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A SUMMARY OF THE APPLICATION OF ACTIVE CONTROLS TECHNOLOGY IN THE ATT SYSTEM STUDIES

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SUMMARY

The application of active controls technology to subsonic, long-range transport aircraft was investigated in three Advanced Transport Technology system studies. Relaxed stability requirements, maneuver and gust load alleviation, and active flutter suppression were the concepts considered. A different configuration was investigated for each of the three airframe manufacturers, and each had a somewhat different approach to the application of active controls technology. Consequently, the results varied in magnitude between the contractors, but several trends were noted. Relaxed stability requirements resulted in the largest benefits - reduced weight, increased return on investment, and decreased direct operating costs. Maneuver load alleviation, gust load alleviation, and flutter suppression resulted in much smaller benefits. Prior to application of active controls technology, a research and development program directed toward fulfilling data base requirements, establishing effective design techniques and criteria, improving systems maintainability and reliability, and demonstrating technology readiness must be completed.

INTRODUCTION

In mid-1970, NASA initiated an Advanced Transport Technology (ATT) Program directed toward defining and developing advances in technology which would contribute to a superior subsonic long-haul transport aircraft. The Langley Research Center played a lead role in carrying out the airframe technology portion of this program. Systems studies were initiated with three airframe contractors early in the program. These were Boeing, General Dynamics-Convair, and Lockheed-Georgia. Subsequently, assessments from the airline viewpoint were made by United and American Airlines.

The major objectives of the systems studies were to

- Incorporate projected advances in aerodynamics, structures and materials, flight controls (including active control concepts), avionics, propulsion, and auxiliary systems into conceptual configurations

- Identify and quantify the potential benefits and costs of the technology advances

- Define and recommend research activities required to bring the advanced technologies to a state of readiness for commercial application by the end of this decade

The purpose of this paper is to broadly summarize the results and recommendations of the system studies which are pertinent to the application of active controls technology. A brief synopsis of the various approaches and the constraints encountered during the course of the studies is included in order that the benefits might be better understood. The reader is encouraged to obtain the listed references if interested in more details. The August 1972 issue of the Astronautics and Aeronautics (ref. 1) provides an overview of the Advanced Transport Technology Program and the airframe manufacturers' final reports are listed as references 2 through 7 of this paper.

CONCEPTUAL CONFIGURATION STUDIES

Each of the airframe companies studied several configurations having varying cruise Mach numbers, ranges, and payloads. Figures 1, 2, and 3 show a representative high-speed configuration from each contractor. Other configurations having design cruise speeds as low as $M = 0.90$ were studied. The Boeing configuration and the General Dynamics configuration are similar in concept, but differ considerably in a number of details. Both are $M = 0.98$, 196-passenger, 3000-nautical-mile design range, three-engine configurations. The primary differences are engine and horizontal tail locations. Lockheed concentrated on a $M = 0.95$, 400-passenger, 5500-nautical-mile design range, four-engine configuration. These are the configurations which will be discussed for the remainder of the paper.

In arriving at the above configurations, a "baseline" aircraft was defined which incorporated relaxed stability requirements in order that the best cruise performance (lowest trim drag) might be obtained without regard to maintaining inherent stability requirements. These baseline configurations had airframes designed for 100-percent strength and stiffness. The configurations were then examined to determine the applicabiltiy of gust and maneuver load control, ride quality control, and active flutter suppression.

Each of these functions were examined to identify potential benefits, system functional design, cost, and weight. Benefits associated with relaxed stability requirements were identified by "backing-off" to a configuration having conventional stability characteristics.

Relaxed Stability

Boeing's initial longitudinal design philosophy was to select the minimum horizontal stabilizer volume coefficient, V_H, which would provide the required center-of-gravity range as illustrated in figure 4. The balance limits selected in this phase provided that the aft-most center-of-gravity location would be limited to the most-forward maneuver point location encountered in the flight envelope. (The maneuver point is defined as that center-of-gravity location at which the stabilizer deflection required for a constant load factor increment becomes zero during a constant speed pull-up.) Ability to trim the aircraft at the landing approach condition with a reasonable tail lift coefficient (C_{L_t} = -0.80) determined the forward center-of-gravity portion.

The early design philosophy resulted in configurations which were unstable in large portions of the flight envelope but stable during cruise, as shown in figure 5. In later phases of the study, it was found that this balance philosophy did not result in the best cruise performance, particularly for a M = 0.98 configuration with two wing-mounted engines. The wing was positioned further forward resulting in a more aft loading envelope which in turn allowed a more aft cruise center-of-gravity position to be maintained. The horizontal stabilizer volume coefficient which provided a compatible aft center-of-gravity limit was found to be larger than the minimum volume coefficient selected earlier, as shown in figure 4.

In sizing the vertical tail, two criteria were considered: a minimum directional stability level (C_{n_β} = 0.002 deg^{-1}) and engine-out control. For the configuration shown in figure 1, the minimum directional stability level was found to be the limiting criterion, based on a two-segment full-span rudder. With the vertical tail sized in this manner, lateral-directional dynamic instability exists over a large portion of the flight envelope, as shown in figure 6. This instability would require a flight-critical augmentation system.

General Dynamics, in investigating relaxed stability requirements, followed a similar, but somewhat different, design philosophy. The configurations investigated were similar in size to Boeing's, with the horizontal tail being a low rather than a high T-tail arrangement and two wing-mounted engines rather than all three aft. Figure 7 illustrates the horizontal tail volume selection for both conventional and relaxed longitudinal stability requirements. In both cases, nose gear unstick and ability to trim in the high lift configuration are considered in establishing the forward center-of-gravity location. For the conventional case, the requirement that the static margin be greater than or equal to zero sets the aft center-of-gravity limit. The criterion selected for the aft center-of-gravity limit in the case of relaxed static stability is the ability to trim the high-speed configuration to a wing-body lift coefficient of 1.0 with a maximum horizontal tail deflection of 15°. This will leave about a 40-percent control power reserve to handle the dynamic aspects of upset disturbances. An operational forward-to-aft center-of-gravity range of 10-percent M.A.C. was maintained. Figure 7 implies that a 25-percent reduction in horizontal tail area may be obtained by employing relaxed longitudinal stability concepts.

Preliminary studies conducted by Genral Dynamics indicate that a further reduction in horizontal tail area (about 20 percent) may be obtained by incorporating a geared trailing-edge control on the all-movable horizontal tail. Balance characteristics of such a configuration are shown in figure 8.

The major impact of this balance concept identified by General Dynamics may be summarized in terms of the changes in structural weight and drag at the trimmed cruise condition. For the Mach 0.98, two-wing and one aft-mounted engine configuration shown in figure 2, the savings are

1. Decreased drag at cruise = 7 counts (0.0007)

2. Structural weight savings <u>due to decreased drag</u> = 690 lb (313 kg)

In backing off to a configuration with conventional inherent stability, General Dynamics determiend only the penalty due to the trim drag increment and did not determine the weight penalty associated with changing the size of the horizontal tail. Thus, the structural weight savings shown are due only to the decreased trim drag and resulting fuel savings.

Implementation of this relaxed stability concept resulted in a configuration which is stable in cruise, but unstable in other portions of the flight profile, requiring an artificial stability system. Figure 9 illustrates a typical flight profile with corresponding values of Mach number and static margin.

Lockheed's ground rules were that their configuration would have a 20-percent M.A.C. center-of-gravity range and a positive static margin of 3-percent M.A.C. Thus, for the configuration shown in figure 3, the forward c.g. limit is constrained by nose wheel lift off, and the aft c.g. limit by the ability of the augmentation system to provide a minimum of 3-percent static stability.

Figure 10 illustrates Lockheed's balance philosophy, assuming an augmentation system with angle-of-attack (α) feedback. Note that as the α gain (K) is increased, the stability line rotates downward. The horizontal tail volume is established by the value of K for which the control system experiences rate or displacement saturation. Using this approach, a reduction in horizontal tail volume of 0.54 was obtained which resulted in a 4.64-percent decrease in ramp weight and a 6.11-percent decrease in required thrust.

The vertical tail sizing philosophy was essentially the same as those of Boeing and General Dynamics.

Load Alleviation and Flutter Suppression

In the application of maneuver load alleviation (MLA), gust load alleviation (GLA), and active flutter suppression (FS), it was found that these functions were not independent and had to be considered at the same time. Each of the contractors included effects of aeroelasticity, multiple load sources, and a number of different flight conditions. Implications of fatigue and ride qualities were also considered in the application of MLA, GLA, and FS.

