

A SURVEY OF ACTIVE CONTROLS BENEFITS  
TO SUPERSONIC TRANSPORTS

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ABSTRACT

Results are drawn from in-house studies and from several contracted system studies of the impact of advanced technologies on the design of an arrow-wing configuration. Information presented includes estimated benefits, effects of combinations of active control concepts, and constraints. Emphasis is placed on characteristics that are uniquely related to a large airframe featuring a slender body with a fixed wing of low aspect ratio, high sweep, and small thickness ratio.

SUMMARY

The benefits of the application of active controls to supersonic transport airplanes are surveyed. Results are drawn from in-house studies and from several contracted system studies of the impact of advanced technologies on the design of an arrow-wing configuration. The characteristics that are uniquely related to a large flexible airframe featuring a slender body with a fixed wing of low aspect ratio, high sweep, and small thickness ratio are discussed, particularly with regard to the need for the various active controls concepts and to the constraints to benefits. The results indicate that significant benefits can be obtained with a configuration that is inherently longitudinally unstable in subsonic flight and is stabilized by active controls. These benefits may be increased by use of center-of-gravity control and angle-of-attack limiting. Benefits from maneuver and gust load alleviation may be small. In any case, load alleviation most likely will require that flutter suppression be used as well. Flutter suppression in itself may provide some saving in structural weight. Ride quality control by a mode suppression system may be needed for passenger acceptance. For safety, active lateral control should be considered for limiting the magnitude of the transient motion due to an engine unstart.

INTRODUCTION

In the course of the United States Supersonic Transport (SST) program it was necessary for the designers to utilize active controls to stabilize an inherently unstable vehicle in order to achieve an economically competitive and safe airplane. This concept is frequently referred to as relaxed static stability.

Subsequently, as a part of research efforts to advance supersonic technology, several studies, both in-house and by contract, were undertaken by the NASA to explore the potential for improvements in SST designs by a more extensive use of ACT. Results from these NASA studies together with some from the U.S. SST program are summarized herein in terms of estimated benefits, effects of combinations of ACT concepts, and constraints. The candidate ACT concepts included relaxed static stability, load alleviation, and mode and flutter suppression. Emphasis is placed on characteristics that are uniquely related to a large airframe, featuring a slender body with a fixed wing of low aspect ratio, high sweep, and small thickness ratio.

The information is organized in the following sequence. Information sources are identified and briefly described. Fixed-wing SST characteristics that are pertinent to ACT are reviewed. Results from the various sources are collected under three main topics that reflect the manner in which the airplane is affected by groups of the various concepts. Relaxed static stability, center-of-gravity control, and angle-of-attack limiting are discussed under the heading of Performance, Airframe Efficiency, and Handling Qualities. Flutter suppression, maneuver load alleviation, and gust load alleviation are considered under the heading of Wing Structural Weight. Gust acceleration alleviation and mode suppression are placed under the heading of Ride Quality.

#### SYMBOLS

A	gust sensitivity factor, $\sigma_{\Delta n}/\sigma_{wg}$
AC	aerodynamic center
c.g.	center of gravity
c	chord
$c_{av}$	average chord
$c_l$	local lift coefficient
$C_L$	lift coefficient
$C_{L\alpha}$	lift curve slope
$C_{L_{max}}$	maximum lift coefficient
$C_{m_0}$	zero-lift pitching-moment coefficient
$\left(\frac{c}{c_{av}} \frac{c_l}{C_L}\right)$	spanwise lift distribution coefficient
g	acceleration of gravity

L/D	lift-to-drag ratio
M	Mach number
MAC	mean aerodynamic chord
$\Delta n$	incremental vertical acceleration
q	dynamic pressure
$w_g$	gust velocity
$w_s$	running weight of structure
y	distance along span
$\alpha$	angle of attack
$\sigma$	root-mean-square value
ACT	active control technology
FAA	Federal Aviation Administration
GAG	Ground-Air-Ground (cycle)
GLA	gust load alleviation
HSAS	hardened stability augmentation system
MLA	maneuver load alleviation
NASA	National Aeronautics and Space Administration
RSS	relaxed static stability
SAS	stability augmentation system
SCAT	supersonic commercial air transport
SST	supersonic transport
TOGW	take-off gross weight

#### INFORMATION SOURCES

The survey reported herein is based on information from the sources described below. The numbers designating each source are used for identification in the subsequent sections of this paper.

1. The U.S. SST Program, FAA
2. SST Technology Follow-on Program, FAA
3. Studies of the impact of advanced technologies applied to a conceptual supersonic aircraft configuration, NASA
4. Langley Research Center in-house studies

The subject matter from Sources 1 and 2 deals with the stabilization by active controls of an inherently longitudinally unstable airplane. An illustration of this airplane is shown in figure 1. The airplane structure and control system design was developed in depth. Aeroelastic effects are considered. Material pertinent to active controls is documented in reference 1.

Source 3 consists of three contract design studies related to an arrow-wing configuration, illustrated in figure 2, which was derived from the NASA SCAT-15F concept. The consideration of active controls constituted only a small fraction of the total effort. The active control concepts treated by the individual contractors are listed below.

Contractor	ACT Concepts	Cruise Mach No.
a.	Relaxed static stability	2.7
	Center-of-gravity (c.g.) control (c.g. location measurement)	
	Angle-of-attack limiting	
b.	Relaxed static stability	
	Maneuver load alleviation	2.2
	Gust load alleviation	
	Flutter suppression	
c.	Relaxed static stability	2.7

The results from Source 3 are not published.

Source 4 consists of two studies:

a. A preliminary assessment of active controls benefits to an arrow-wing configuration (fig. 2). The effects of relaxed static stability, maneuver and gust load alleviation, flutter suppression, and ride quality control were considered.

b. Follow-on design development of the arrow-wing configuration. Studies are in progress on alternate methods of balancing the airplane to improve

performance. Changes in the wing camber and twist of the baseline airplane to improve the cruise lift-drag ratio and the use of relaxed static stability and angle-of-attack limiting for subsonic flight are being investigated.

The results from Source 4 are not published.

### SST CHARACTERISTICS

Some of the characteristics, unique to the fixed-wing SST configuration, result in design problems that active controls may resolve. However, some of these characteristics also place constraints on the benefits of active control application. These characteristics are summarized below, together with remarks on their effects. Some of the geometric characteristics are illustrated in figures 1 and 2.

