Response of Hypersonic Winged Vehicles to Abrupt Control Displacements

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Analytical studies of the response of large hypersonic winged vehicles to pilot induced longitudinal maneuvers indicate that these vehicles may rapidly approach their structural limits at combinations of high dynamic pressure and Mach number. Results developed in an investigation of response for a class of vehicles that have been studied by General Dynamics/Astronautics are discussed. Parametric studies to determine the effect of vehicle characteristics and operational requirements upon vehicle response were conducted. A discussion of the relative influence of design and operational parameters upon vehicle response to control surface deflection is included. Possible means of partially alleviating the problem while still in the preliminary design phase are discussed. Solution of similar problems encountered on present generation supersonic aircraft are mentioned.

Nomenclature

a = acceleration, ft/sec^2
ac = aerodynamic center location, fraction $\bar{c}$ from leading edge
cg = center of gravity location, friction $\bar{c}$ from leading edge
$\bar{c}$ = mean aerodynamic chord, ft
C_L = lift coefficient
C_M = pitching moment coefficient
C_{M_0} = pitching moment coefficient at zero lift
$C_{M_{C_L}}$ = static margin, $dC_M/dC_L = ac - cg$
g = acceleration of gravity, 32.2 ft/sec^2
l_t = distance from center of pressure of load due to elevon deflection to reference station
L = lift $C_L qS$, positive up
M = moment $C_M qSc$, positive nose-up
n = load factor, a/g
q = dynamic pressure, psf
S = reference area, ft^2
W = vehicle weight, lb
Δx = distance from center of gravity to reference station
x, y, z = Cartesian coordinates
α = angle of attack, rad
γ = flight path angle, rad
δ_e = elevon deflection, rad
θ = angle of pitch, rad
$(\ )_s$ = $\partial(\ )/\partial s$
$(\dot{\ })$ = $d(\ )/dt$

Introduction

THE structural weight of a large hypersonic aerospace vehicle may be as much as 50% of the empty weight. Accordingly, achieving maximum payload capacity requires that design load factors be limited as necessary to provide for structural integrity of the airframe throughout the operational regime without imposing undue limitations that might preclude flight under all but the most proverse circumstances. Analytical studies of the response to abrupt longitudinal control displacement of a class of large hypersonic vehicle indicate that vehicle structural limits may be rapidly approached at combinations of high dynamic pressure and Mach number. Structural design criteria for the class of vehicles studied were predicated upon longitudinal maneuver requirements and atmospheric turbulence considerations, whichever proved to be more critical. Minimum maneuver requirements sufficient to satisfy operational requirements are provided. Additional margins are necessary to allow for control malfunctions, avoidance tactics, corrections to the flight pattern, and escape and abort maneuvers. Design criteria exceed these requirements in order to provide a factor of conservatism in determining aerodynamic loading on the vehicle. The design criteria, then, establish vehicle structural capabilities whereas operational requirements define required control system capabilities. Unfortunately, the necessity to provide control capabilities for phases of operating regime provides excess capabilities over a large portion of the flight envelope. Most present day aircraft possess the capability to exceed design limit load factors at certain conditions. However, the wide range of operating latitudes provided for in design criteria preclude the possibility of such an occurrence during actual flight. Further, such factors as pilot attentiveness, available pitch damping, and airplane static margin tend to maintain response below design levels. The necessity of designing aerospace vehicles to more restrictive criteria results in the limit load factor being rapidly approached at certain portions of the flight regime. Consideration to such effects should be given in formulation of design criteria for this class of vehicle. Operating limitations and/or control system capabilities may be defined by vehicle response to longitudinal control displacements.

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Structural Design Criteria

The studies discussed in the present paper are based on the vehicle configuration depicted in Fig. 1. This is a large manned vehicle that utilizes the atmosphere for lift during conventional, horizontal takeoff and a lifting trajectory thereafter. The large elevon configuration satisfies the need for both trim to $C_{L_{max}}$ during re-entry and ability to flare at landing. Design air loads were found to occur during the initial portion of the flight path; accordingly, the present paper is limited to a discussion of control capabilities and airframe strength in the altitude range to 60,000 ft.