For MLA, Boeing considered using both inboard and outboard control surfaces to shift the maneuver induced load inboard. Figure 11 shows the potential wing box weight savings, considering only strength requirements, in terms of control surface lift and moment capabilities. The wing of the baseline aircraft was shown by analysis to be flutter free up to the required 1.2 V_D. Figure 12 illustrates the impact of removing material by an MLA system on the flutter (stiffness) requirements. The additional material required to prevent flutter is shown as a function of the material removed by the use of MLA. It should be noted that this analysis was based on a configuration with no wing-mounted engines. Configurations with wing-mounted engines would possibly have greater flutter requirements.

A fatigue analysis was then conducted based on the number of ground-air-ground cycles and the percent damage due to gusts. Figure 13 illustrates the additional material required to achieve acceptable (gust-induced) fatigue damage rates as a function of the amount of material removed through the application of MLA. Since the fatigue increment is large relative to the MLA weight reduction, the need for a gust alleviation system to reduce the gust-induced fatigue damage is indicated.

GLA was considered in order to reduce material requirements for fatigue and to improve ride qualities. A center-of-gravity accelerometer feedback driving a wing trailing-edge surface to reduce gust-induced vertical accelerations which operated in conjunction with the pitch control surface to maintain attitude was the control system concept considered. Figure 14 illustrates the results of a two-degree-of-freedom power spectral density gust analysis. Airplane response in terms of root-mean-square center-of-gravity accelerations and the associated flap angles are shown as a function of acceleration feedback gain. A gain of 150 deg/g was selected. Figure 13 shows the amount of material required for fatigue as a function of the material removed when both MLA and GLA are employed.

The application of an active flutter suppression system in conjunction with the MLA and GLA system was also investigated. The control system concept arrived at was an outboard trailing-edge surface responding to a wing-mounted accelerometer signal fed back through a compensation filter. Difficulty was encountered in maintaining stability of both higher and lower frequency airplane modes while controlling the somewhat violent flutter mode at 3.8 Hz. A root locus plot for one of the more promising filter designs is shown in figure 15. Although successful stabilization of the flutter mode was indicated, active flutter control was not included in the final configuration because the added weight due to the control system was approximately equal to the structural weight savings.

General Dynamics considered application of a "wing design load control" to their configuration. This concept was used to reduce wing maneuver loads, as well as gust-induced loads. Implementation concepts which were considered include:

1. Inboard flaperon
2. Outboard spoiler
3. A combination of inboard flaperon and outboard spoiler

Figure 16 illustrates the weight savings obtained through the use of each of the above concepts. Note that the net savings shown are the differences between structural weight reductions and control system weight additions.

Since gust-induced loads were found to be critical on the forward fuselage, further structural weight savings were possible using the inboard flaperon. Reductions in rms gust response all along the fuselage were also found using this concept. Figure 17 illustrates the gust responses at different fuselage locations with and without the active control system. However, since the structural weight savings would not offset the weight associated with the inboard flaperon system and since the unaugmented ride qualities were considered satisfactory, the inboard flaperon was not included in the final results.

General Dynamics also considered the application of active flutter suppression to the configuration incorporating the wing design load control system. Various sensor and control surfaces were considered, in several combinations. Figure 18 shows the degree of damping obtained with several of these control system concepts, as well as the damping for the unaugmented airplane. Two fuel conditions are shown.

Difficulties were encountered in maintaining stability of a higher frequency mode while stabilizing the critical flutter mode. Also, the results shown in figure 18 were based upon feeding back idealized response signals. Figure 19 shows the results of a study on approximating such signals with accelerometers and compensation networks. This work, which was not done on exactly the same configuration as that of figure 18, indicates that when sensors and compensation networks were included, successful stabilization of the flutter mode is not achieved. However, due to a lack of detailed aerodynamic data on supercritical wings with leading-edge (tip) controls, no attempt was made to optimize the proposed flutter suppression system. It was anticipated that successful stabilization could be achieved, but the benefits would be smaller than those predicted assuming ideal feedback signals. The most promising concept appears to be the combination leading- (tip) trailing-edge control system investigated by Nissim (ref. 8).

Fatigue damage calculations were performed to determine the effects of MLA and GLA on the aircraft service life. Three configurations were investigated

1. 100-percent strength without active control system (ACS)
2. 100-percent strength with ACS
3. Reduced strength with ACS

Fatigue damage rates were calculated for two wing stations and two fuselage stations. Figure 20 summarizes the results for the three configurations. Damage rates which caused gust, maneuver, and ground-air-ground cycle are presented and all values are normalized to the 100-percent strength without ACS configuration.

Lockheed investigated the application of MLA, GLA, and active FS to the configuration shown in figure 3. They found the use of MLA and GLA for reducing peak loads to be inappropriate for their configuration. The maximum allowable wing-bending deflections were limited by ground clearance during rough surface taxi and the maximum dihedral for acceptable stability and control during cruise. Thus, the wing of the large, four-wing-mounted engine configuration was bending-stiffness critical and no benefits were obtained from the application of MLA and GLA.

In investigating possible application of an active fatigue load alleviation system, it was found that for this configuration, the ground-air-ground cycle was the major source of wing fatigue damage. Thus, it was concluded that the benefits of a fatigue load alleviation system in reducing the fatigue damage on their recommended configuration was negligible.

An active flutter suppression system which would be used only for that portion of the flight envelope between V_D and $1.2\ V_D$ was considered. This was done in view of the catastrophic nature of most main-surface flutter instabilities and the low probability of making a first-generation flutter-suppression system absolutely reliable. A flutter analysis was conducted and it was found that approximately 575 lb (260 kg) of stiffness material could be removed in lowering the flutter speed from $1.2\ V_D$ to V_D. An active flutter suppression system was not synthesized; however, the weight of such a system was estimated and found to be about 320 lb (145 kg). Thus, a maximum net structural weight saving of about 255 lb (115 kg) per aircraft was indicated. In resizing the aircraft, this becomes a 500-lb (227-kg) or a 0.17-percent reduction in operating weight. Lockheed concluded that these benefits would not justify the added cost, complexity, and risk of an active flutter suppression system for their recommended design.

SUMMARY OF RESULTS

The benefits of interest are weight savings and economics for the selected configurations. In some cases, there is a fairly wide spread in the benfits indicated by the various contractors since they investigated different configurations and had different basic ground rules. The high-speed configurations discussed in this paper were found to benefit more from ACT than did the lower speed configurations investigated in the system studies. The fact that the benefits of active controls are dependent on the configurations being studied is well recognized. Research and development recommendations of the contractors do agree quite closely. The recommendations presented herein are general and somewhat broad in scope. For the more detailed, task-level recommendations, the reader is referred to references 3, 5, and 7.

Benefits

Figure 21, from the Boeing study, shows the changes in configuration resulting from the application of active controls. Comparing the conventional technology airplane to the advanced technology airplane with active controls, one can see the differences in horizontal and vertical tail areas. Figure 22 summarizes the weight benefits attributable to the application of active controls as predicted by the contractors. Some caution should be used in examining this figure. Note:

1. Boeing indicates benefits attributable to MLA and GLA and FS in terms of structural weight, not resized aircraft TOGW or OWE.

2. The weight savings shown for RSS by General Dynamics includes no weight savings based on resizing the vertical tail, but is based only on the reduced trim drag.

In addition to weight savings, each of the contractors was able to minimize the trim drag through relaxing stability requirements. This resulted in operational benefits, such as reduced fuel requirements, which will be reflected in Direct Operating Cost (DOC) improvements to be discussed below. None of the contractors included systems specifically for improving the ride qualities, as these were predicted to be adequate. However, reductions in fuselage accelerations of 20 to 40 percent were considered feasible. Fatigue damage rates due to gust and maneuver loads were either improved or at least not increased due to the application of MLA and GLA, as shown in figures 14 and 20. The impact on the ground-air-ground cycle fatigue damage, however, does appear to be detrimental.

Two economic measures were utilized: Return on Investment (ROI) and Direct Operating Costs (DOC). Figure 23 summarizes the percent increase in ROI resulting from the application of active controls. Again, note that the General Dynamics results for relaxed stability include only the effect of reduce trim drag. Boeing used a somewhat different approach in their economics study and did not show the effects of only active controls on ROI or on DOC. Airplane price, which was an input to the ROI calculations, was estimated to be 4.0 to 6.0 percent lower when active controls were used (refs. 4 and 6).

Figure 24 summarizes the findings with respect to DOC, which includes such factors as: maintenance (airframe, engines, avionics, etc.), fuel usage, insurance, and other operating expenses. In general, application of active controls would reduce structural weight which would result in lower maintenance costs for the airframe and engine. However, avionics maintenance costs would increase. Reduced trim drag would result in lower fuel costs. As can be seen, the overall effect of applying active controls was seen to be beneficial in terms of DOC. More comprehensive economic studies have since been completed and are contained in reference 9.

