BOOSTER-STRUCTURE-MODIFICATION STUDIES FOR WINGED DYNA-SOAR VEHICLES

By R. M. Haynes, R. T. Boll, and M. T. Braun
Boeing Airplane Company

INTRODUCTION

The utilization of booster systems based on those utilized in current ICBM's (Intercontinental Ballistic Missiles) for boosting manned winged payloads to orbital or near orbital speeds requires modifications of the booster structure and an increase in the engine deflection limits, or the addition of large stabilizing fins. These changes and modifications are required in part because of the addition of the lifting surface on the front of the booster and in part because of the design criteria which are unique to manned winged Dyna-Soar type vehicles.

This paper discusses some of the implications as to effects of these items on the booster structural requirements, touches on the aeroservo-elastic stability characteristics, and finally illustrates several potential load-reduction schemes which have been considered.

SYMBOLS

q	dynamic pressure, lb/sq ft
C_{L_α}	lift-curve slope, per deg
S	reference area, sq ft
P_{eq}	equivalent end load, lb
P_{axial}	axial load, lb
M_b	bending moment, in-lb
R	radius, in.

[redacted]

[redacted]

R_1	pitch-fin area ratio, S/S_o
Z	stiffness parameter, $(\omega/\omega_o)^2$
K_θ	pitch attitude gain, deg/deg
$K_{\dot\theta}$	pitch rate gain, deg/deg/sec
K_β	control-surface gain, deg/deg
L	normalized body length
α	angle of attack, deg
θ	local pitch angle at booster-glider transition, deg
$\dot\theta$	local pitch rate at booster interstage, deg/sec
ω	frequency of first bending mode, radians/sec
δ_T	thrust deflection from center line, deg

L1121

Subscript:

o	nominal value representative of design value

UNIQUE CRITERIA

Four major unique criteria which have directly influenced structural design and structural weight in the Dyna-Soar Phase Alpha studies are listed in figure 1. The significance of these criteria is explained as follows:

(1) The criterion to provide at least neutral aerodynamic stability during first-stage boost reflects directly in the design and attachment problem of the stabilizing fin and also influences the aeroelastic behavior of the vehicle.

(2) The influence of a factor of safety of 1.4 is somewhat obvious since the standard missile structural factor of safety is 1.25.

(3) The third criterion, pilot safety from hazardous malfunction conditions, establishes that adequate time must be allowed for the pilot

[redacted]

to escape from the booster before the occurrence of major structural failure due to engine or autopilot servo failures.

(4) The 5° angle-of-attack capability during boost has been selected to provide a margin for pilot and control-system tolerance and lag during flight through the lower altitude wind profiles.

PARAMETRIC STUDIES

Application of these criteria to one of the Phase Alpha winged configurations, in conjunction with the usual design wind criteria, for example, wind shear-turbulence and ground wind, results in the design bending moments shown in figure 2. The requirement for 5° angle-of-attack capability is most severe when the aerodynamic loading is highest (maximum $qC_{L_{\alpha}}$) and actually results in the most critical loading condition over most of the booster.

The pilot-safety criterion, which requires that structural integrity following a malfunction be maintained for something on the order of 1 second, results in the condition shown in figure 2 as engines hard-over. The loads resulting from this condition are not critical for this particular configuration, but such is not always the case.

In general, it may be assumed that storm turbulence and wind-shear conditions do not occur simultaneously. However, there is a distinct possibility of nonstorm turbulence in the vicinity of the tropopause, and the loads resulting from this turbulence must be combined in some manner with the wind-shear loads. The exact correlation between wind shear and gust loads is not known, but it is probably positive. The loads which would result from such turbulence were approximated by determining the response to a 12 ft/sec discrete gust. These loads were combined directly with the load response for flight through a synthetic 1-percent wind-shear profile for Patrick Air Force Base. The resulting bending moments are not critical for this configuration.

The ground-wind condition, which was based on a 60 ft/sec steady wind plus a 30 ft/sec gust, is critical on the aft end of the booster.

The effect of variation in reentry-device weight is to change the relationship between the 5° condition and the wind-shear response. A comparison of the severity of the 5° trim condition at maximum $qC_{L_{\alpha}}$ with that of the wind-shear-plus-gust condition is shown in figure 3. This comparison illustrates the point that for the range of reentry-device weight studied, the 5° trim condition is the critical condition. It should be pointed out, however, that this figure is based on an area of 250 square feet for the reentry device and that an increase in reentry-device area would cause an increase in the bending-moment ratio. That is,

[redacted]

the 5° trim condition becomes more severe relative to the wind-shear-plus-gust condition as the reentry-device area is increased.