#### Large Sweepback and Low Aspect Ratio

##### Advantages

1. Higher cruise lift-drag ratio
2. Lower sonic-boom overpressure

##### Disadvantages

1. Low maximum lift coefficient ( $C_{L_{max}}$ ) requires low wing loading for reasonable landing speeds
2. Long chord lengths, together with structural requirements, limit the ratio of trailing-edge control surface chord to wing chord to small values. The ratios of control surface areas to wing area are small.
3. Structure contains a large amount of minimum gage material

#### Small Wing Thickness Ratio

##### Advantages

1. Lower drag
2. Low stiffness plus sweepback provides some inherent load alleviation by aeroelastic effects

##### Disadvantages

1. Low stiffness results in reduced control effectiveness from aeroelasticity
2. Low flutter speeds
3. Low natural structural mode frequencies

### Long, High-Fineness Ratio Fuselage

#### Advantages

1. Provides adequate payload volume
2. Lowers sonic-boom pressure

#### Disadvantages

1. Low natural bending frequencies
2. Aeroelastic effects

### Aft-Mounted Engines

#### Advantages

1. Favorable airframe interference for propulsion efficiency
2. Low noise in passenger compartment

#### Disadvantages

1. Creates balance problem due to aft-located heavy weight
2. Contributes to lower flutter speeds
3. Space occupied by engines reduces available area for trailing-edge control surfaces

### Large Dynamic Pressure

#### Disadvantages

1. Aggravates adverse aeroelastic effects such as loss of control effectiveness

## RESULTS

### Performance, Airframe Utilization Efficiency, and Handling Qualities

#### Relaxed Static Stability

Essentially all recent SST studies (Sources 1, 2, 3a, 3c, and 4b) have advocated the use of a hardened stability augmentation system (HSAS) to provide safe handling qualities for an SST configuration that is inherently statically unstable at subsonic speeds. Hardened means that the reliability must equal that of the airframe structure. Source 3b considers a neutrally stable airplane with a nonhardened SAS. Benefits include either increased range for a given payload (416 km (225 n. mi.) from Sources 1 and 2) or increased payload for a given range. Benefits from Source 3b were expressed in terms of a reduced take-off gross weight (TOGW) of a resized airplane having a fixed

payload and range. The reduction in TOGW was estimated to be about 18,000 kilograms (40,000 lb) for a baseline TOGW of 338,000 kilograms (750,000 lb).

These benefits accrue from an improved lift-drag (L/D) ratio for both cruise and low-speed flight, along with a more efficient utilization of airframe volume, while retaining safe handling qualities. The need for an HSAS arises from two SST characteristics. One is the shift in aerodynamic center with Mach number as illustrated in figure 3. The other is the aft location of the center of gravity (c.g.) for the operating weight empty condition due to engine locations. These combine to make extremely difficult the longitudinal balancing of the airplane while avoiding or minimizing (1) the need for ballasting, (2) unproductive portions of the fuselage that must be kept empty of payload fuel, (3) large tail areas and loads, (4) high trim drag, and (5) unacceptable handling qualities. Some of the considerations of the problem are described in reference 1.

The U.S. SST design features a configuration (fig. 1) that is inherently statically unstable longitudinally (in fact, the c.g. is aft of the maneuver point) at subsonic speeds. An active flight control system was designed to provide good handling qualities for normal operations. This system was backed up by an HSAS designed to provide poor but safe handling qualities with a reliability equal to the airframe structure. In essence, the HSAS is a pitch-rate feedback control that produces an apparent positive maneuver margin. There remained a negative static margin resulting in an unstable phugoid mode; this, however, could be controlled safely by the pilot. This design is documented in reference 1 together with some design guidelines and criteria. The flexibility of the airframe was taken into account. A particularly significant problem identified was the difficulty of providing control gains that were high enough for rigid-body mode stabilization without destabilizing the lower frequency elastic modes.

Source 3b included a preliminary design of an active control system which consisted of a stability augmentation system (SAS), gust load alleviation, and gust acceleration alleviation (rigid-body mode acceleration) for ride quality improvement. The airplane was considered rigid and the aft-most c.g. location was limited to the neutral point. Thus, the SAS would not need to be hardened as the aircraft could be controlled without it. In this application the benefit stemmed from a reduction in tail volume, hence, decreases in structural weight and in drag. The procedure used in the preliminary design of the system of combined ACT concepts included an optimal method and system practicalization.

In Source 4b, currently under way, the philosophy is to increase L/D for cruise and lift for landing by arranging an upload on the horizontal tail. For cruise, the airplane is designed to be inherently statically stable. Lift is increased and drag is decreased by means of a small upload on the tail, created by a suitable wing camber and twist ( $C_{m_0} > 0$ ). For landing, the lifting tail load is obtained by designing the airplane to be inherently statically unstable; therefore, an HSAS is required. Thus an advantage is taken of the AC shift with Mach number. This approach is in general agreement with that taken in Source 3c.

In contrast to results of some other relaxed static stability applications, particularly to subsonic transports, this approach will not allow a smaller tail size because the airplane concept features flaps for take off and landing and the associated pitching moments size the tail.

Safe application of the relaxed static stability concept will require the use of an angle-of-attack limiting system or a larger tail surface than required only for stability in order to avoid problems such as lock-in stall or an excessive sink rate.

### Center-of-Gravity Control

Even with an HSAS, achievement of a highly efficient SST with good handling qualities is difficult due to the need to allow a substantial tolerance for c.g. location. The benefits of a relaxed static stability HSAS might be greatly enhanced if the c.g. location appropriate to the particular flight speed could be tightly controlled automatically. Source 3a recommends research on defining the requirements for an onboard c.g. measurement system that is a prerequisite to c.g. control.

### Angle-of-Attack (Alpha) Limiting System

As previously mentioned with regard to the benefits of relaxed static stability, an angle-of-attack limiter would enhance the benefits of an HSAS. This recommendation is also made in Source 3a which points out the hazard of a lack of warning to the pilot that the airplane is approaching an excessive angle of attack. This may result in a locked-in stall due to exceeding the control authority of the HSAS, or an excessive sink rate. Source 3a suggests the following research: (1) Establish criteria for longitudinal stability and control at the alpha limit; (2) establish any limitations to the applications of an alpha limiter on an SST; (3) synthesize a system for a selected airplane; and (4) validate the system by flight test over the desired flight envelope. An outstanding need is an alpha sensor that is accurate and reliable in an environment featuring a wide range of Mach number, dynamic pressure, and temperature, and such hostile agents as rain, hail, and bird strikes.

### Wing Structural Weight

The potential benefits of maneuver and gust load alleviation, and flutter suppression were explored in Sources 3b and 4a. Both sources recognized that the several concepts must be considered in terms of their aggregate effects and of constraints imposed by structural requirements for other than the controlled quantities. The need for this is discussed with the aid of figure 4 from Source 4a. This chart indicates the structural requirements of the arrow-wing configuration in terms of the individual spanwise distributions of the weight of structure necessary for each of the items listed on the right. These curves are conceptual, not calculated. However, the relative positions of the flutter, maneuver load, and gust load curves are believed to be representative. The extent of the wing area for which some of these structural requirements are dominant for the baseline arrow wing is roughly indicated in figure 5.