Recommended Research and Development

The recommendations of interest will be summarized under three broad headings:

A. Research and Technology (R&T) Base
B. Integrated Design Concepts
C. Technology Demonstration

A. Research and Technology Base

1. Conduct analytical and experimental (wind-tunnel) evaluation of characteristics of leading-edge and trailing-edge devices designed for operation on supercritical wings. Both static and dynamic data are required for speeds through the transonic flow regime.

2. Develop improved aeroelastic methods for flight controls analysis. The accuracy of this method should be established by comparisons with wind-tunnel and flight test data and the sensitivity of airplane balance and flight control design to the accuracy of the method should be established.

3. Develop control laws which are compatible with advanced onboard computing systems and which maintain effectiveness of the system over the entire operating flight envelope.

B. Integrated Design Concepts

1. Conduct a detailed study of structural design criteria and handling qualities requirements for vehicles designed with active control concepts included.

2. Carry out a survey of operational flight conditions to point out the critical load cases. This survey should cover the effects of angle-of-attack and Mach number variations, aeroelasticity, control surface deflection and rate limits, and both clean and high lift configurations.

3. Develop design methods which are more suitable for use in preliminary design allowing rapid trade studies between active and passive techniques.

4. A detailed design study should be conducted, integrating the active controls early in the design process (control configured vehicle concept), optimizing the control systems, and establishing the resulting benefits.

C. Technology Demonstration

1. Design validation under actual flight conditions will provide the degree of confidence required prior to incorporation of active control concepts into commercially certifiable transport airplanes. This flight test program could be accomplished using existing airplanes.

Airline Assessment

Under contract to NASA, United Air Lines, Inc., conducted an assessment of the system studies (ref. 10). American Airlines was awarded a similar contract and, although their results are not published as yet, they appear to be reaching conclusions quite like those of United.

The primary area of concern to an aircraft operator, is that of systems reliability and maintainability. They recommended that a great deal of effort be put into systems which would allow the operators to detect system degradation and apply preventive or progressive corrective actions prior to complete system failure. The maintenance procedures should be given a great deal of thought by both the manufacturers and the airlines to insure that the maintenance program which evolves will be simple, timely, and responsive to the airline desires. It was felt that the benefits offered by active control concepts would be seriously degraded if necessary to include mechanical backup systems in the aircraft. All, or major portions, of an active control system will be required to be operative prior to flight. Consequently, the level of redundancy must be such that dispatch will be possible with one system inoperative and must sustain a second failure in flight.

Demonstration and service life evaluation in flight of realistic active control systems was considered to be almost essential. Several on-going and complete active control demonstration programs, such as the Air Force CCV program with the B-52, were noted. However, the airlines would like to have years of operational experience rather than hours. It was recommended that gust/maneuver load control and ride quality control systems be retrofitted into several contemporary aircraft in such a manner that current operations are not disrupted. This would allow protracted service life evaluation. It was felt that this approach would not only benefit future aircraft, but could prolong existing aircraft life. Such retrofit systems would be designed such that the aircraft would be able to dispatch with the system failed. Thus, redundancy requirements would be much less critical for these installations.

There was more concern expressed by the airlines about the technology readiness of relaxed stability and flutter suppression systems, primarily because of the flight-critical nature of these functions and apparent remoteness of the solution to the system's reliability problem. They felt the basic study programs should be accelerated utilizing both ground-based and research flight experiments. Contemplated hardware for relaxed stability could be installed in current aircraft, performing other functions, to gain in-service life data. United stated that, from their experience, there is no substitute for the aircraft as a test bed and no laboratory or test cell yet has adequately simulated the aircraft environment.

CONCLUSIONS

Although somewhat different approaches were taken in these system studies, a number of interesting possibilities for applying active controls technology were indicated. However, there is a need for further in-depth studies which would introduce the active control concepts earlier in the design process and in a more integrated manner.

Relaxing the stability requirements offered the greatest benefit and was the only concept included in the initial design process. Flutter suppression offered the smallest benefit according to the results of two of the contractors and was identified as being the concept most removed from the current state of the art by all of the contractors. Maneuver load alleviation and gust load alleviation were found to yield significantly smaller benefits than relaxed stability requirements; however, the contractors pointed out that these concepts should be introduced at the initiation of the design process in order to maximize the benefits.

Each of the contractors pointed out areas where the benefits could have been greater if more data and/or more time were available for design refinements and system optimization. Problem areas or areas of concern encountered by the contractors in the course of the system studies were reflected in the recommended research and development tasks. Based on the results of these studies, it appears as though active controls technology can provide significant benefits when applied to subsonic, long-range transport aircraft. However, application will require completing a research and development program directed toward fulfilling data base requirements, establishing effective design techniques and criteria, improving systems maintainability and reliability, and demonstrating technology readiness.

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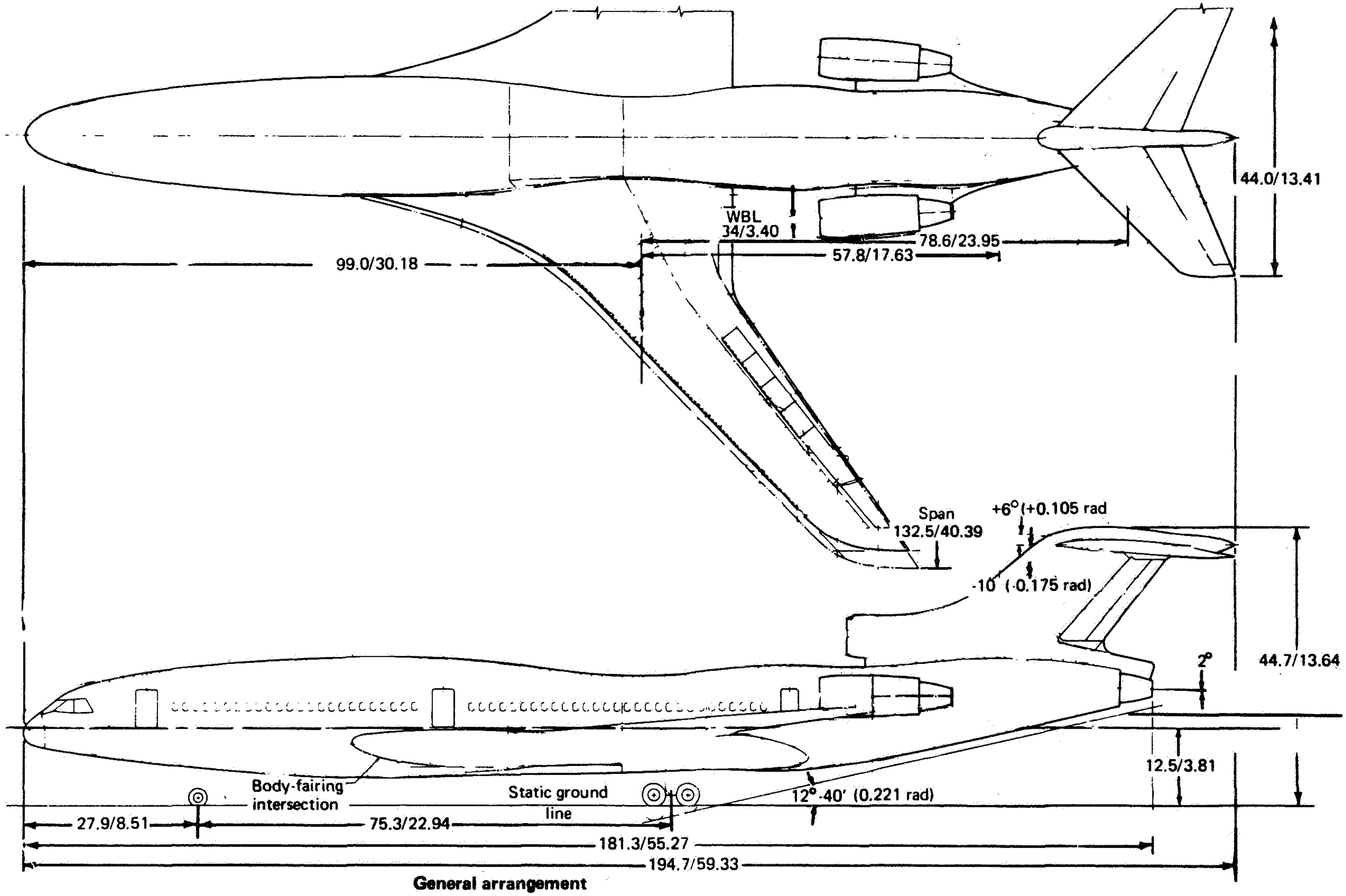


FIGURE 1. BOEING M=0.98, 195 PASSENGER CONFIGURATION
(From ref. 2)