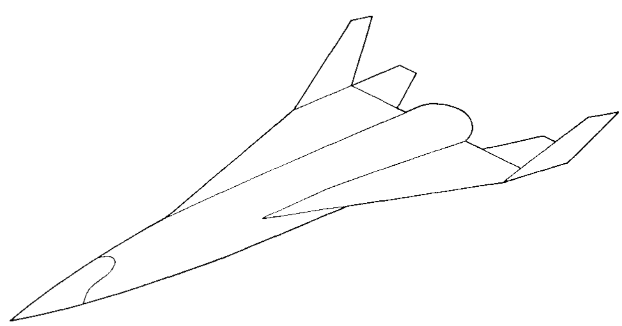

Fig. 1 Typical vehicle configuration.

Design criteria were based upon the requirements of military specification.[1] The structural capabilities developed using these criteria define vehicle operating limitations as functions of load factor, surface temperature, flight path angle, etc. Manueuver and gust loads were considered as developed during an excursion from a normal flight condition. Maneuver load factors between 0 and 2.0 were considered throughout the exit trajectory. Gust analysis was based upon the "gust at V_H" velocities specified in Ref. 1. A comparison of the resultant load factors is shown in Fig. 2. The reduction in vehicle weight due to fuel burnoff is taken into consideration in applying these criteria. Vehicle static balance in a maneuvering condition was maintained assuming the incremental load generated by elevon deflection is balanced by an incremental load due to angle-of-attack-change. Gust loads are developed by adding the airload increments, resulting from the angle-of-attack-change due to gust encounter, to the normal loads for unit load factor flight. The load due to elevon deflection is unchanged, vehicle balancing being retained by pitching acceleration. Elevon hinge moment requirements for structural design are established by distributed loads resulting from the foregoing analysis and are used as actuator requirements.

Control System Capability

Elevon size is dictated by pitching moment requirements necessary to trim the vehicle during re-entry and to flare to a high lift attitude during landing. During exit, the vehicle is trimmed to maximum lift-drag ratio for maximum range. Re-entry is effected at maximum lift to minimize aerodynamic heating. Sufficient elevon control to trim to the re-entry trajectory is needed. In addition, the need to flare at touchdown establishes certain elevon requirements. Geometric considerations are employed in the selection of the elevon configuration to minimize hinge moment requirements. The short chord configuration usually amenable to reducing elevon hinge moments is not compatible with the pitching moment requirements for the low aspect ratio wings typical of advanced hypersonic vehicles. The long moment arm necessary to achieve the required pitching effectiveness is reflected in the long chord elevons shown in Fig. 1. For the configurations being discussed, it may be noted that the elevon effectiveness requirements are at odds with the desire for reduced hinge moments. However, the increased hinge moments typical of long chord elevons will tend to alleviate the vehicle response problem by limiting available surface deflection at high dynamic pressure-Mach number conditions where the problem has been found to be predominant.

Maximum control surface velocity was determined to be required at landing. Vehicle response is slow in this condition; however, gust inputs and/or instrument landing requirements can require rapid surface deflections. A maximum velocity of 20°/sec was selected. At high altitude conditions, aerodynamic control was required down to dynamic pressures as low as 20 psf. Again, vehicle response is slow and inputs other than thrust are not large (thrust moment is assumed not to design the elevon control).

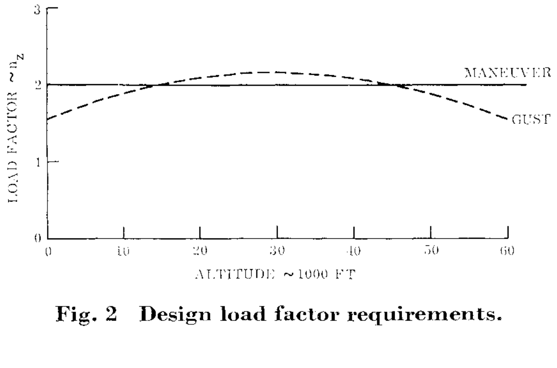

Fig. 2 Design load factor requirements.

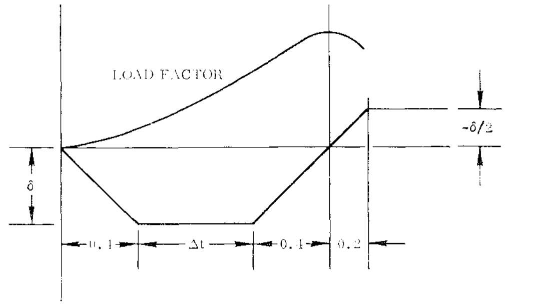

Fig. 3 Longitudinal control displacement, time diagram.