The variation of booster loads during first-stage burn time for the 5° trim and engines hard-over conditions is presented in figure 4 for a winged reentry device. Equivalent end load $\left(P_{eq} = P_{axial} + \frac{2M_b}{R}\right)$ for a particular booster station is shown plotted against first-stage burn time for a reentry-device area of 330 square feet and weight of 9,283 pounds. The 5° trim condition essentially increases with increasing dynamic pressure, reaching a maximum value at maximum qC_{L_α} and then decaying as burn time increases. The contribution of bending moment is illustrated by the difference between the axial-load-alone curve and the total-end-load curve. The end load due to engines hard-over increases with burn time, primarily as the axial load increases since the contribution due to bending moment is practically constant with burn time. The end load due to ground wind is also shown for comparison. As may be seen from figure 4, the critical condition varies from ground wind at time zero to the 5° trim condition, with the engines-hard-over condition becoming critical near first-stage burnout. The design condition at this particular station is, of course, the 5° trim condition. A similar variation of equivalent end load is shown in figure 5 for a ballistic reentry device with an area of 54.5 sq ft and a weight of 7,221 pounds. The condition of engines hard-over is seen to be critical throughout the range of first-stage burn time. A comparison of this figure with figure 4 illustrates the effect of reentry-device area on booster design.

I 1 1 2 1

It should be pointed out that the remainder of the parametric data presented is based on strength-designed boosters and, therefore, is based on a booster stiffness obtained from the design of a booster for the particular reentry-device area and weight for which the parameters SC_{L_α} and weight are being read. The data presented are based on the Titan Lot "J" ICBM modified to meet the appropriate strength requirements. The effect of reentry-device area and weight on booster maximum bending moments is further emphasized in figure 6. These data are based on the 5° trim condition at maximum dynamic pressure. For the 9,000-pound reentry-device weight, an increase in SC_{L_α} from 1.20 to 15.0 increases the maximum bending moment by 1,320 percent. Since the value of SC_{L_α} of 1.20 is representative of a ballistic device, these increases in booster bending moment emphasize again the effect that winged reentry devices have on booster design. The reduction in maximum bending moment due to increasing the reentry-device weight is, of course, due to the increase in inertia relief. At a value of SC_{L_α} of 7.50, an increase of reentry-device weight from 6,000 pounds to 12,000 pounds decreases the maximum bending moment by 20 percent.

[redacted]

[redacted]

The effect of these bending moments on the booster structural material required for strength-designed boosters is shown in figure 7, where cross-sectional area is plotted against body station for SC_{L_α} values of 1.2, 7.50, and 15.0. Once again, since the value of 1.20 for SC_{L_α} is representative of a ballistic device, the difference in area required between this curve and the other values of SC_{L_α} emphasizes the effect of winged reentry devices on booster design. It should also be noted that this difference increases toward the forward end of the booster.

Because of flexibility in the structure, the angle of attack at the reentry device will be greater than the angle of attack at the vehicle center of gravity, and the angle of attack at the fins will be less than the angle of attack at the vehicle center of gravity. The ratio of the angle of attack at the reentry device to the angle of attack at the fins is a measure of the amount of structural deformation present. The effects of the reentry device SC_{L_α} and weight on this flexibility ratio are shown in figure 8. This flexibility effect is directly related to the pitch-fin-area requirements, as illustrated in figure 9. Here the effect of the reentry device SC_{L_α} and weight are related to the pitch fin SC_{L_α} required for neutral aerodynamic stability at the maximum dynamic pressure 5° trim condition. The effects of structural deformation, which are included in these requirements result in from 2 percent to 73 percent more fin than would be required from rigid-body considerations.

Conversion of the pitch-fin-area requirement from figure 9 and the structural-material-area requirements from figure 7 directly into weight results in a structural weight requirement as a function of the reentry-device area (fig. 10). It is seen that for a 9,000-pound reentry device and an $SC_{L_\alpha} = 9.8$ (representative of a 330-sq-ft glider), approximately 65 percent of the weight added to the ICBM booster system is directly attributable to the fins and booster modification required for their installation. This weight is a direct result of the requirement for neutral aerodynamic stability. Of the remaining 35 percent of added weight, which is necessary because of the air loads resulting from the winged device on the front of the booster, the contribution of the second stage is the largest and that of the first stage is the least.

Comparing the data for other reentry-device weights with the 9,000-pound data gives the results shown in figure 11. The conclusions are, as would be expected from the trends shown previously (figs. 6, 7, and 9), that the heavier the reentry device, the smaller the structural-weight penalty to the booster; and the greater the reentry-device area, the greater the structural-weight penalty to the booster.

[redacted]

[redacted]

AEROSERVOELASTIC CONSIDERATIONS

The interaction between the elastic structure and the automatic control system is always of some concern for flexible missiles. This problem is potentially intensified by the addition of the glider on the front of the booster and the attendant destabilizing effect of the wing. The rigorous treatment of this problem would require a very detailed analysis and an extensive knowledge of the structure and the flight control system of the configuration. Such an analysis was not suitable, nor warranted, for a study such as that conducted for Dyna-Soar Phase Alpha. However, a preliminary study of this problem was conducted for a 7,800-pound, 330-square-foot glider on a modified Titan ICBM. Rigid-body pitch, rigid-body translation, and the first body-bending mode were considered as degrees of freedom. The system analyzed was assumed to have a thrust-vectoring control system governed by a simple linear control law expressed as follows:

L
1
1
2
1

$$\delta_T = K_\theta \theta + K_{\dot{\theta}} \dot{\theta}$$

Nominal values of K_θ and $K_{\dot{\theta}}$ (1.0 and 0.5, respectively), which resulted in a rigid-body pitch frequency of 0.3 cps with approximately 0.7 critical damping for the system with the nominal stability fins, were chosen. Figure 12 illustrates the effect of pitch-fin area ratio R_1, as a function of booster-bending-stiffness parameter Z, on the aeroservoelastic characteristics of the system. The nominal configuration is indicated. For small pitch-fin areas the system is unstable in the pitch mode, as illustrated by the area below the stable portion of the curve. As fin area is increased, the system first becomes stable and ultimately again becomes unstable in the first elastic mode. The pitch-fin area required to cause this modal instability is a function of the bending stiffness, as indicated. The nominal configuration is well within the stable region. However, this figure has illustrated only one effect. Adjustment of the attitude gain K_θ can result in a considerable change in the stability characteristics, as illustrated in figure 13. The effect of fin area is reflected in the position of the stability boundary in this figure. For the configuration without stabilizing fins ($R_1 = 0$), it is apparent that, although unstable at the nominal gain and stiffness, the system can be gain stabilized. This effect is also apparent for the case where the pitch-fin area is twice the nominal value ($R_1 = 2$). For $R_1 = 0.5$ and 1.0, gain changes do not affect the stability characteristics appreciably. As shown in figure 12 and again in figure 13, it is of significance that a large static stability margin can result in a modal instability. The approximate stability margins resulting from the tail (pitch-fin) areas considered in this study are:

Tail area ratio	Stability margin, percent body length
0	-40
.5	+1
*1.0	+12
2.0	+20

*Nominal tail area = 425 sq ft.

Figures 12 and 13 have shown to some extent how control gain, bending stiffness, and static stability (pitch-fin area) can influence the aeroservoelastic stability problem and, potentially, how they might influence a stiffness requirement for the vehicle. The structural-load response to atmospheric disturbances is not insensitive to these same parameters. Figure 14 indicates some of the trends in maximum bending-moment response to a wind-shear profile which results from variation of one of these parameters, with all others held at their nominal value. These trends become particularly significant if wind-shear considerations are critical from the design-load standpoint. Fortunately, from the load analysis point of view, wind shear was not a critical condition for the Phase Alpha studies.

BENDING-MOMENT-REDUCTION DEVICES

It has been shown previously in figures 4 and 5 that the booster loads associated with a forward-mounted lifting device are quite large in comparison with those incurred by a ballistic device. Consideration of the use of existing ICBM's as potential boosters for the Dyna-Soar glider has resulted in considerable thought as to how existing boosters could be utilized with a minimum of modification and the least possible loss in performance. Alleviation of the large glider-induced bending moments is potentially one means of minimizing this modification.

Three different "forward flying" schemes for load alleviation which have been investigated at Boeing are shown in figure 15. The first involves use of the existing glider elevons. Proper actuation and phasing of the glider elevons during boost reduces the net aerodynamic load on the glider and thereby also reduces the booster bending moments and the thrust force required for pitch trim. The second scheme requires the addition of a set of "flippers" just aft of the glider. These flippers serve essentially the same purpose as the elevons. That is, by proper actuation, the flipper load can be made to cancel the glider aerodynamic load so that the booster bending moments are reduced. The third scheme requires the glider to be supported, free in pitch, at the glider center of gravity. Since the aerodynamic center of the glider is aft of the pivot point, the glider will seek a zero angle-of-attack position, so that the glider aerodynamic loads and the booster bending moments are reduced.

In figure 16 the magnitude of bending-moment reduction which can be achieved by one of these schemes is illustrated. The bending-moment response of a typical system with geared elevons to a sharp-edge-gust disturbance is shown as a function of the body-length ratio L/L_o. An elevon control gain K_β of 6.0 (that is, 6° of elevon angle per degree of engine thrust deflection) results in a 60-percent reduction in applied bending moment. Figure 17 illustrates, comparatively, the typical reductions which can be achieved by each of these three schemes. Although the load distribution varies somewhat, the reductions are of the same order of magnitude. These results were obtained from preliminary dynamic analyses, and although these systems appear to have promise as far as the required modification to the booster structure is concerned, additional work must be done to prove their full feasibility. Some other considerations which must be included in a complete feasibility study would be the loss in performance due to additional drag, the power-system requirements to drive the control surfaces, the complication of the aeroservoelastic problem, the weight penalties, and the decrease in total system reliability.

L1121

It must be pointed out that reduction of bending moment can be carried past the point of no return. The data of figure 4 show that if the moment is reduced to the point where the total end load, at the maximum air load point (t = 65 seconds), is less than the total end load resulting at first-stage burnout (t = 136 seconds), the air load is no longer the critical design condition. It could very well be that the loads at first-stage burnout are in excess of those incurred in the ballistic missile application of the same booster. In such case, modification of the missile is required anyway, and in essence, the price of admission may have already been paid.

CONCLUDING REMARKS

Results presented have shown that the addition of a winged reentry device to an existing ICBM can result in large structural weight penalties to the booster. Similarly, it has been shown that criteria unique to the particular system also have a significant influence on the final booster structural weight. The influence of certain control-system and stability parameters on aeroservoelastic stability has been illustrated. Several methods for load alleviation have been illustrated, and the structural benefits and limitations of these methods have been described.