Flutter requirements are likely to be critical for a substantial portion of the wing structure. Thus, a potential benefit from use of a flutter suppression system is indicated. More important, however, is the need for flutter suppression in order to realize any benefits from load alleviation. If flutter is suppressed then the maneuver load becomes critical, and, in turn, if maneuver load alleviation is effective, the gust load may then be critical. If gust load alleviation is effective, the benefits of a combined flutter suppressor, and maneuver load and gust load alleviation system will ultimately be limited by the structural requirements of other loads, such as landing, 6-g crash, and fuel overpressure, and by static stiffness and minimum gage requirements.

If appreciable reduction of the structural material is obtained from load alleviation, the burden on the flutter suppression system is increased over that required to only remove the flutter weight penalty with respect to the unalleviated wing. For baseline structures that are flutter free, effective load alleviation may require flutter suppression.

To summarize, some of the normally noncritical structural requirements may become critical, contingent on the use of active controls. It is also probable that structural requirements not subject to active controls will significantly constrain the benefits from active controls.

#### Flutter Suppression

To provide adequate flutter speeds by conventional techniques for an arrow-wing airplane, it is estimated in Source 3b that the weight of material added to the strength-designed wing is in the range of 1800 to 2700 kilograms (4000 to 6000 lb). A candidate flutter suppression system was designed that reduced this penalty by about 680 kilograms (1500 lb). This study was a relatively small effort. Presumably, a larger effort might provide a system of greater effectiveness.

#### Maneuver Load Alleviation

Maneuver load alleviation (MLA) was considered in Sources 3b and 4a. The results, based on calculations for a rigid airplane, varied from 5 to 9 percent reduction in wing root bending moment, depending on the flight condition assumed to be critical. The estimated attendant reductions in structural weight ranged from 450 to 1010 kilograms (1000 to 2200 lb). These figures are probably optimistic because the constraints from other structural requirements, discussed earlier, were not imposed.

The effect of these constraints is illustrated conceptually in figure 6. If the requirements for gust and other loads and for minimum gage, etc., exceed that for the alleviated maneuver load, only a fraction of the reduced weight benefit can be realized as indicated by the shaded area in figure 6. The utilization of gust load alleviation would relax, but not eliminate these constraints. Another constraint, not included in the study, is the effect of aeroelastic deformations on MLA performance. The influence of aeroelasticity on control surface effectiveness is touched upon subsequently in this section

of the paper, but the overall alleviation of loads on the flexible wing is not evaluated.

In assessing benefits of MLA an adverse side effect must be recognized. Effective MLA will increase the mean (one g) stress level over that of the unalleviated wing. This will substantially increase the fatigue damage rate. In view of the predominant effect of the ground-air-ground cycle on fatigue, this may be a significant additional structural requirement. On the other hand, the MLA concept can be used to increase fatigue life if the strength requirements of the unalleviated airplane are retained.

For the sake of generality, it is of interest to examine the properties of the control surfaces for maneuver load alleviation. As can be observed for the arrow wing in figure 7, the total area of the usable control surfaces is a small percentage of the wing area. An increase in control surface area by increasing the span of the control is precluded by the space required by the engines. An increase in control surface chord is restricted by the wing box structure. It is likely that the outboard surfaces 1 and 2, shown crossed out in figure 7, will not be usable due to loss of effectiveness from aeroelastic deformation. The inboard surface 3 between the engines may also suffer a large loss in effectiveness in supersonic flight. However, the load alleviation inherent in flexible sweptback wings at high dynamic pressure reduces the need for active alleviation at supersonic speeds. The need for MLA is likely to be highest at transonic speeds having dynamic pressures that are lower than those for cruise. For the transonic condition, the effect of aeroelasticity on surfaces 3 and 4, shown shaded in figure 7, is not as severe. These surfaces were used in load alleviation calculations in Source 4a.

The influence of these small separate surfaces on the theoretical spanwise aerodynamic load distribution is shown in figure 8 from Source 4a for the arrow wing. These results were obtained using Woodward aerodynamics for a  $M = 1.2$ , lightweight condition, assuming a rigid structure and maximum control surface deflections of  $20^\circ$ . The reduction in net (aerodynamic and inertia) bending moment can be shown to be about 5 percent at the root and about 9 percent at the mid-semispan station.

Although only effects on bending moment were examined, the additional chordwise loads accompanying the control surface deflections may be significant. Also significant may be the differences between theoretical and actual loads at limit load levels due to nonlinear aerodynamic phenomenon such as flow separation on control surfaces and pressure limiting.

### Gust Load Alleviation

Gust load alleviation (GLA) was considered in Sources 3b and 4a. GLA is defined herein as the reduction of the rigid-body-mode gust load responses. The load increments from vibration of structural modes are not accounted for. It is assumed that these would be controlled by a mode suppression system which is mentioned under the subject of ride quality control. The results for a rigid airplane in terms of structural weight reduction, assuming no constraints from other structural requirements, varied from zero to about 225 kilograms (500 lb)

As in the case of maneuver load alleviation, these constraints may reduce the higher value cited. The magnitude of benefits can vary depending on bookkeeping methods. If GLA is needed to realize the benefits of MLA then the somewhat greater benefit of MLA may be attributed to GLA as well.

The reason for the small benefits of GLA to the arrow-wing configuration is that the airplane is somewhat less sensitive to gusts than subsonic jets. The gust load factor for the arrow-wing airplane was estimated in Source 4a to be about 2.0g in contrast to the 2.5g maneuver limit load factor. At first glance, this seemed surprising in view of the low wing loading (lowest value is approximately 1900 newtons/meter<sup>2</sup> (40 lb/sq ft). However, the low wing loading is compensated for by the characteristically low value of lift curve slope for highly swept, low-aspect-ratio wings.

For reasons given in the discussion of MLA, the available control surfaces for GLA are the two inboard surfaces. It is of interest to note that the sense of the deflection of these inboard surfaces for GLA is opposite to that for MLA. For example, for the alleviation of a positive maneuver load the trailing edges of the controls should deflect downward, whereas for the alleviation of a positive gust load the trailing edges should deflect upward. For outboard control surfaces, were they effective, the sense of the deflection for MLA and GLA would be the same.