Dynamic Response to Control Displacement

Although a variety of elevon inputs have been investigated, discussion of results is limited to those cases based on the longitudinal control displacement-time diagram is shown in Fig. 3 for comparative purposes.

Load factor was attained by a control moment resulting in the displacement curve shown in Fig. 3. In all cases, 0.4 sec time to maximum displacement was considered. The time Δt and control displacement δ were sufficient to attain design load factor coincidentally with the attainment of $\delta/2$. This maneuver is the "reversed elevator" condition specified in Ref. 1.

Dynamic response of the vehicle to an applied elevon displacement was determined assuming the vehicle to be initially in steady, unaccelerated flight and trimmed for zero control force at any air speed along the exit trajectory. The assumption of unaccelerated flight is not entirely legitimate for an exiting vehicle; however, within the small intervals of time considered herein, it is sufficient for the purposes of the present investigation and considerably simplifying. A vehicle design maneuvering load factor is used as a limit for all maneuvers. The equations of motion are derived using the relations established in Fig. 4. For small flight path angles, vehicle lift may be assumed equal to the vertical force component

$$L \simeq \Delta Z = -F = Ma = (W/g)a$$

where acceleration normal to the flight path is

$$a = R\omega^2 = V_T\omega$$

Angular velocity,

$$\omega = \mathring{\gamma} = \mathring{\theta} - \mathring{\alpha}$$

so that

$$\Delta Z = (W/g)V_T(\mathring{\theta} - \mathring{\alpha})$$

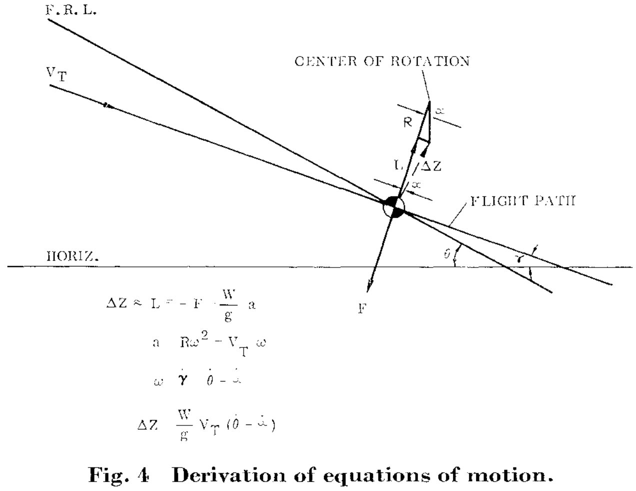

Fig. 4 Derivation of equations of motion.

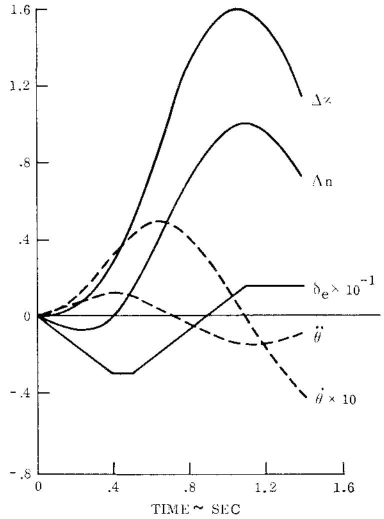

Fig. 5 Typical transonic time history.

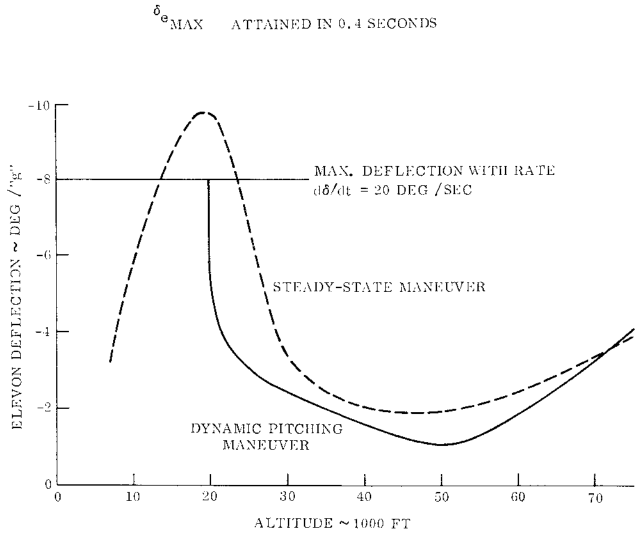

Fig. 7 Elevon deflection to attain unit load factor.