[redacted]

At the present time the approach being used to handle the structural modification problem on the Dyna-Soar boost system is that of the simple straightforward approach of structural "beefup."

[redacted]

[redacted]

DESIGN CRITERIA UNIQUE TO DYNA—SOAR BOOSTER SYSTEM

1. NEUTRAL AERODYNAMIC STABILITY
2. SAFETY FACTOR, 1.4
3. PILOT SAFETY FROM HAZARDOUS MALFUNCTION CONDITIONS
4. 5° ANGLE OF ATTACK CAPABILITY

Figure 1

BENDING — MOMENT COMPARISON

330 - FT^2, 9,283 - LB REENTRY DEVICE, MODIFIED TITAN LOT "J"

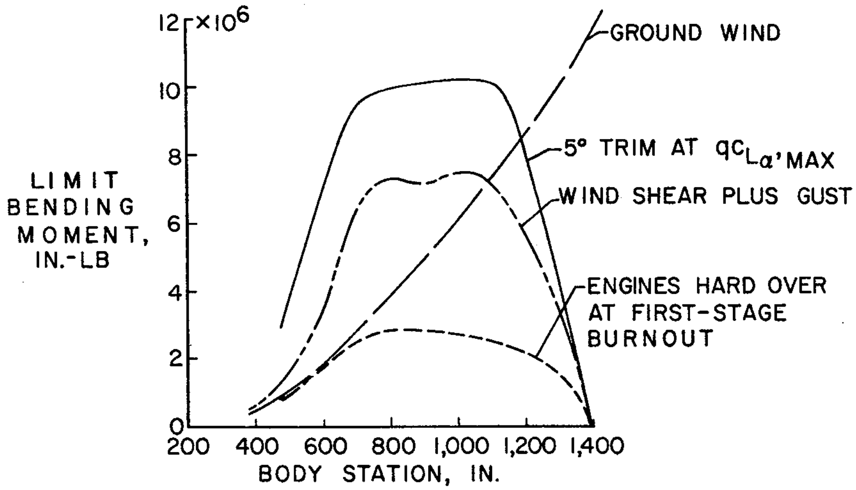


Figure 2

[redacted]

[redacted]

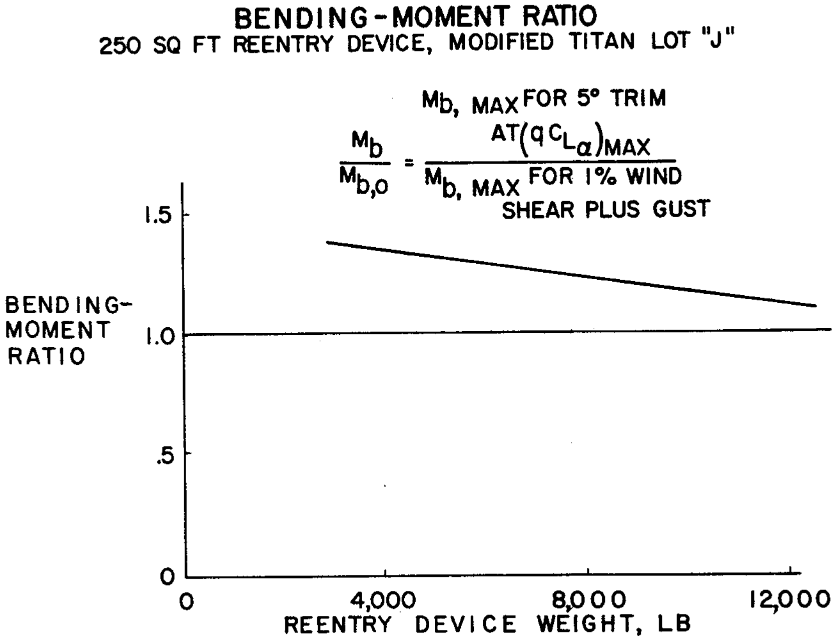


Figure 3

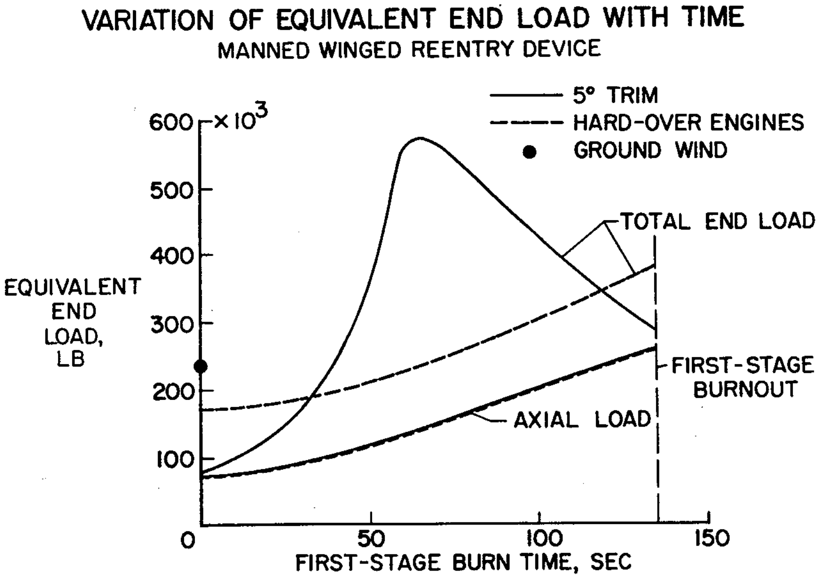


Figure 4

[redacted]