#### Ride Quality

The unpleasant accelerations during flight in turbulence can be regarded as arising from two sources; (1) the response of the airplane rigid-body modes and (2) the vibratory response of the elastic modes. These are illustrated schematically in figure 9. The total vertical acceleration response is shown by the sketch at the top and consists of the sum of high frequency structural oscillations and lower frequency rigid-body-mode responses. The use of mode suppression by means of small canards or other auxiliary control surfaces to reduce the structural vibration may be necessary as suggested by the flight experience with the XB-70 airplane and by Source 3b. (Source 3b indicates that need is marginal.) Effective mode suppression would then leave the rigid-body-mode acceleration as indicated by the middle sketches in figure 9. The rigid-body-mode accelerations can be controlled by gust acceleration alleviation. However, for the SST these lower frequency responses are not likely to be objectionable on the basis of gust sensitivity estimates in Sources 3b and 4a.

The gust sensitivity,  $\bar{A} = \frac{\sigma_{\Delta n}}{\sigma_{w_g}} \approx 0.01$  (ratio of root-mean-square values of acceleration and gust velocity) for the rigid-body modes is well below values for subsonic jet transports. It is just as well, for the effectiveness of the available control surfaces to alter the wing lift for the reduction of low frequency gust accelerations, indicated by the bottom sketch in figure 9, is low.

In general, effective use of maneuver and gust load alleviation (of loads from rigid-body-mode responses) will tend to increase the severity of structural

vibrations over that of the unalleviated wing and, therefore, increase the need for mode suppression. Incidentally, the mode suppression may provide a degree of flutter suppression and vice versa. It could be advantageous to combine the two concepts.

#### Other

Although they are not found in most lists of active control systems, there are two other concepts that may benefit an SST.

One is the concept of automatically controlling the airplane lateral transient accompanying an engine unstart at supersonic speeds. Conceivably, following an unstart the airplane could be disturbed so rapidly that the pilot could not apply corrective action before the vehicle exceeded design loads or a controllable angle of attack or sidelsip. The second concept is an actively controlled landing strut to reduce the loads and unpleasant motions of the elongated SST during taxi runs. Research on this concept is being conducted at the Langley Research Center.

#### CONCLUDING REMARKS

The information surveyed indicates that some significant benefits to SST designs may be obtained through active controls. There is considerable agreement that a large transport will require active stabilization of an inherently statically unstable condition at subsonic speeds. The benefit of the relaxed static stability may be increased by use of center-of-gravity control and angle-of-attack limiting. Benefits from maneuver and gust load alleviation may be small for the arrow-wing concept. In any case, load alleviation most likely will require that flutter suppression be used as well. Flutter suppression in itself may provide some saving in structural weight. Ride quality control by a mode suppression system may be needed for passenger acceptance. For safety, active lateral control should be considered for limiting the magnitude of the transient motion due to an engine unstart.

#### REFERENCES

1. Tomlinson, L. R.: Control System Design Considerations for a Longitudinally Unstable Supersonic Transport. AIAA Journal of Aircraft, Vol. 10, No. 10, October 1973, pp. 594-601.

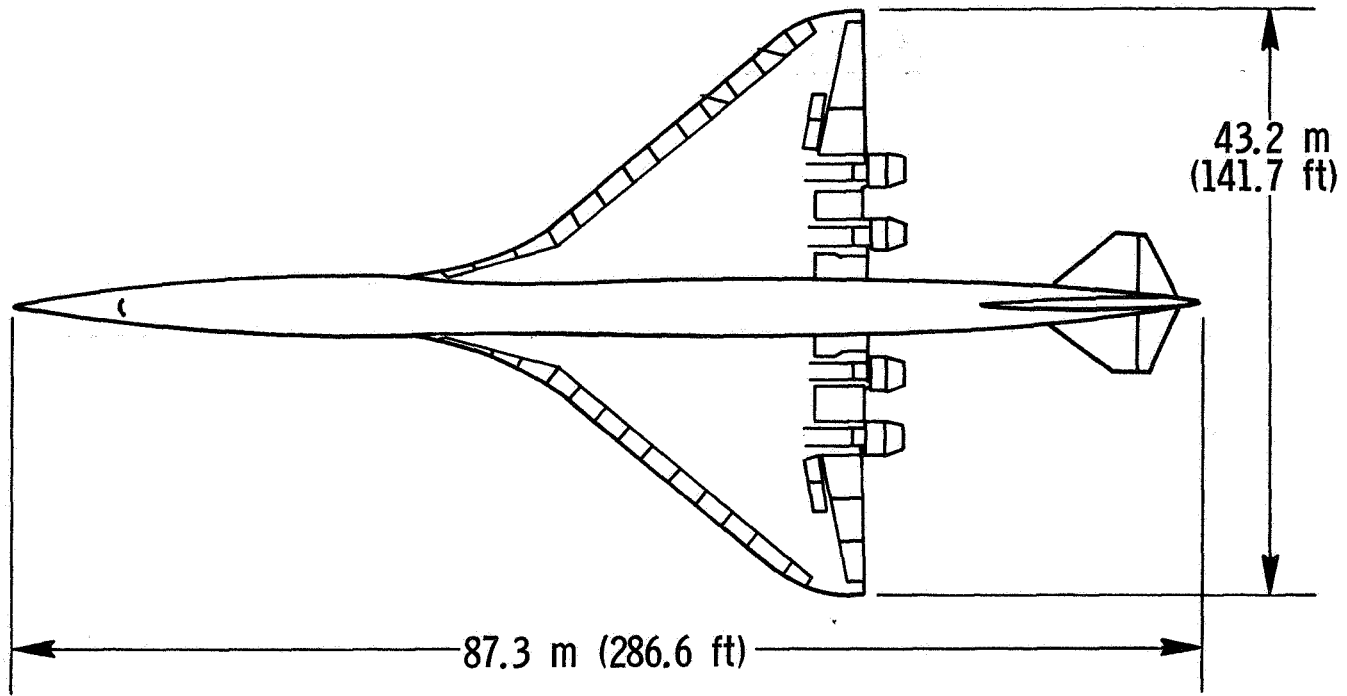


Figure 1.- United States SST design.