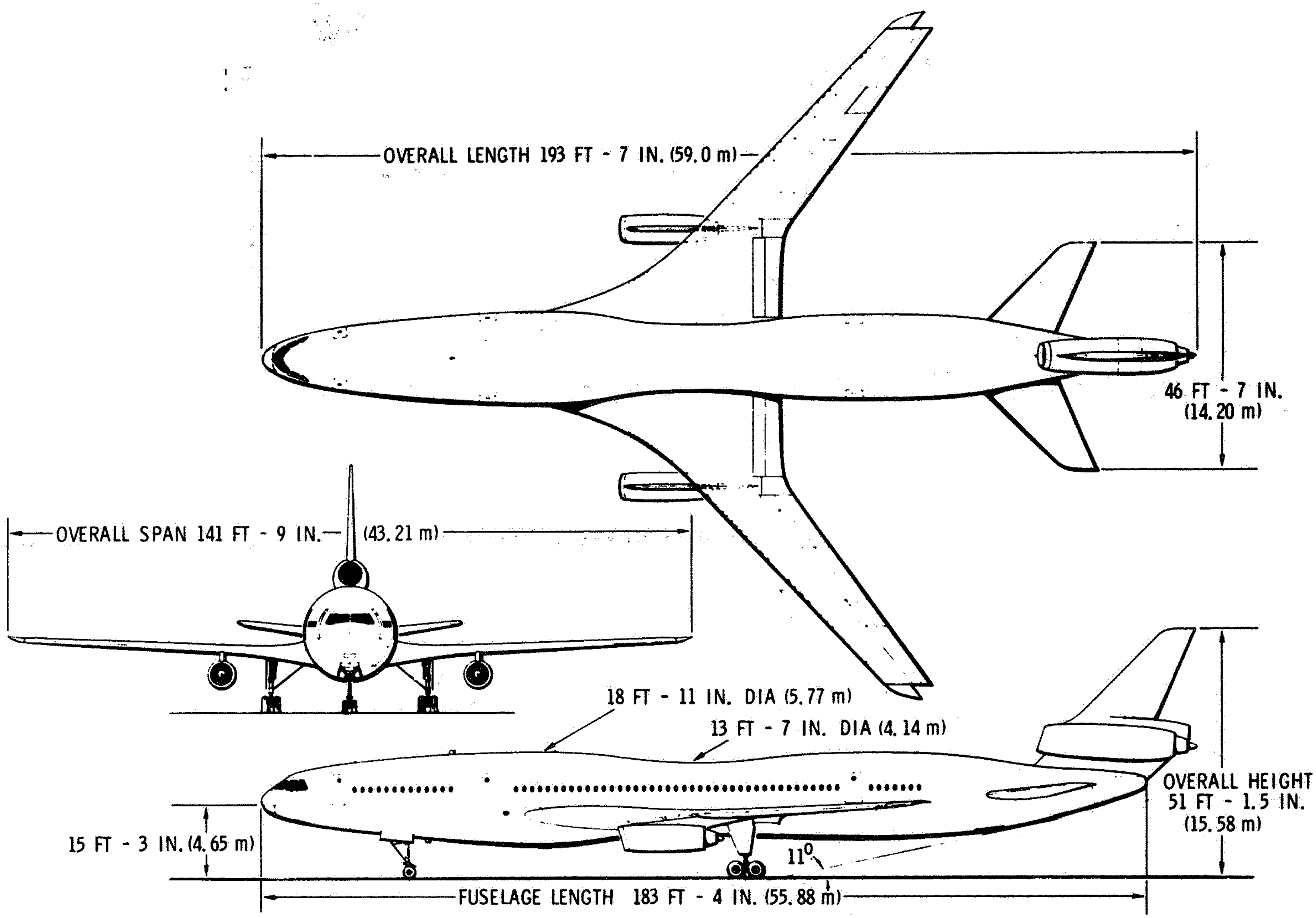


FIGURE 2. GENERAL DYNAMICS M=0.98, 195 PASSENGER CONFIGURATION
(From ref. 4)

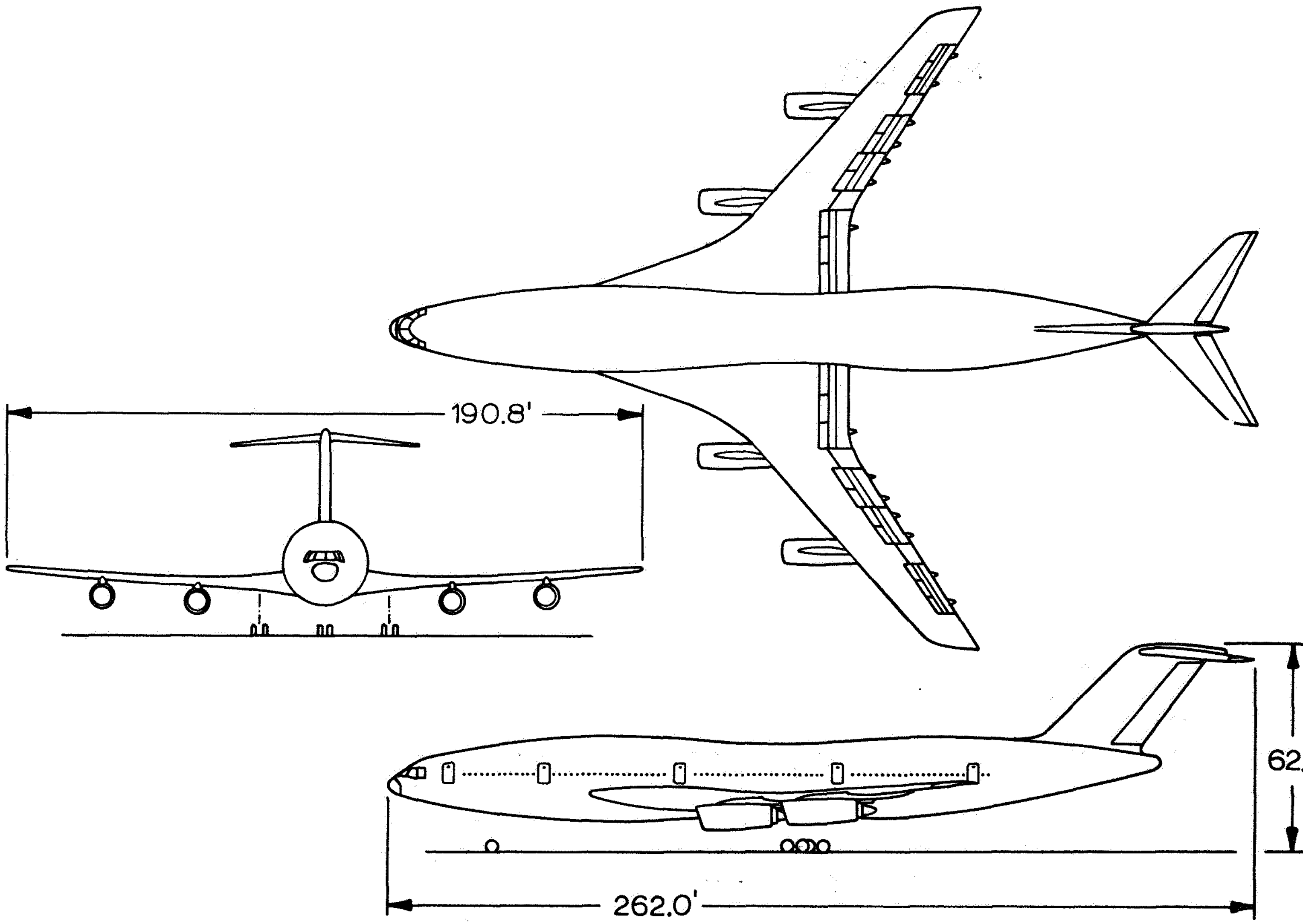


FIGURE 3. LOCKHEED M=0.95, 400 PASSENGER CONFIGURATION
(From ref. 6)