[redacted]

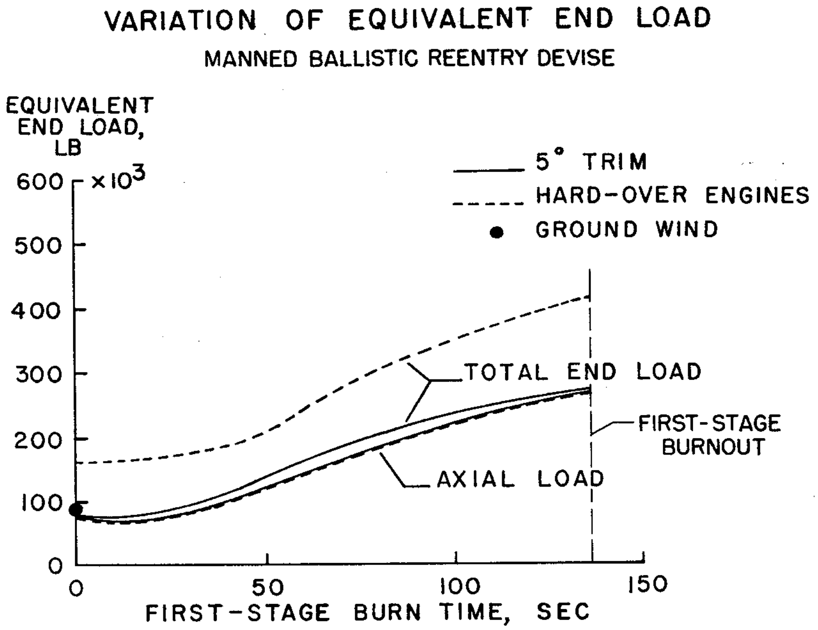


Figure 5

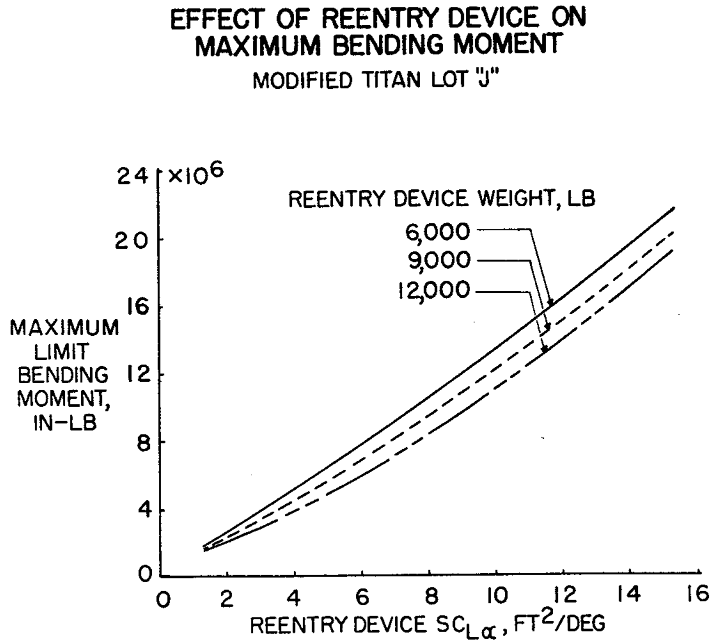


Figure 6

[redacted]

[redacted]

EFFECT OF REENTRY DEVICE ON STRUCTURAL MATERIAL REQUIREMENT

REENTRY DEVICE WEIGHT, 9,000 LB; MODIFIED TITAN LOT "J"