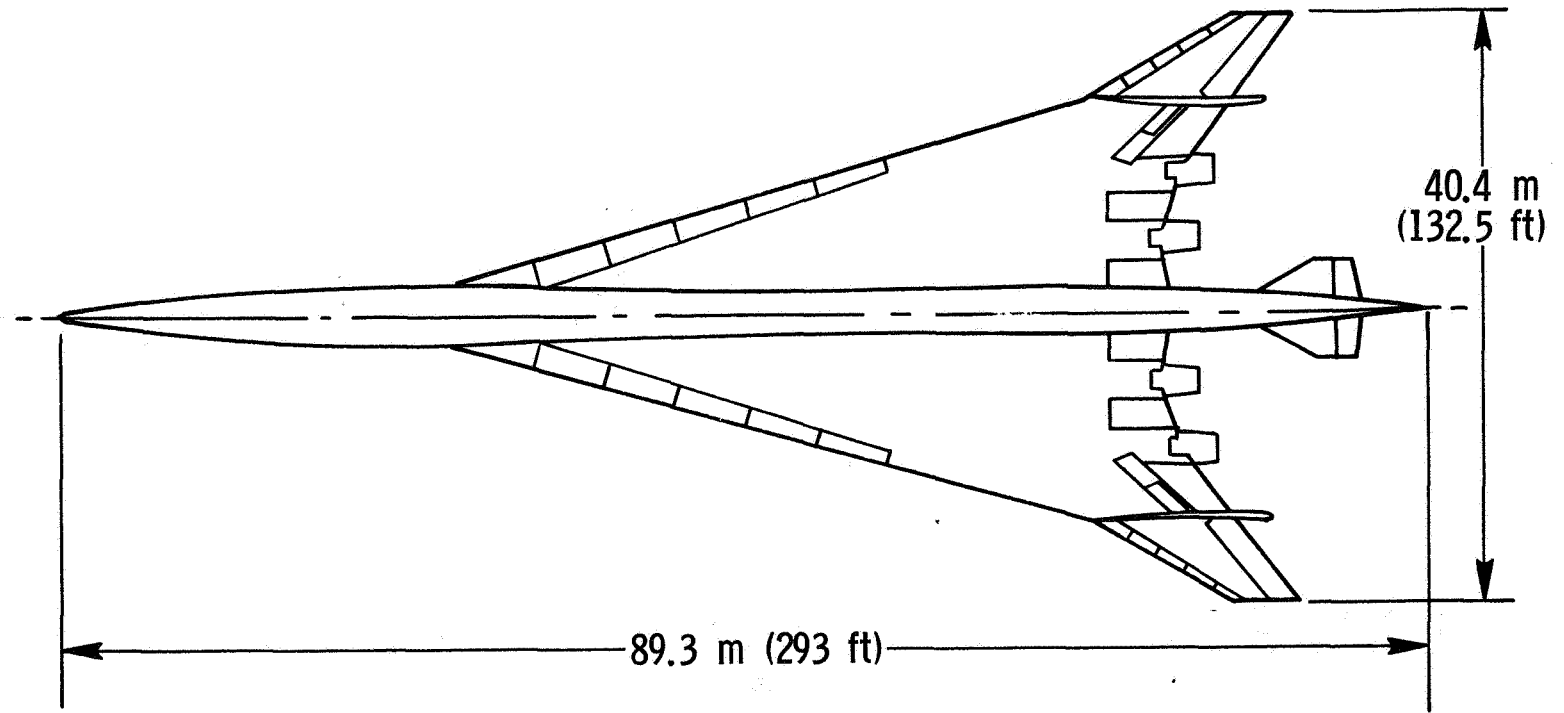


Figure 2.- Arrow-wing design.

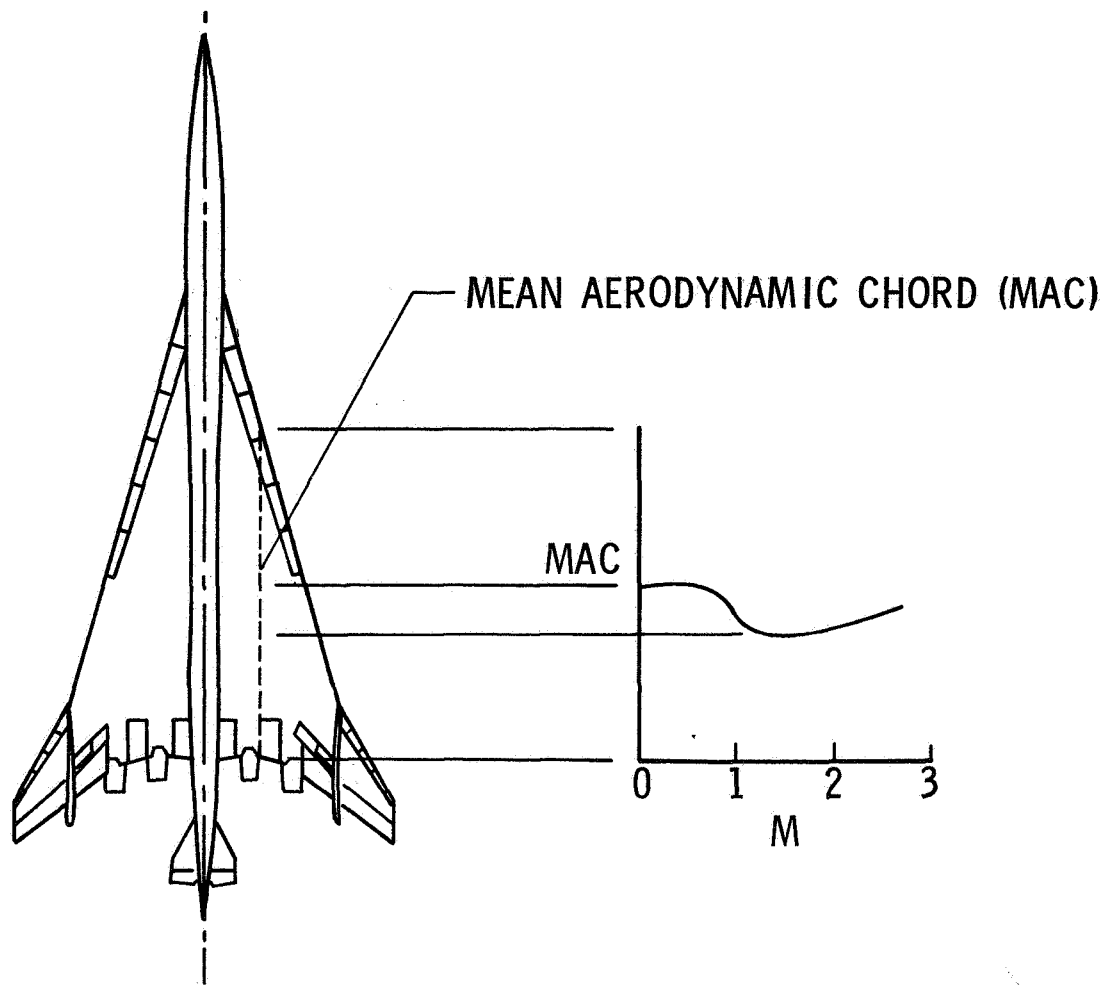


Figure 3.- Variation of airplane aerodynamic center (AC) with Mach number (M).