Force and moment equations were established as follows:

$$\Sigma F_Z = C_{L_\alpha}\Delta\alpha qS + C_{L_{\dot\theta}}\dot\theta q(S\bar c/2V_T) + C_{L_{\delta_e}}\delta_e qS - (W/g)V_T(\dot\theta - \dot\alpha) = 0$$

$$\Sigma M_{CG} = \{C_{M_\alpha} + C_{L_\alpha}[(x/c) - 0.50]\}qS\bar c\Delta\alpha + \{C_{M_{\dot\theta}} + C_{L_{\dot\theta}}[(x/c) - 0.50]\}qS\bar c(\bar c/2V_T)\dot\theta + \{C_{M_{\delta_e}} + C_{L_{\delta_e}}[(x/c) - 0.50]\}qS\bar c\delta_e - I_{YY}\ddot\theta = 0$$

Solution of the simultaneous equations produces

$$\dot\alpha = \dot\theta + F_1\Delta\alpha + F_5\dot\theta + F_6\delta_e$$

$$\Delta n_Z = F_7[F_1\Delta\alpha + F_5\dot\theta + F_6\delta_e]$$

$$\ddot\theta = F_2\Delta\alpha + F_3\dot\theta + F_4\delta_e$$

where

$$F_1 = C_{L_\alpha}(qSg/WV_T)$$

$$F_2 = C_{M_\alpha} + C_{L_\alpha}[(x/c) - 0.05](qS\bar c/I_{YY})$$

$$F_3 = C_{M_{\dot\theta}} + C_{L_{\dot\theta}}[(x/c) - 0.50](qS\bar c/I_{YY})(\bar c/2V_T)$$

$$F_4 = \{C_{M_{\delta_e}} + C_{L_{\delta_e}}[(x/c) - 0.50]\}(qS\bar c/I_{YY})$$

$$F_5 = -C_{L_{\dot\theta}}(qs/V_T)(g/W)(\bar c/2V_T)$$

$$F_6 = -C_{L_{\delta_e}}(qS/V_T)(g/W) \qquad F_7 = -(V_T/g)$$

Solution of these equations was effected using an iterative process that had been programed for an IBM 1620 digital computer. Typical time histories of vehicle response to the assigned control surface motion are shown in Figs. 5 and 6 for maneuvers at transonic and supersonic speeds, respectively. The parameters included are incremental and represent the change from the initial steady state attitude. Although many combinations of time Δt and elevon deflection may be combined to produce the desired maximum load factor, the maximum allowable deflection within the load factor limitations will occur with time Δt equal to zero. These deflections, then, define an upper limit on the desired control sensitivity in regions where maximum rate is not the limiting factor. Allowable elevon deflections along the vehicle exit trajectory are shown in Fig. 7. The sensitivity problem becomes most acute at combinations of high Mach number and high dynamic pressure (approximately 50,000 ft alt) and is alleviated as dynamic pressure is reduced at higher Mach numbers and altitudes. Elevon requirements to reach limit load factor assuming a steady state maneuver are included in Fig. 7 for purposes of comparison. The vehicle was considered disturbed from a normal flight altitude using elevon deflection

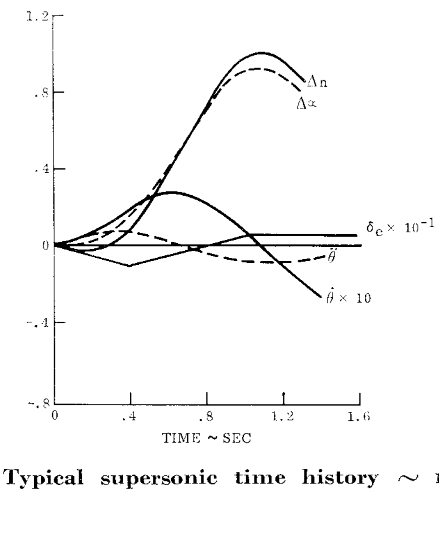

Fig. 6 Typical supersonic time history ~ max "q."