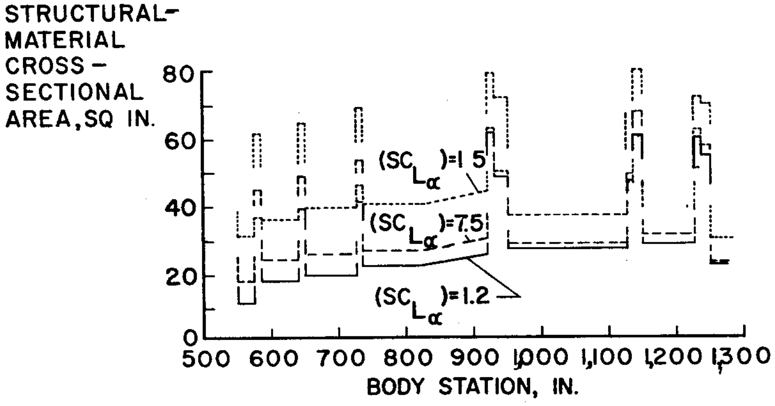


Figure 7

EFFECT OF REENTRY DEVICE ON FLEXIBILITY RATIO

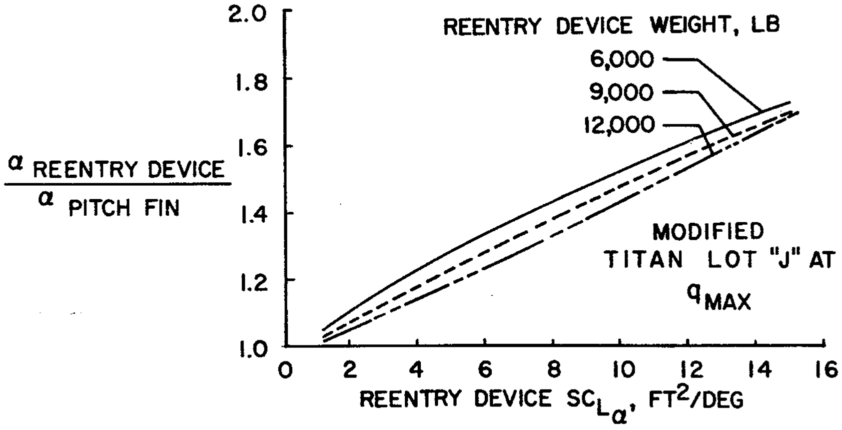


Figure 8

[redacted]

[redacted]

EFFECT OF REENTRY DEVICE ON PITCH FIN REQUIREMENTS

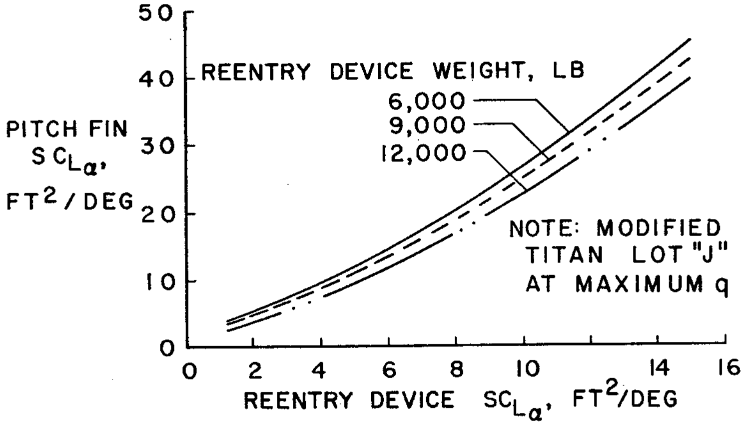


Figure 9

EFFECT OF REENTRY DEVICE ON STRUCTURAL COMPONENT WEIGHT

REENTRY DEVICE, 9,000 LB; MODIFIED TITAN LOT "J"

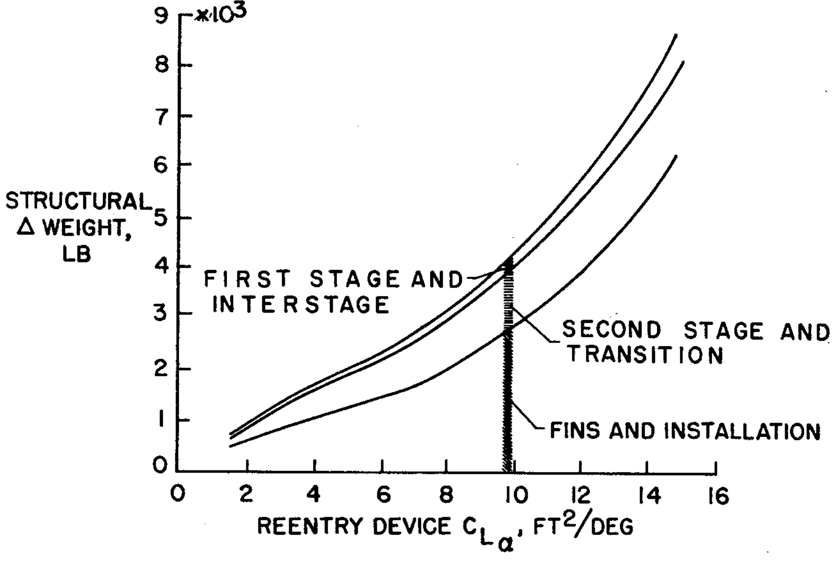
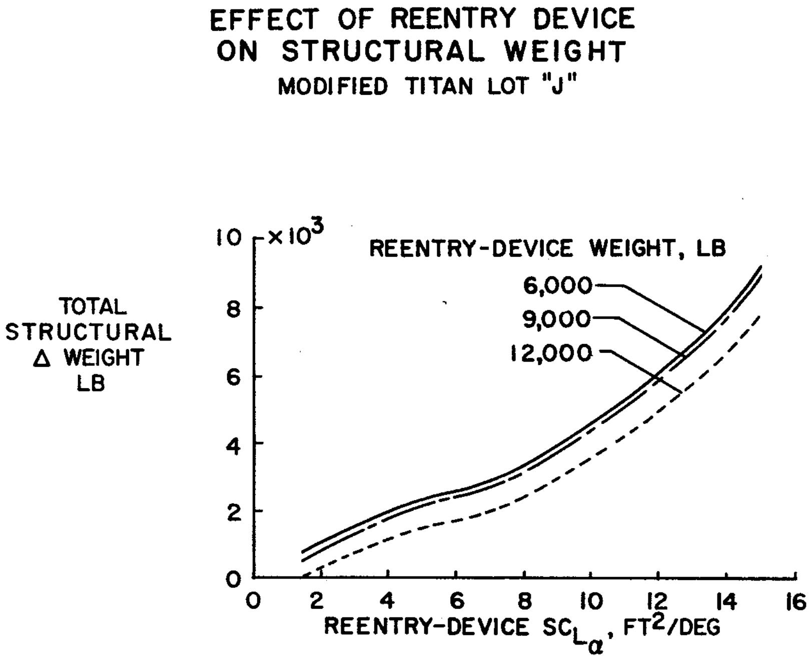