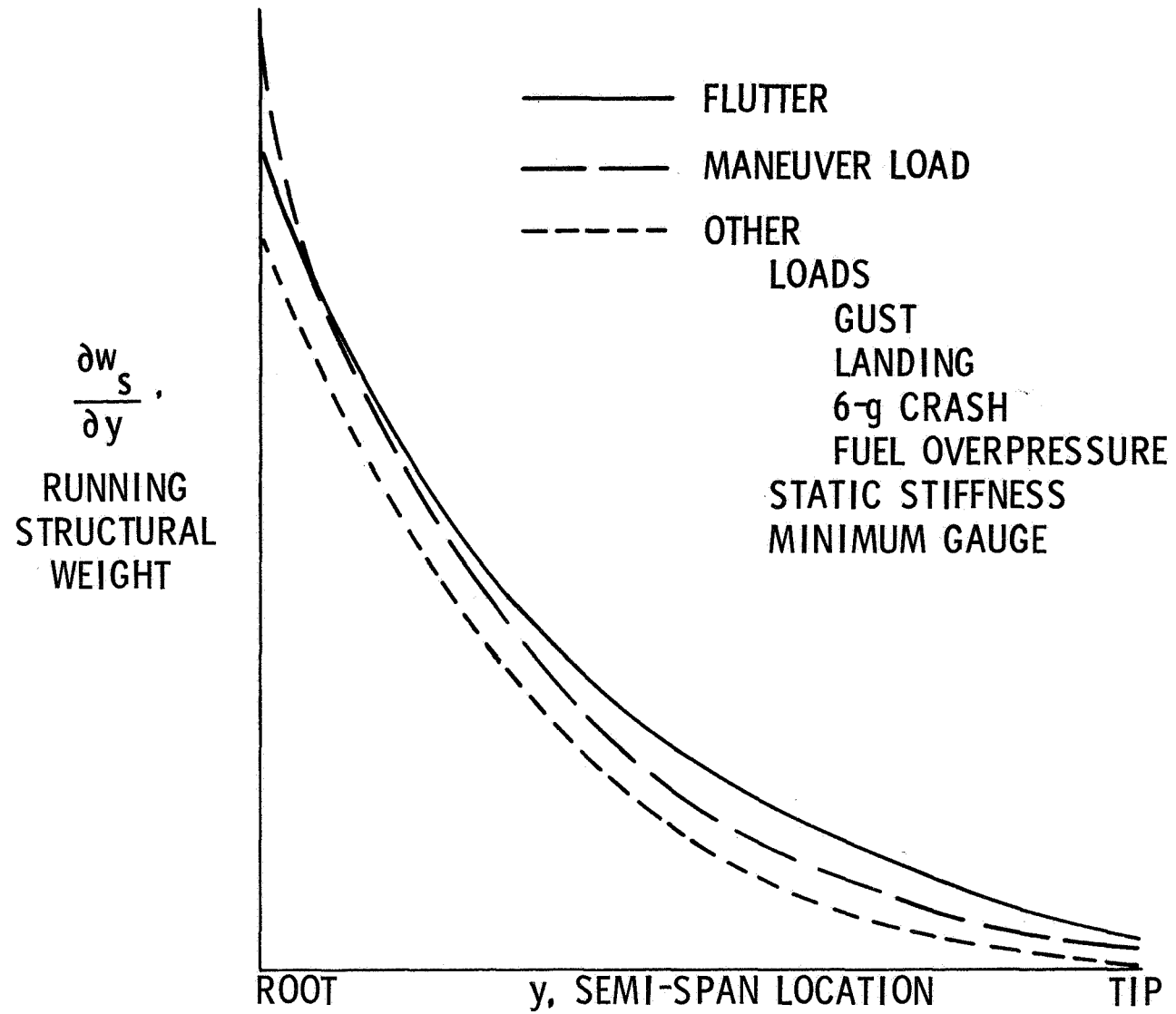


Figure 4.- Wing structural requirements of baseline arrow-wing airplane.



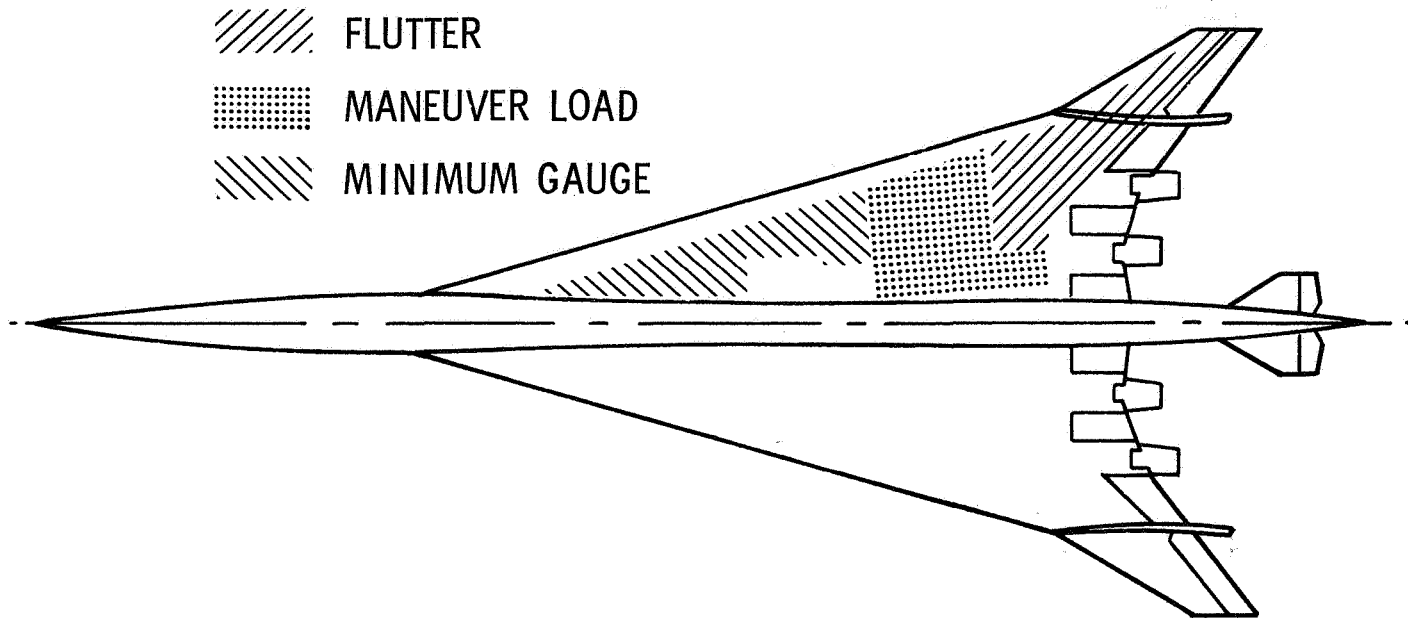


Figure 5.- Critical structural requirements for baseline arrow wing.