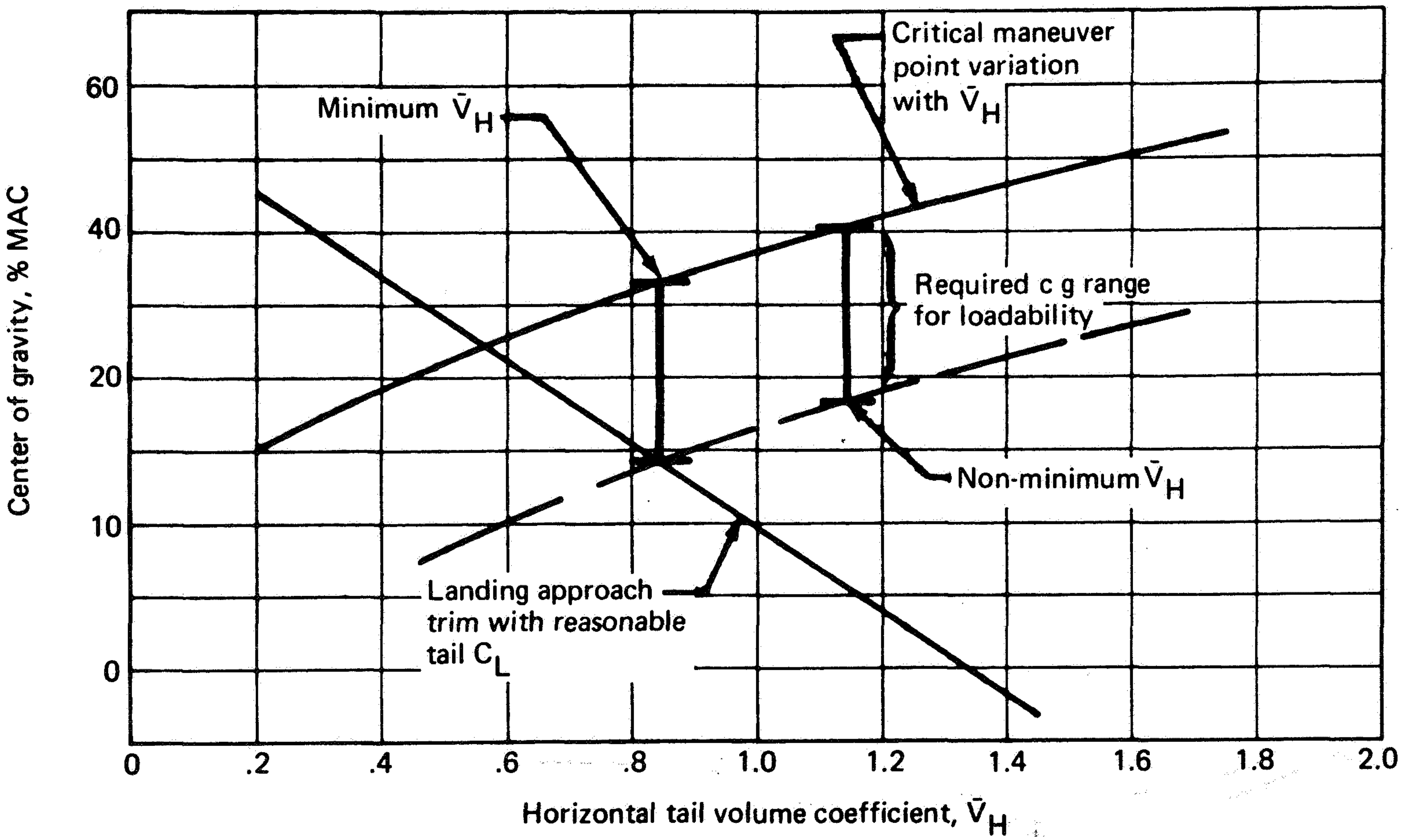


FIGURE 4. BOEING HORIZONTAL TAIL SIZING PHILOSOPHY
(From ref. 2)

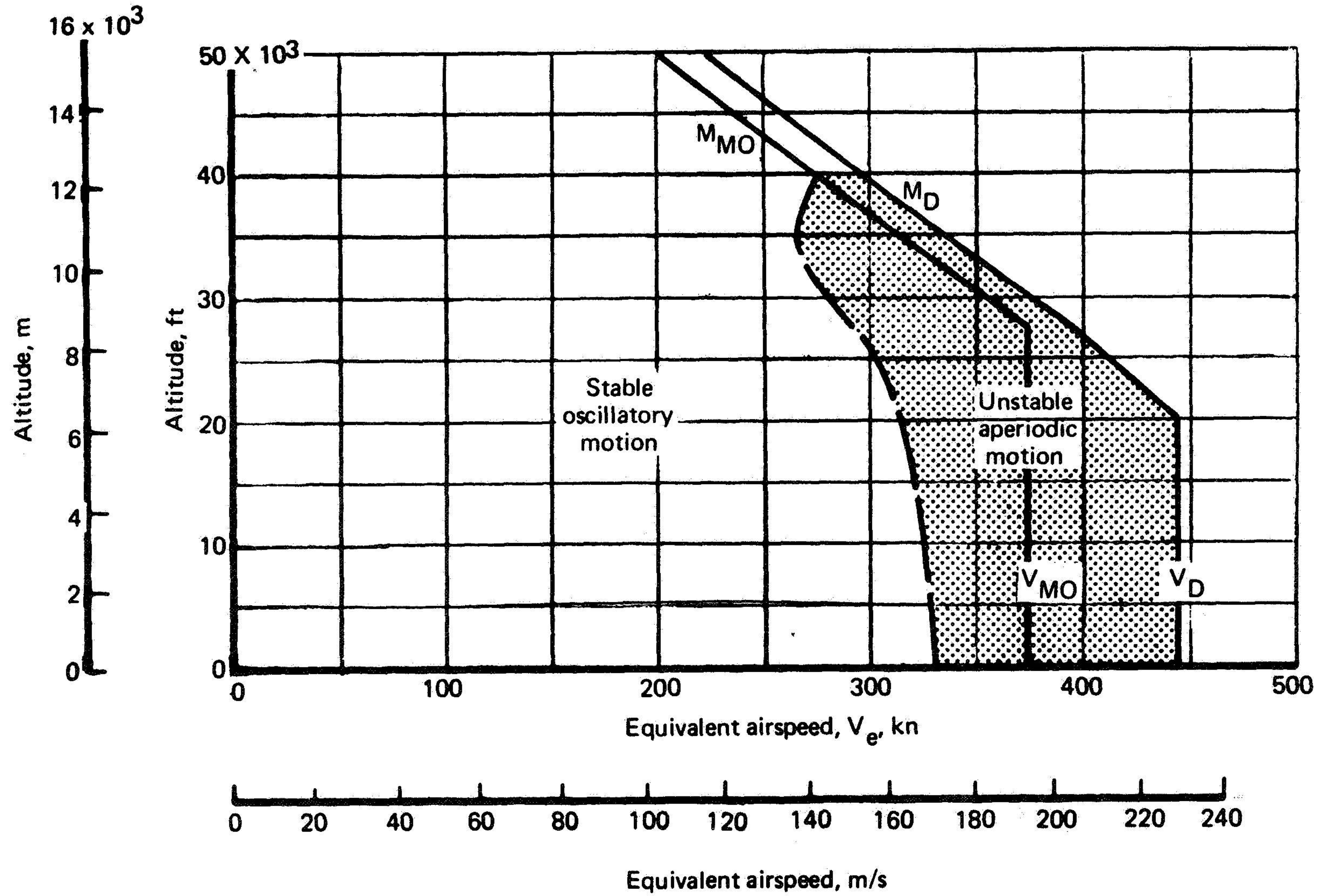


FIGURE 5. UNAUGMENTED LONGITUDINAL DYNAMIC STABILITY
(From ref. 2)