Figure 10

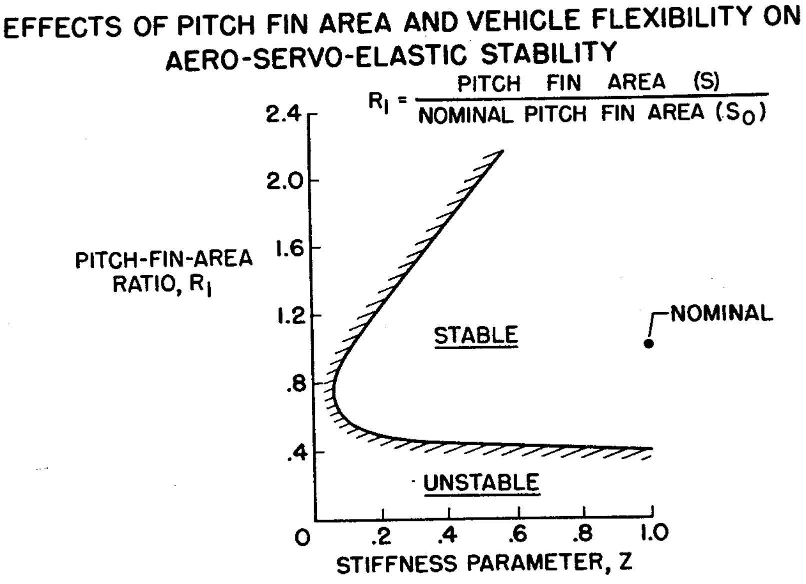
[redacted]

[redacted]



EFFECT OF REENTRY DEVICE ON STRUCTURAL WEIGHT
MODIFIED TITAN LOT "J"

Figure 11



EFFECTS OF PITCH FIN AREA AND VEHICLE FLEXIBILITY ON AERO-SERVO-ELASTIC STABILITY

Figure 12

[redacted]

[redacted]

