of pitch command and total pitch angle with pitch error inferred as the difference between the total and commanded angles. No lateral-directional dynamics were included.

The equations for the displayed variables are:

$$\text{total pitch} = \theta_i(x_p, t) = \theta(t) - 0.025\xi_1(t) - 0.029\xi_2(t) \quad (5)$$

$$\text{pitch command} = \theta_c$$

$$\text{pitch error} = e_\theta = \theta_i - \theta_c \quad (6)$$

where 0.025 and 0.029 are the slopes of the two elastic modes at the pilot station. Four pilots each flew eight cases, which were combinations of elastic mode frequencies representing different amounts of rigid-elastic mode interaction. The Cooper-Harper ratings of the four pilots were averaged on each case; these ranged from 1.6 to 6.7. The worst case was for the elastic mode frequencies very close to the short-period frequency, which induced severe mode interaction. Full details are presented in Ref. 3.

Future Research

The key to developing handling qualities criteria and eventually specifications for severe mode interaction situations is to establish when and under what conditions the pilot can visually separate the rigid body response from the total response. In conditions when he cannot, structural mode suppression control systems probably will be required.

Both analytical and piloted simulation work should be done on this problem. Since the structure of the pilot model is totally unknown for tracking where rigid and elastic motion cannot be visually separated, the Kleinman optimal control pilot modeling method should be used.[4] The form of the pilot equalization is automatically determined by solution of a linear, quadratic, Gaussian optimal control formulation of the tracking problem. The performance index can then be related to a pilot rating on the Cooper-Harper scale by use of a method due to Hess.[5] By applying this pilot modeling and rating method to a series of parametrically selected mode interaction cases, separation boundaries can be obtained. Simulation of the analytical cases would then follow to verify the predicted pilot ratings. This work is in progress at Oklahoma State University.

Acknowledgment

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High-Altitude Long-Range Sonic Boom Propagation

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I. Introduction

THIS Note investigates the magnitude and importance of on-track secondary sonic booms, which are propagated upward from supersonic aircraft, and then reflected back down to the Earth's surface by gradients in sound propagation velocity in the atmosphere, as sketched in Fig. 1. The results of the approximate analysis and computations show that the on-track secondary booms are extremely weak, except close to the aircraft, and are not likely to be of any importance to observers on the ground or to measurably affect the Earth's atmosphere.

The sonic boom under the track of an aircraft such as the Concorde will typically consist of N-shaped signatures of order 100 N/m^2 amplitude. Signals from the Concorde which initially propagated upward and to the side but were then reflected down have also been measured by Balachandran, Donn, and Rind.[1] These signatures are typically below 2 N/m^2 in amplitude. However, after various reports of audible and infrasonic disturbances on the East Coast of the U.S. beginning in December 1977, some speculation arose that the reflection of upward-traveling booms from the thermosphere might be the cause of some of these events, and that significant changes in the upper atmosphere might be caused by the upward-propagating sonic booms from supersonic aircraft.[2,3]

This Note reports on the analysis and prediction of on-track booms propagated initially upward from a supersonic aircraft. On-track booms are those which propagate in the vertical plane through the flight path. Numerical results are presented for numbers representative of a maximum weight Concorde at cruise conditions. The atmosphere is assumed quiescent and stratified but with properties homogeneous in planes parallel to the Earth's surface assumed locally flat.

The analysis and calculations follow Ref. 4. Given an initial perturbation pressure δp at altitude H, the pressure at a new location is found in terms of properties at the new altitude from $(\delta p)^2 A/\rho c = \text{const.}$, where A is the ray tube area and ρ the density. The nonlinear advance in time of any portion of the wave compared to an infinitesimal acoustic wave is[4]:

$$\Delta t = \left(\frac{\delta p}{p}\right)_H \frac{\gamma+1}{2\gamma a_H} \int_{r_H}^{r} \frac{p_H}{p} \left(\frac{\rho a_H A_H}{\rho_H a A}\right)^{1/2} \frac{M}{\beta}\, \mathrm{d}r$$

Due to the increase in the integrand with altitude, Δt is very large for upward-propagating sonic boom waves leading to very strong nonlinear dissipative effects. On the other hand, downward-propagating waves in the atmosphere are much less affected by nonlinearity.

Once the advance Δt has been found, δp vs t is constructed at a given point and then each δp point is advanced (or retarded for $\delta p < 0$) and then shocks are introduced, balancing the cutoff areas of the multivalued advanced δp vs t curve, as discussed in Ref. 4. In the present analysis, this was carried out analytically in the computer program for assumed asymptotic (triangular) wave shapes, except for one case carried out graphically for the logarithmically singular wave shape resulting for an idealized linear caustic, as discussed later.

The energy carried by a wave can be found from the acoustic intensity (power/area/time) which is $(\delta p)^2/(\rho c)$. Integrating over the wave period, one finds the energy/area carried by the wave as $E/A = \int (\delta p)^2/(\rho c)\,\mathrm{d}t$. Assuming a triangular wave with amplitude Δp and length T (half of an N-wave), one obtains $E/A = (\Delta p)^3 T/3\rho c$. The impulse is given by $I = \int_0^T \delta p \,\mathrm{d}t$. At the ground, Δp and I are multiplied by a ground reflection coefficient of approximately two.

II. Estimated Behavior in the Caustic Region

The rays from the aircraft will become horizontal and turn downward at a caustic at the altitude where the speed of sound is equal to the aircraft speed. This occurs at 160.86 km in the U.S. Standard Atmosphere, 1976, for a Concorde flying at $M=2$, where the speed of sound is 295.03 m/s. The low density at 160 km results in a mean free path of approximately

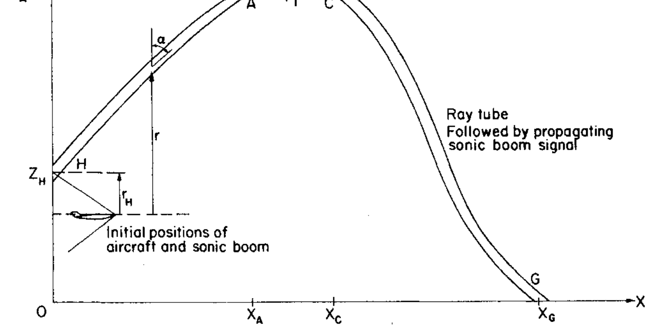

Fig. 1 Sketch of upward ray tube trajectory and definition of symbols.

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Index categories: Aeroacoustics; Noise; Supersonic and Hypersonic Flow.

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