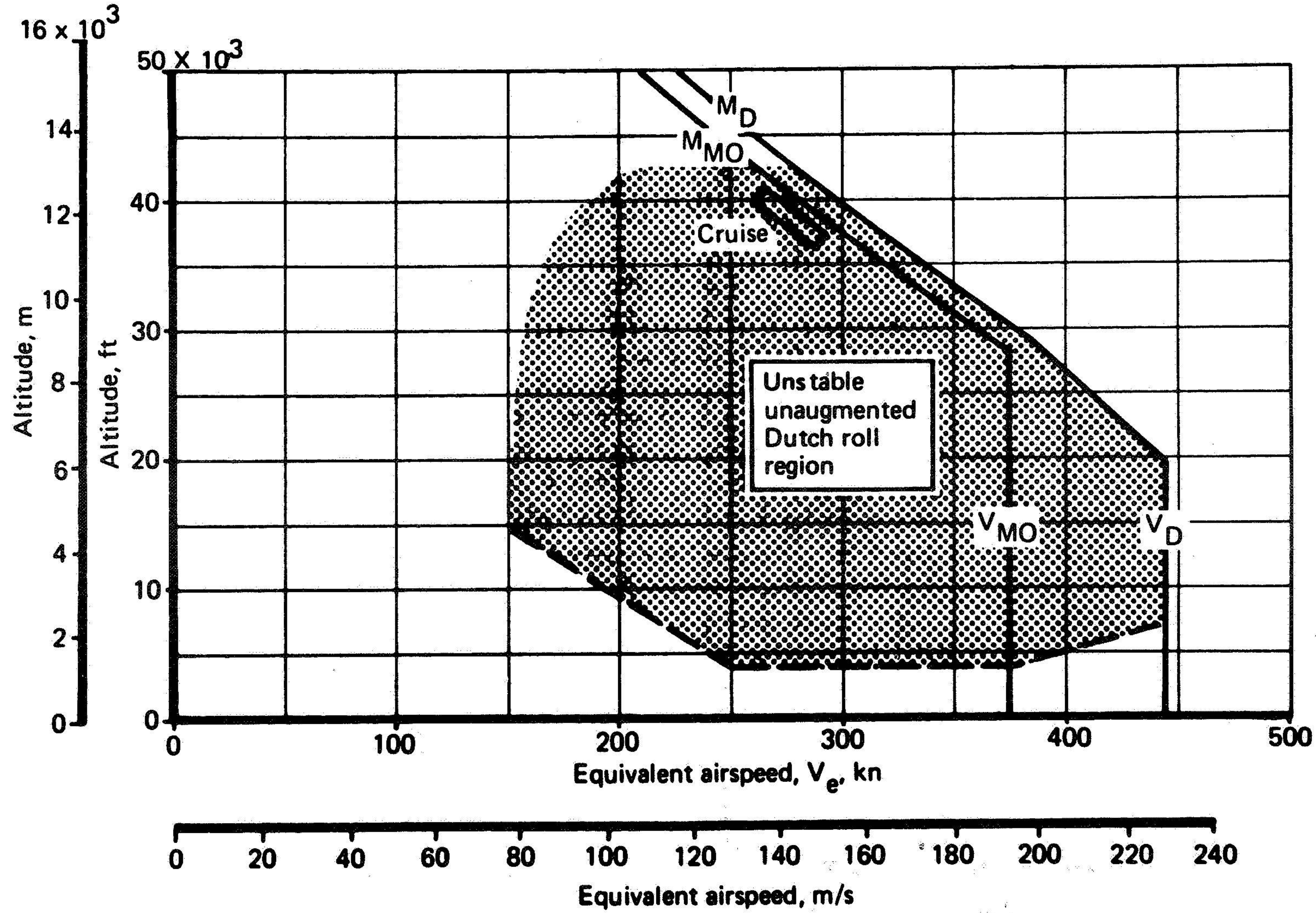


FIGURE 6. LATERAL-DIRECTIONAL DYNAMIC STABILITY, UNAUGMENTED
(From ref. 2)

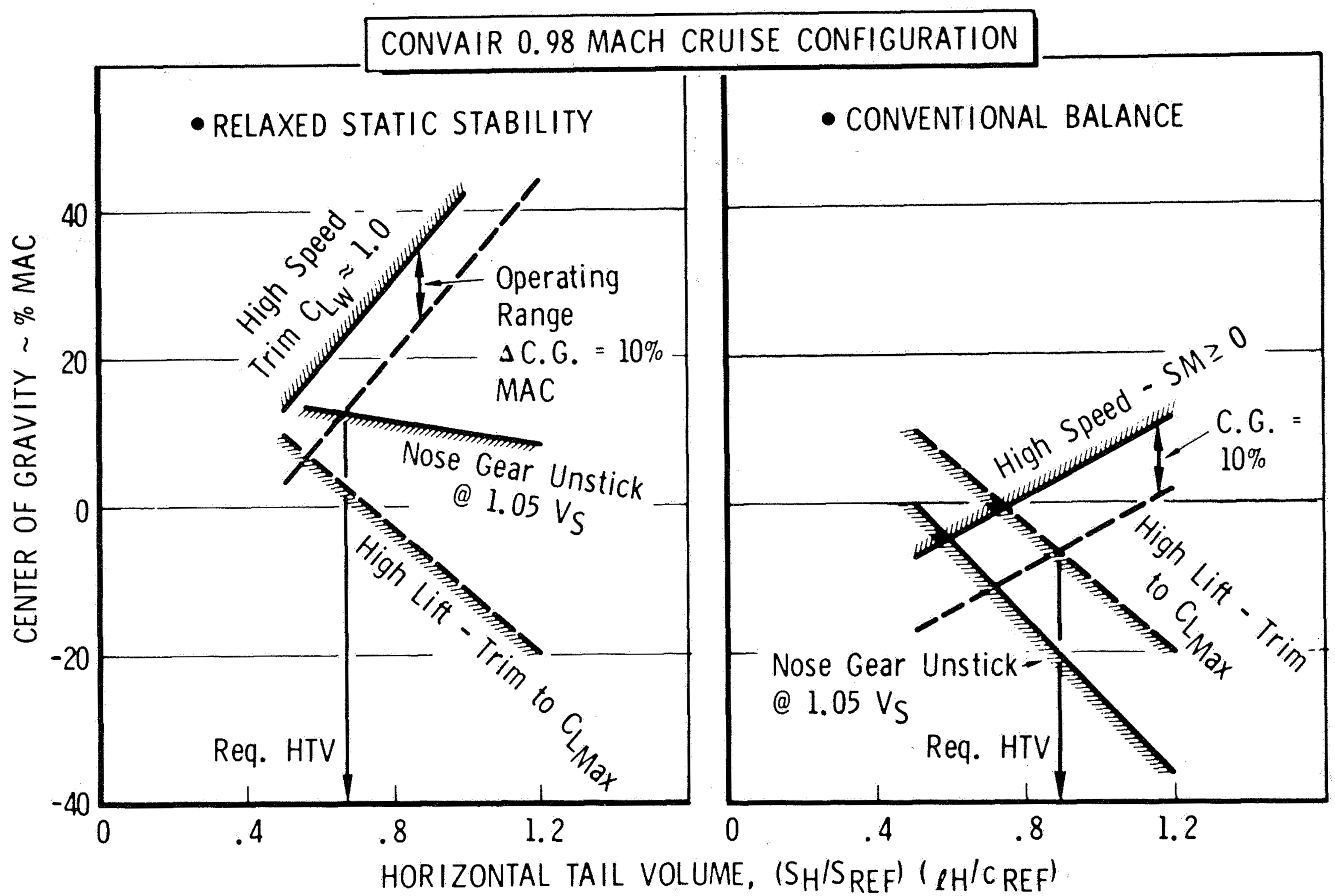


FIGURE 7. GENERAL DYNAMICS HORIZONTAL TAIL SIZING PHILOSOPHY
(From ref. 4)