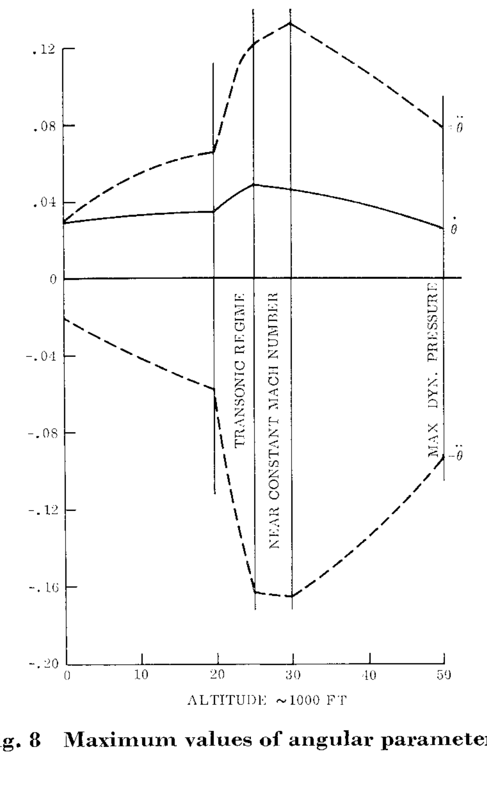

Fig. 8 Maximum values of angular parameters.

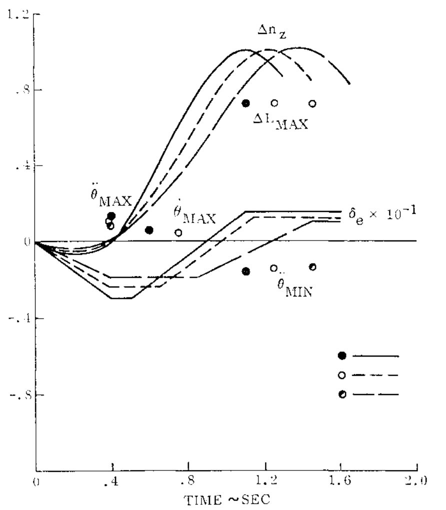

Fig. 9 Influence of rate of control deflection.

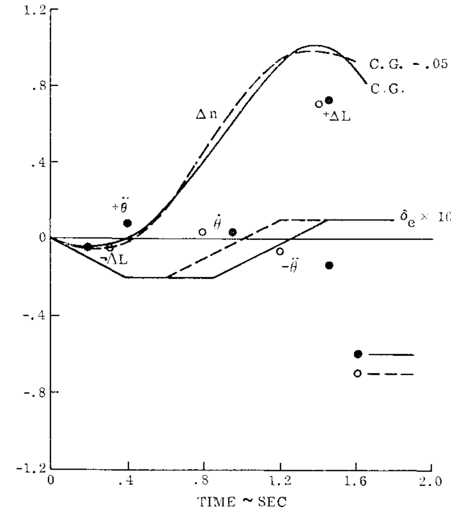

Fig. 11 Influence of center of gravity.

with the resultant unbalanced forces offset by incremental angle of attack at several points along the flight path for these calculations. The steady state results generally confirm the elevon effectiveness variation shown, the lower limits for the dynamic conditions resulting from the restriction on load factor to the maximum developed during the maneuver including overswing. The variation of maximum and minimum pitching velocity and acceleration along the exit trajectory is shown in Fig. 8. These values illustrate the slow rotational response of this type vehicle to sudden elevon pulses and indicate the response problem to be primarily reflected in vehicle load factor. Maximum values of angular parameters occur in the low supersonic speed region of the exit trajectory and decreases as Mach number is increased. Reference to the elevon limits of Fig. 7 indicates that the allowable elevon deflection is reduced rapidly in this region to avoid exceeding the allowable vehicle load factor. The center of pressure of the load due to elevon deflection reaches its most aft location in this region, thus maintaining high elevon effectiveness as a pitch control.

Parametric Studies

A parametric study was conducted to evaluate the effect of certain vehicle characteristics and operational requirements upon vehicle response. Variables considered were rate of control deflection, vehicle weight, vehicle center of gravity, mass moment of inertia in pitch and Mach number.