EFFECTS OF PITCH ATTITUDE GAIN AND VEHICLE FLEXIBILITY ON AERO-SERVO-ELASTIC STABILITY

$\delta_T = K_\theta \theta + K_{\dot{\theta}} \dot{\theta}$

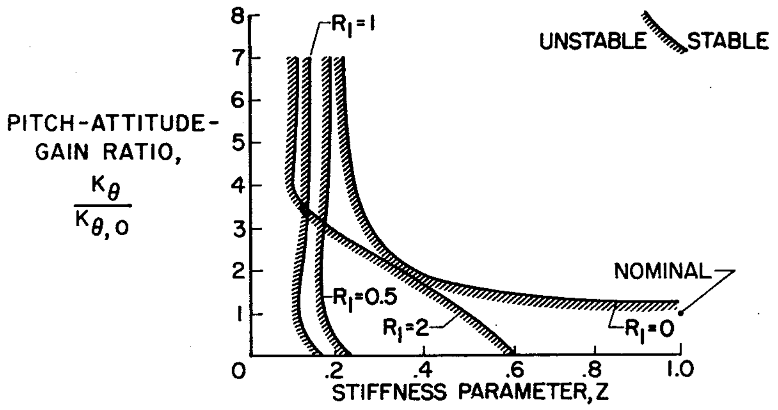


Figure 13

EFFECT OF DESIGN PARAMETERS

WIND SHEAR LOAD

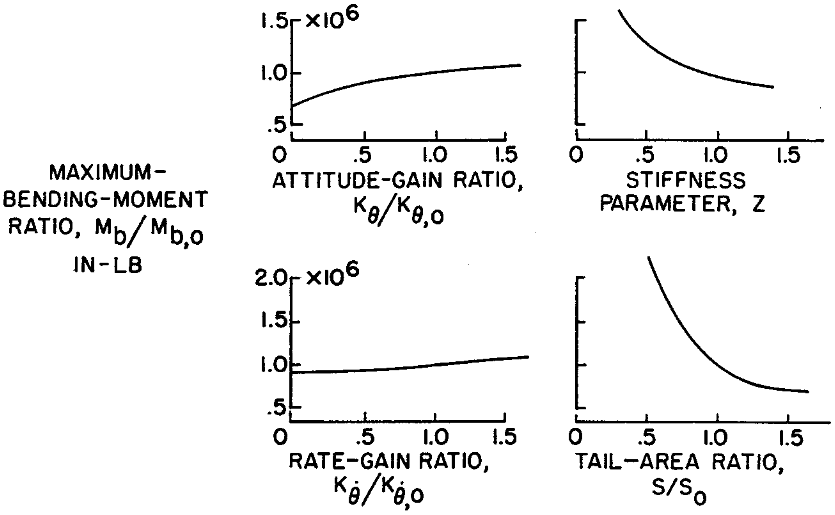
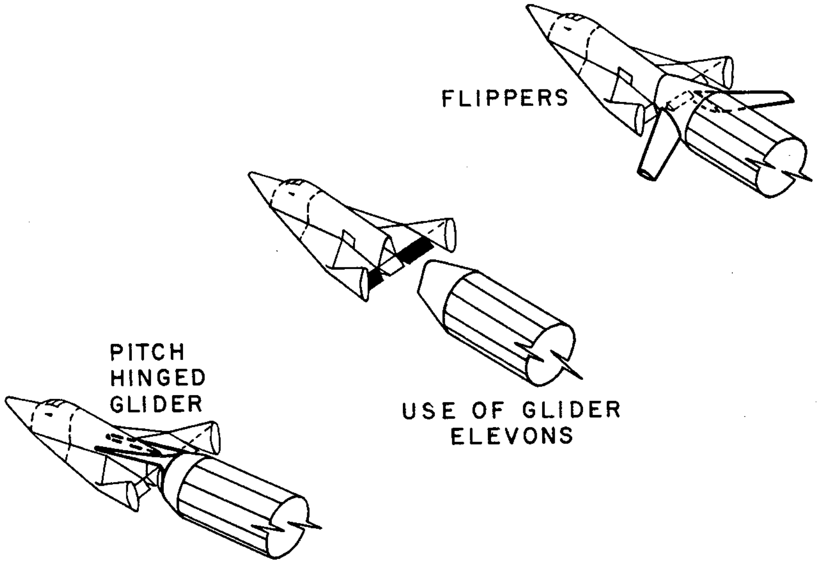


Figure 14

[redacted]

[redacted]



LOAD REDUCTION DEVICES

Figure 15

BENDING-MOMENT REDUCTION DUE TO GEARED ELEVON
SHARP-EDGE GUST

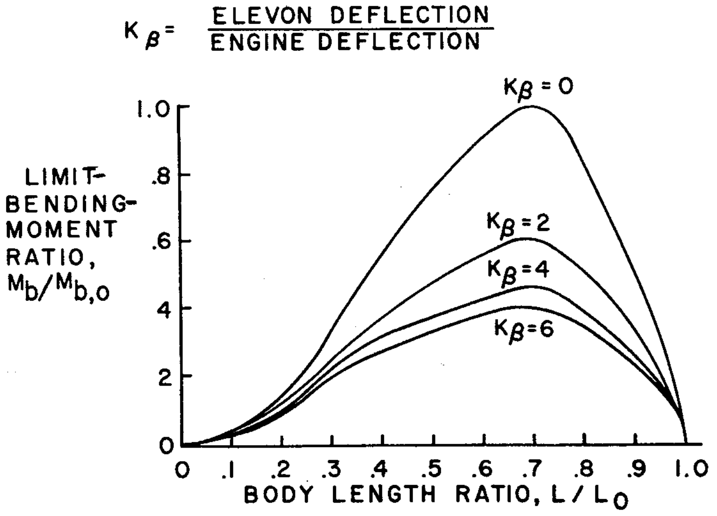


Figure 16

[redacted]

[redacted]

BENDING-MOMENT-REDUCTION DEVICES
SHARP-EDGE GUST

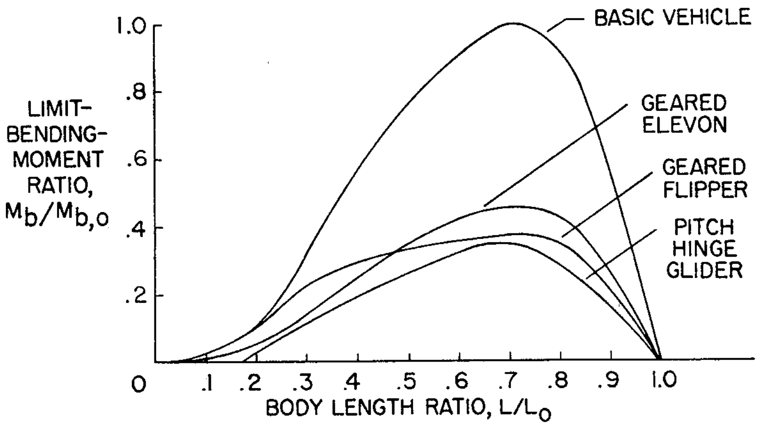


Figure 17

[redacted]