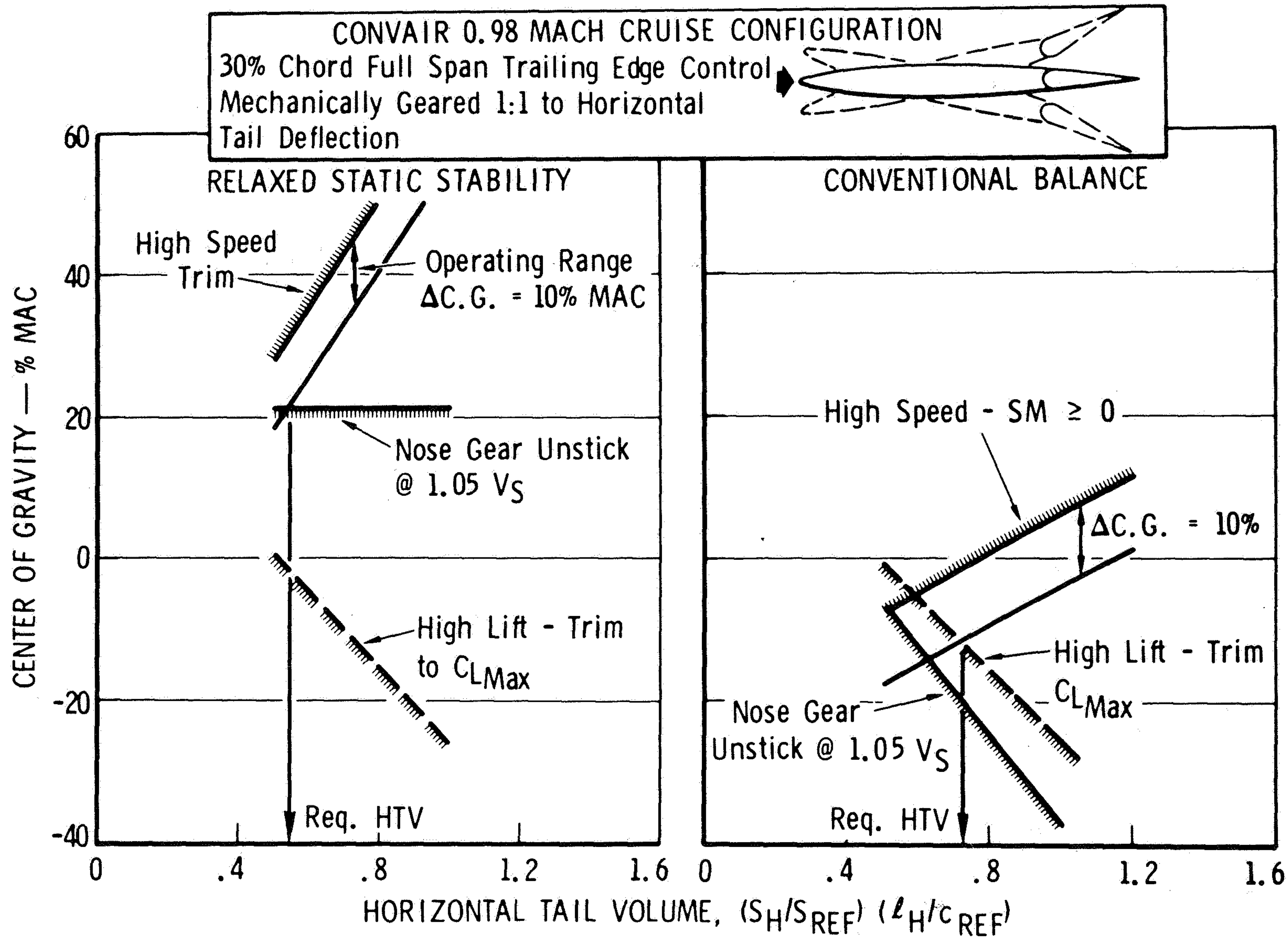


FIGURE 8. BALANCE CHARACTERISTICS - ALL MOVABLE HORIZONTAL TAIL PLUS GEARED TRAILING EDGE
(From ref. 4)

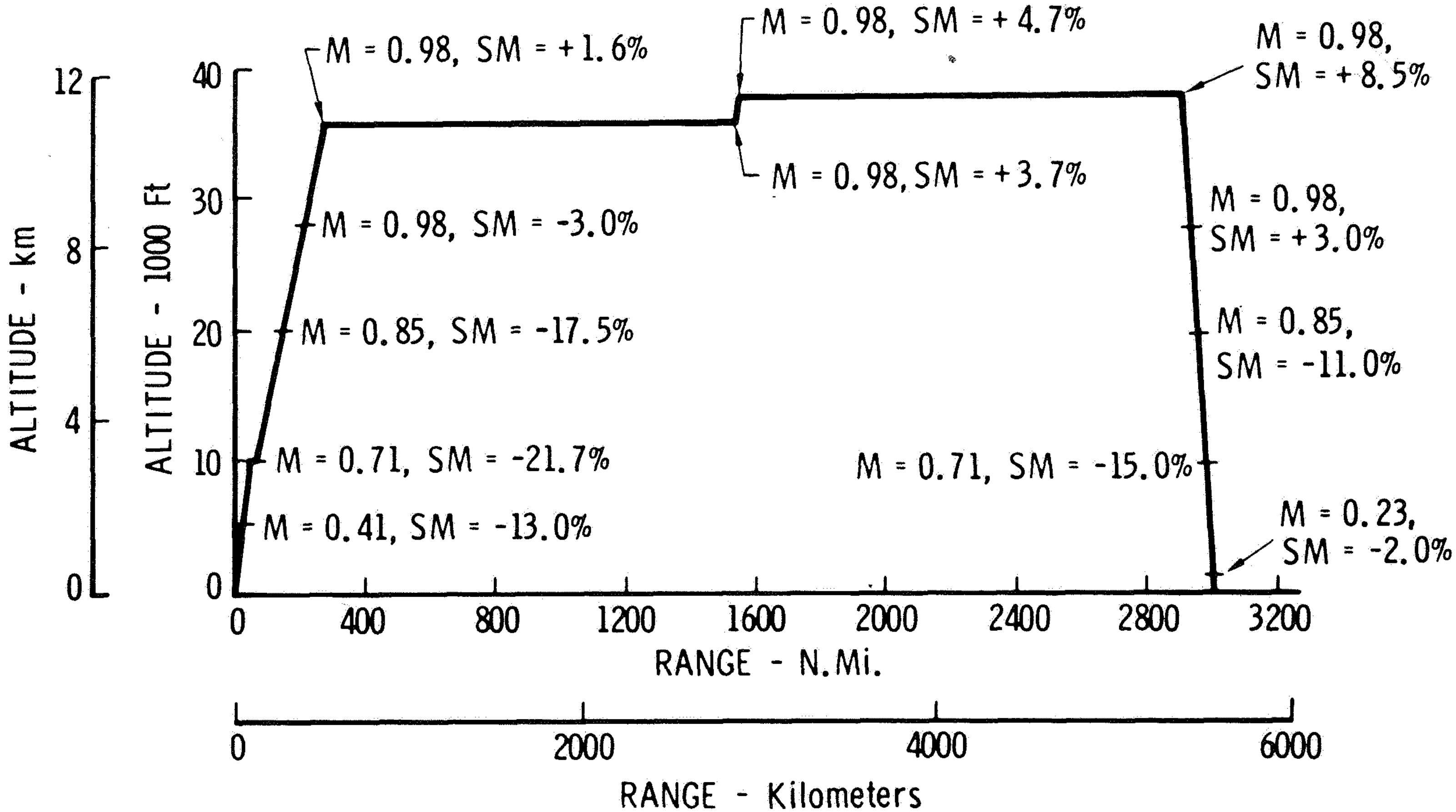
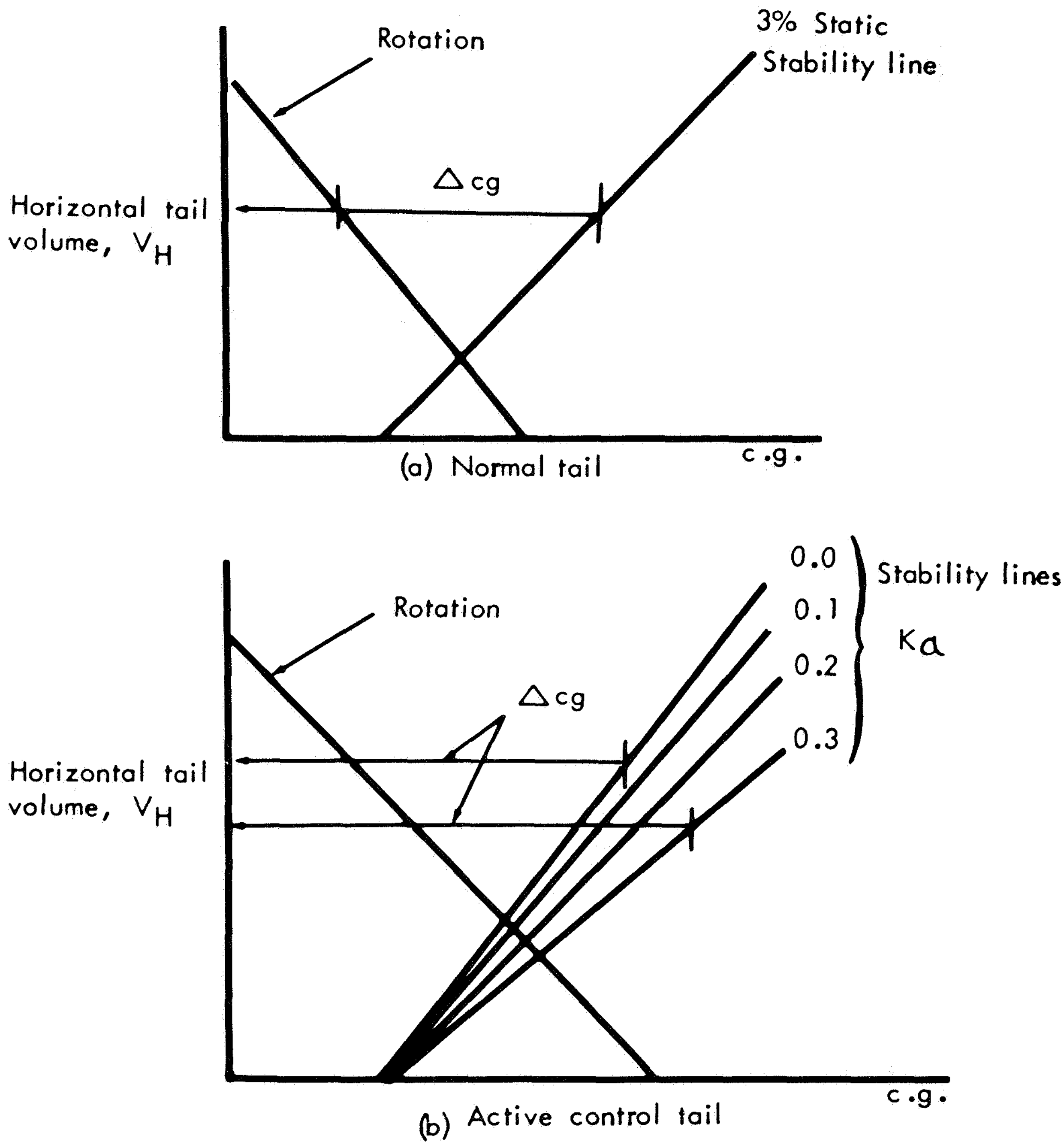


FIGURE 9. VARIATION OF AERODYNAMIC STATIC MARGIN DURING TYPICAL FLIGHT PROFILE
(From ref. 4)



Typical horizontal tail sizing for a given set of flight conditions.