The influence of rate of control deflection upon vehicle response is shown in Fig. 9. The larger control deflection attained in the assigned time with increased rate caused maximum response to be attained sooner; however, no perceptible change in magnitudes of the angular response or vehicle load level was produced.

Decrease in vehicle weight permits a shorter time in which maximum elevon displacement may be maintained to preclude exceedance of limit load factor as shown in Fig. 10. A higher positive loading due to the maneuver is produced with the higher vehicle weight. Response rates are relatively unaffected.

Aft movement of the center of gravity appreciably reduces the interval of time wherein maximum control displacement may be held (Fig. 11). Maximum negative pitching acceleration is reduced with the more aft center of gravity and occurs sooner in the maneuver. The longer time interval in which maximum load factor was maintained with the more aft center of gravity is worthy of note. Unfortunately the investigation conducted was too limited in scope to permit additional analysis of this influence.

Data presented in Fig. 12 depict the appreciable influence due to a 5% increase in mass moment of inertia in pitch upon vehicle longitudinal response. Reference to Fig. 9 indicated that the effect of increased rate of control with shorter time for maximum displacement will not appreciably affect vehicle response. The indicated increase in vehicle response is re-

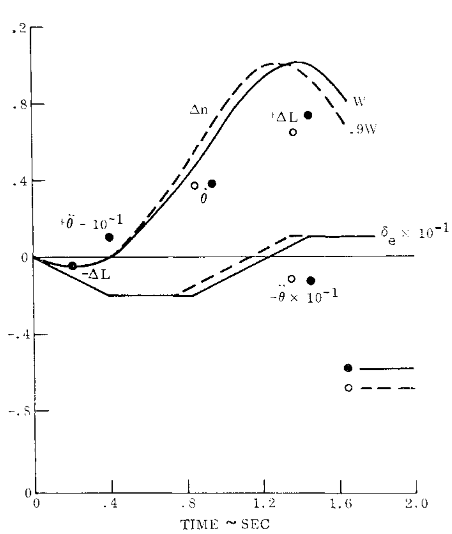

Fig. 10 Influence of vehicle weight.

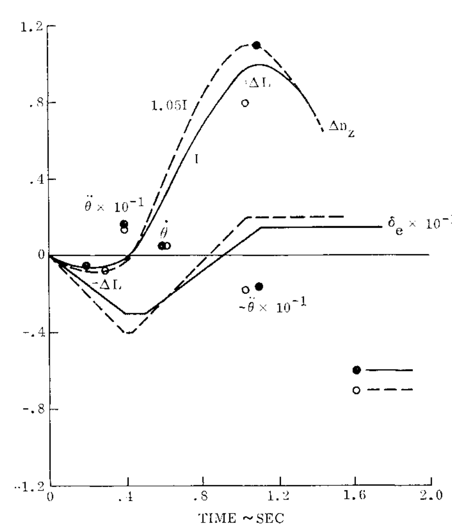

Fig. 12 Influence of mass moment of inertia in pitch.

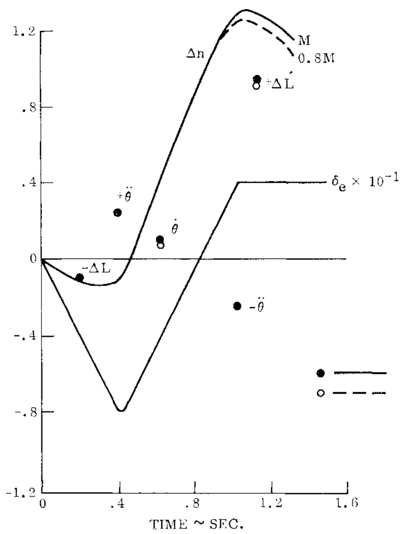

Fig. 13 Influence of Mach number.

flected in the increased incremental vehicle loading due to the maneuver, although angular responses are not significantly affected.

The influence of a 20% decrease in Mach number upon vehicle response to abrupt elevon displacement is small as shown in Fig. 13. These data pertain to a transonic speed case where aerodynamic parameters are extremely sensitive to small changes in Mach number.