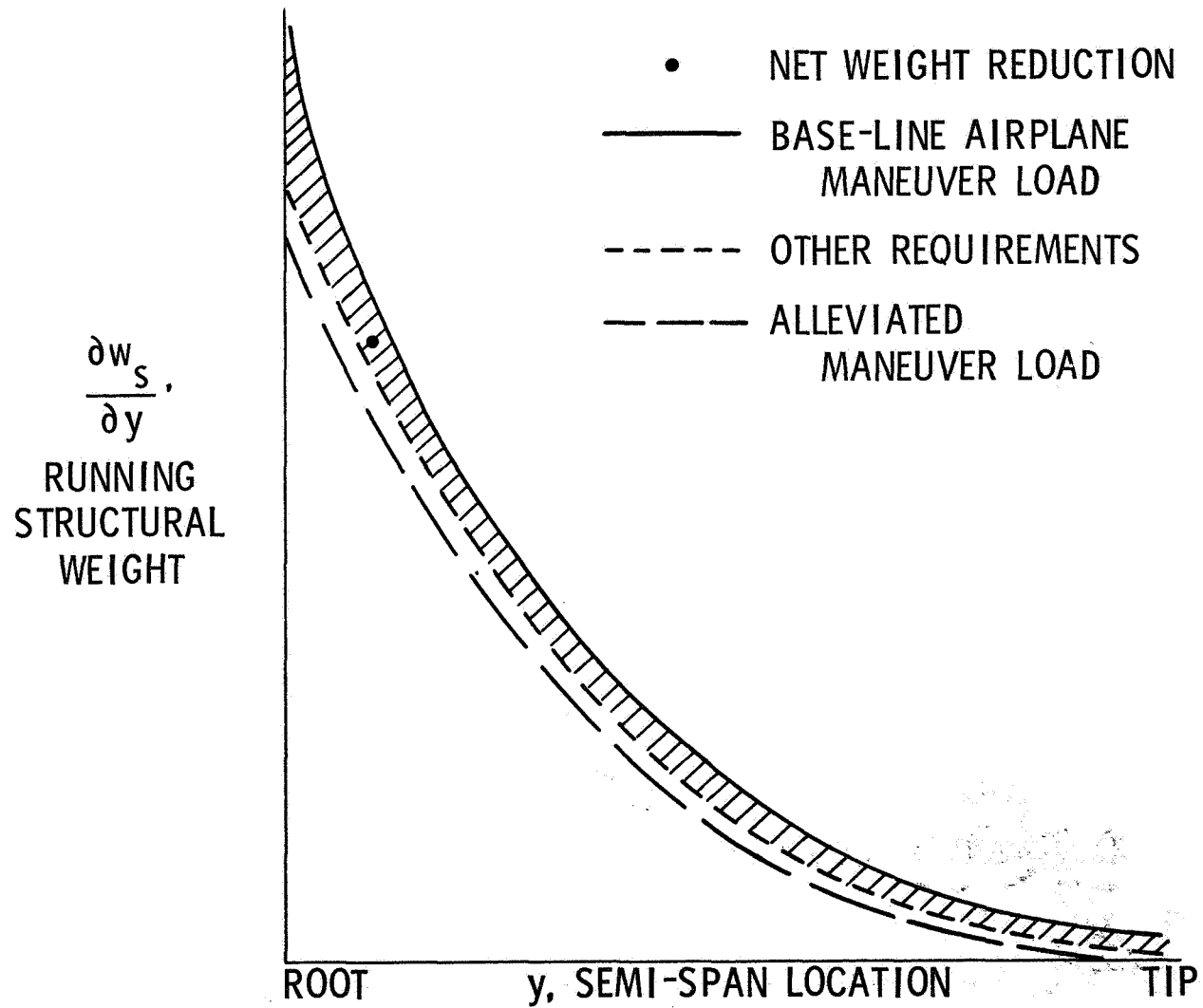


Figure 6.- Structural requirement constraint for maneuver load alleviation.

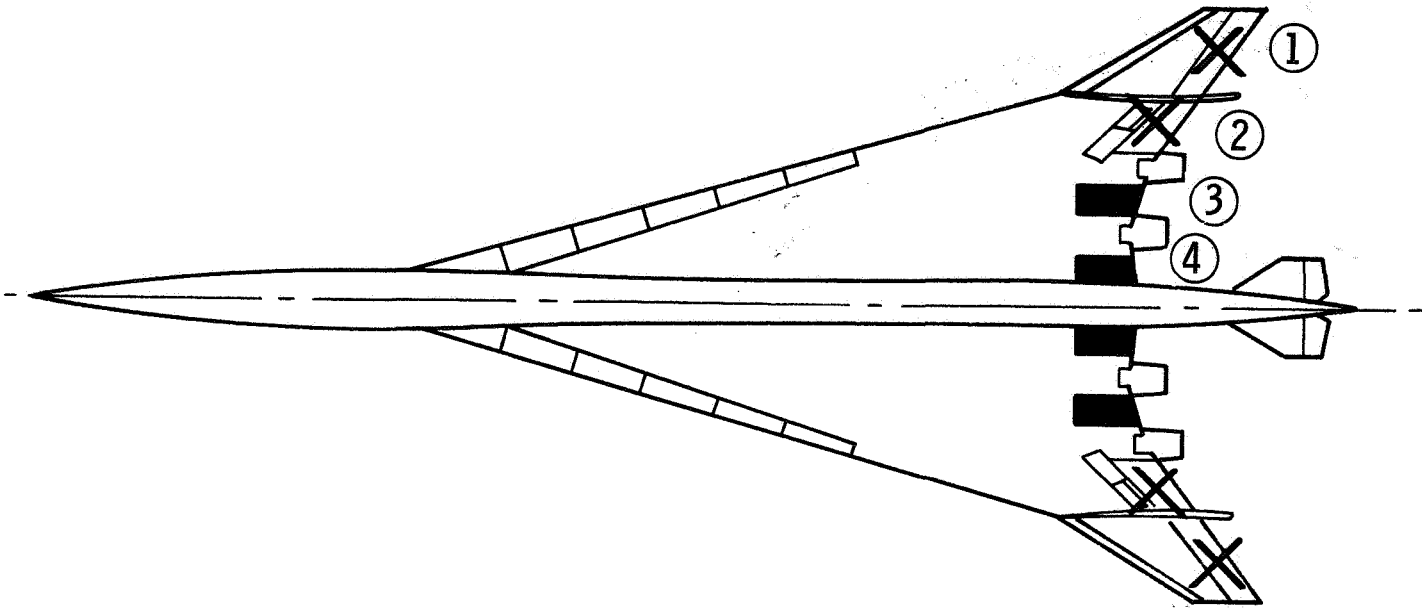


Figure 7.- Control surfaces for maneuver and gust load alleviation.