System Design Considerations

As previously stated, the problem of control sensitivity is considered to be primarily one of system design. The problem will be of continuous concern during development of a control system for hypersonic manned vehicles. Similar problems have been encountered on present generation supersonic aircraft. A control sensitivity problem at high speeds and dynamic pressures for the F-106 airplane is controlled by a fuel transfer system that moves the center of gravity aft supersonically to reduce the static margin (Fig. 14) and trim drag and increase maneuverability. A stable subsonic configuration is produced by a forward center of gravity movement. The sensitivity problem for the F-106 is worst near Mach 0.9 at sea level because of the combination of high dynamic pressure, low static margin, and high elevator effectiveness at this point. Maintaining a large static margin causes large elevon deflection per "g" and hinge moment per "g" so that the airplane is both hinge moment and control limited, thus alleviating the sensitivity problem. Operational restrictions of the type illustrated in Fig. 15 are thus imposed.

Control of the static margin of the B-58 airplane at supersonic speeds is also attained utilizing fuel transfer to reduce the static margin. In addition, the magnitude of elevator deflection produced by a sudden stick motion is reduced by means of a ratio changer between the control and the surface. Early studies indicated that the ratio changer would operate as an approximate function of dynamic pressure, Mach number, center of gravity, and weight. However, further analysis

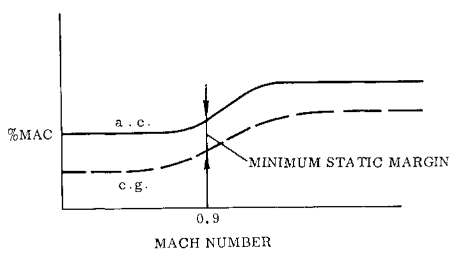

Fig. 14 Alleviation using center of gravity control.

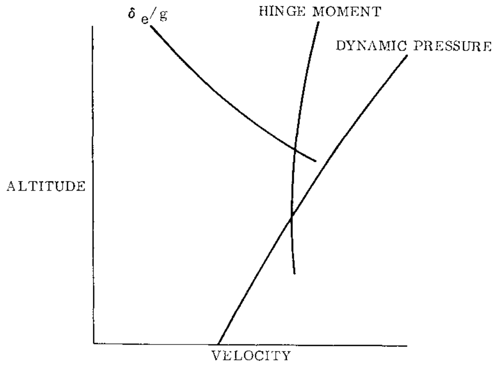

Fig. 15 Possible operating limitations.

indicated that these parameters could be reflected in trim elevator requirements with minor corrections for Mach number and altitude. Large elevator deflections are required for trim at large static margins.

Alleviation of the response problem of high speed vehicles may be achieved by utilization of concepts currently under development such as variable geometry wings. Configurations featuring variable sweep or folding wing tips offer a means of aerodynamic center control to reduce the static margin. Folding wing tips or sweeping the wings aft will move the aerodynamic center (a.c. curve on Fig. 14) forward. Thus using an unfolded or unswept configuration subsonically and utilizing the variable planform capability to maintain a forward aerodynamic center location through the transonic range and at supersonic speeds will essentially change the elevon required to trim in the operating regime where longitudinal sensitivity is of concern.

The foregoing solutions for the longitudinal control sensitivity problem may apply in whole or in part in alleviating the problem for hypersonic space vehicles The use of auxiliary surfaces for low speed control only would allow greater surface movement at high speeds. The use of a double elevon configuration wherein one-half would be locked out at high speeds might be a present state-of-the-art solution, whereas development of a retractable canard surface, which would be used only at low speeds, represents an advanced state-of-the-art development that would allow the use of very small surfaces for high speed controllability.

A possibility exists that design criteria for hypersonic winged vehicles may be defined in part by dynamic pitching maneuvers. Whether the specific maneuvers considered in the present paper are rational or less severe criteria should be imposed in evaluating vehicle response deserves additional consideration. The effect of abrupt control displacements upon longitudinal response may define operating limitations and/or control system capabilities for the approaching generation of flight vehicles.

Conclusions

Although conditions investigated in the study reported herein did not disclose any critical design loadings, the results indicated the load factor response of the vehicle to be highly sensitive to small elevon deflections. Although no critical loads are produced as long as the maneuver is limited to design load factor, there always will be a control sensitivity problem that will be critical near minimum δ_e/g. Careful attention to the possibility of overstressing the vehicle due to excess elevon deflection will be a continuous problem during control system development.

Reference

[1] "Airplane strength and rigidity—flight loads," MIL-S-8861 (ASG).