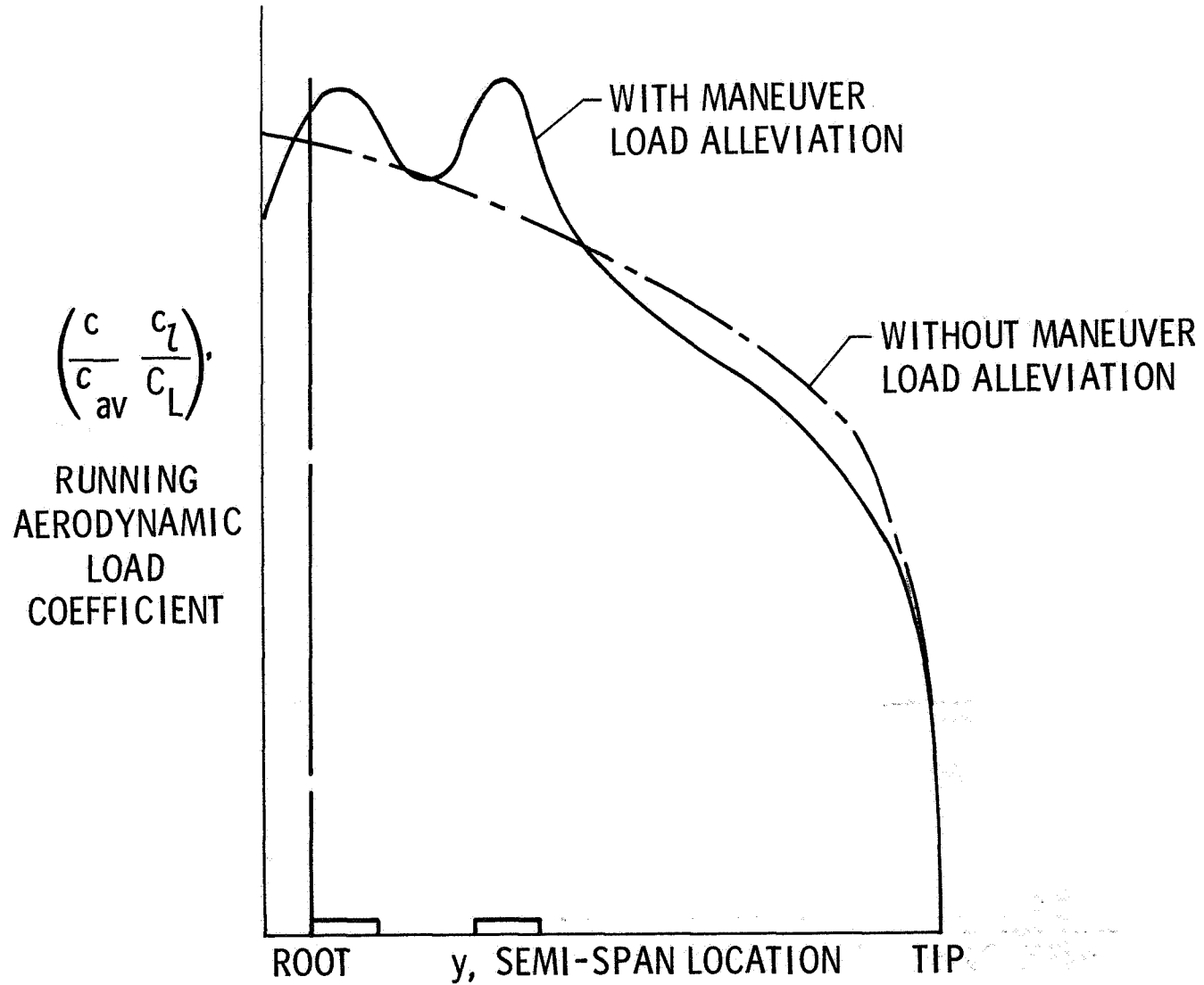


Figure 8.- Spanwise aerodynamic load distributions at limit load, Mach number 1.2, control deflection 20°.

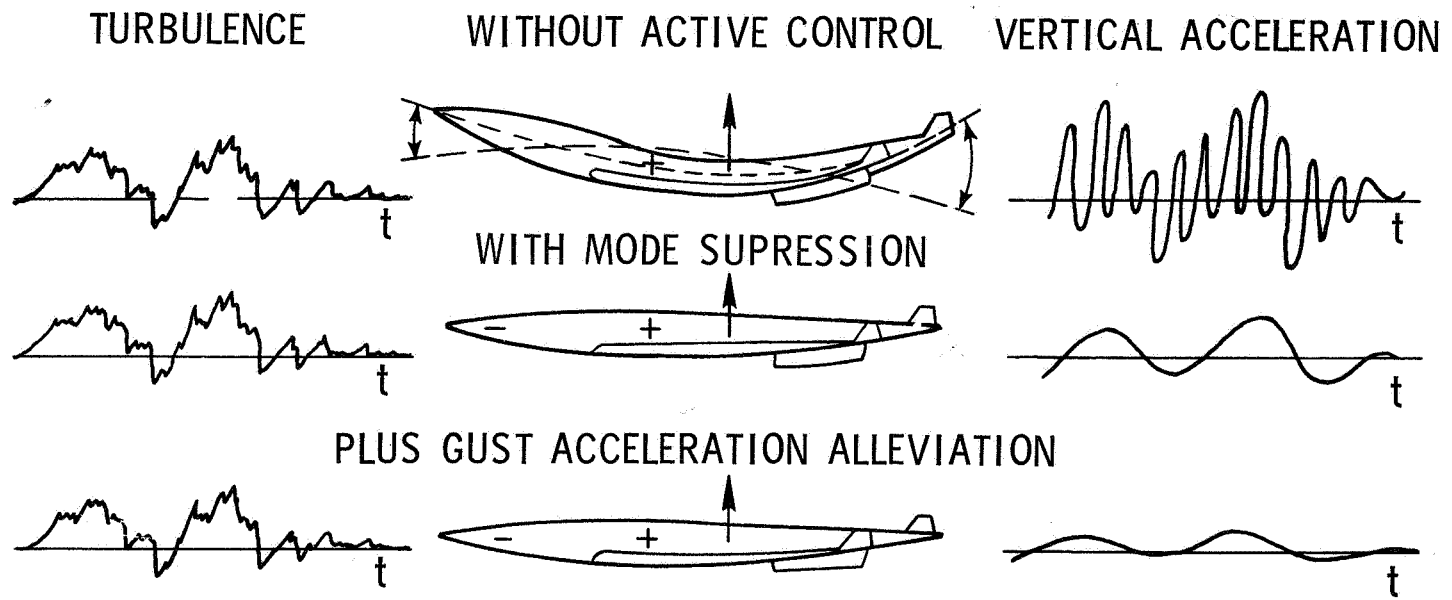


Figure 9.- Ride quality control with mode suppression and gust acceleration alleviation.