FIGURE 10. LOCKHEED HORIZONTAL TAIL SIZING PHILOSOPHY
(From ref. 6)

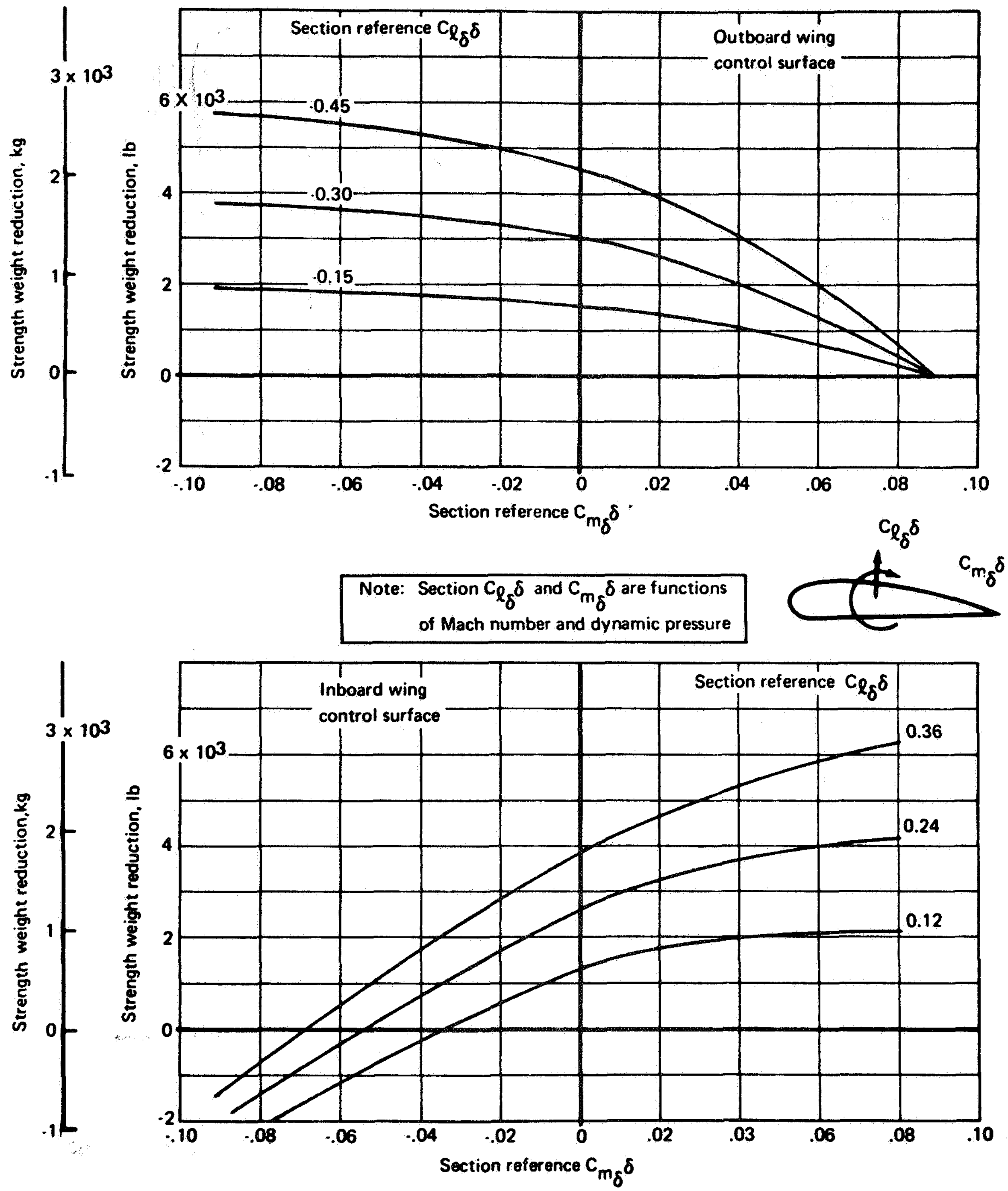


FIGURE 11. POTENTIAL WING BOX MATERIAL SAVINGS BY MLA
(From ref. 2)

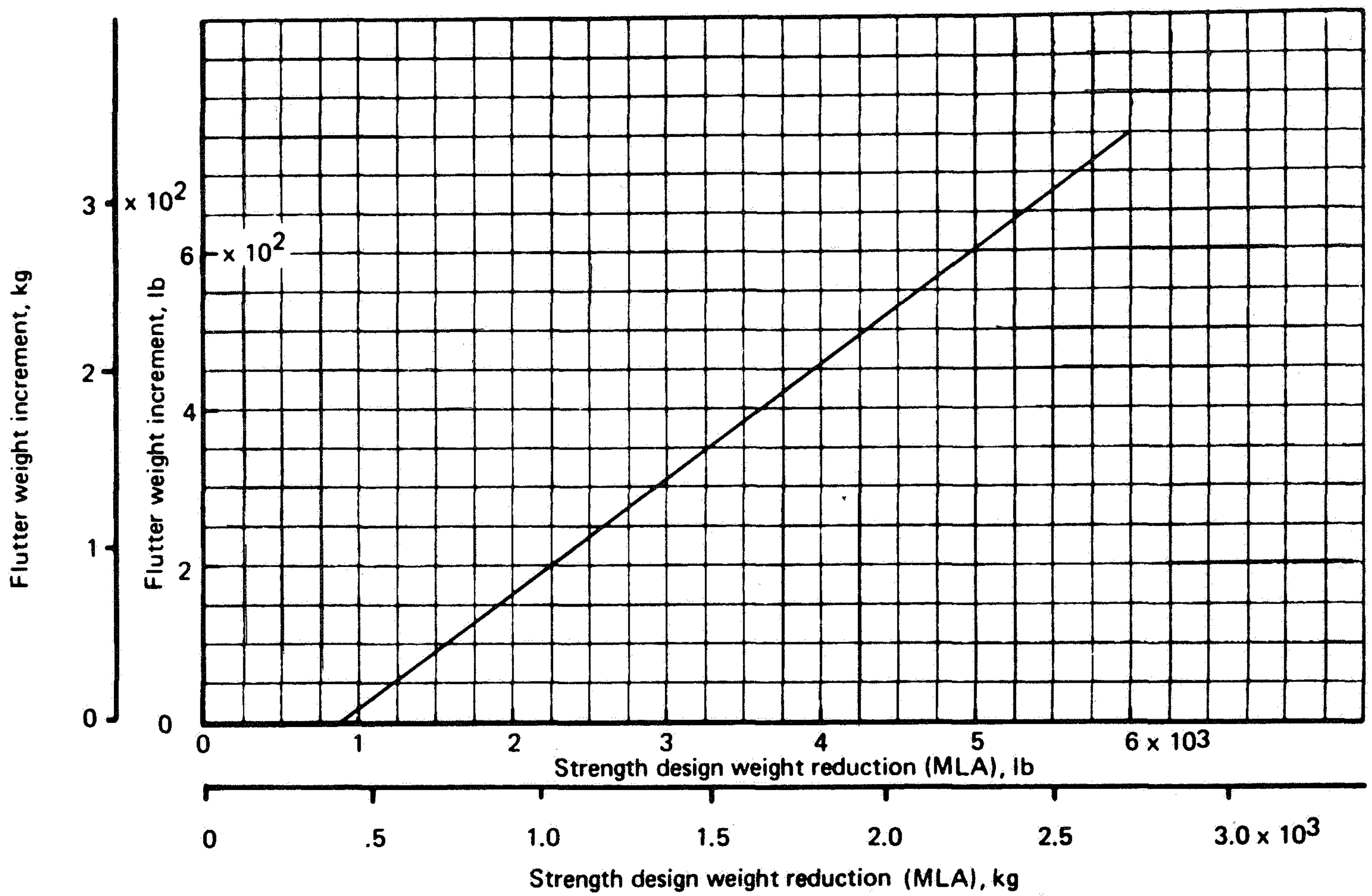


FIGURE 12. FLUTTER REQUIREMENT
(From ref. 2)

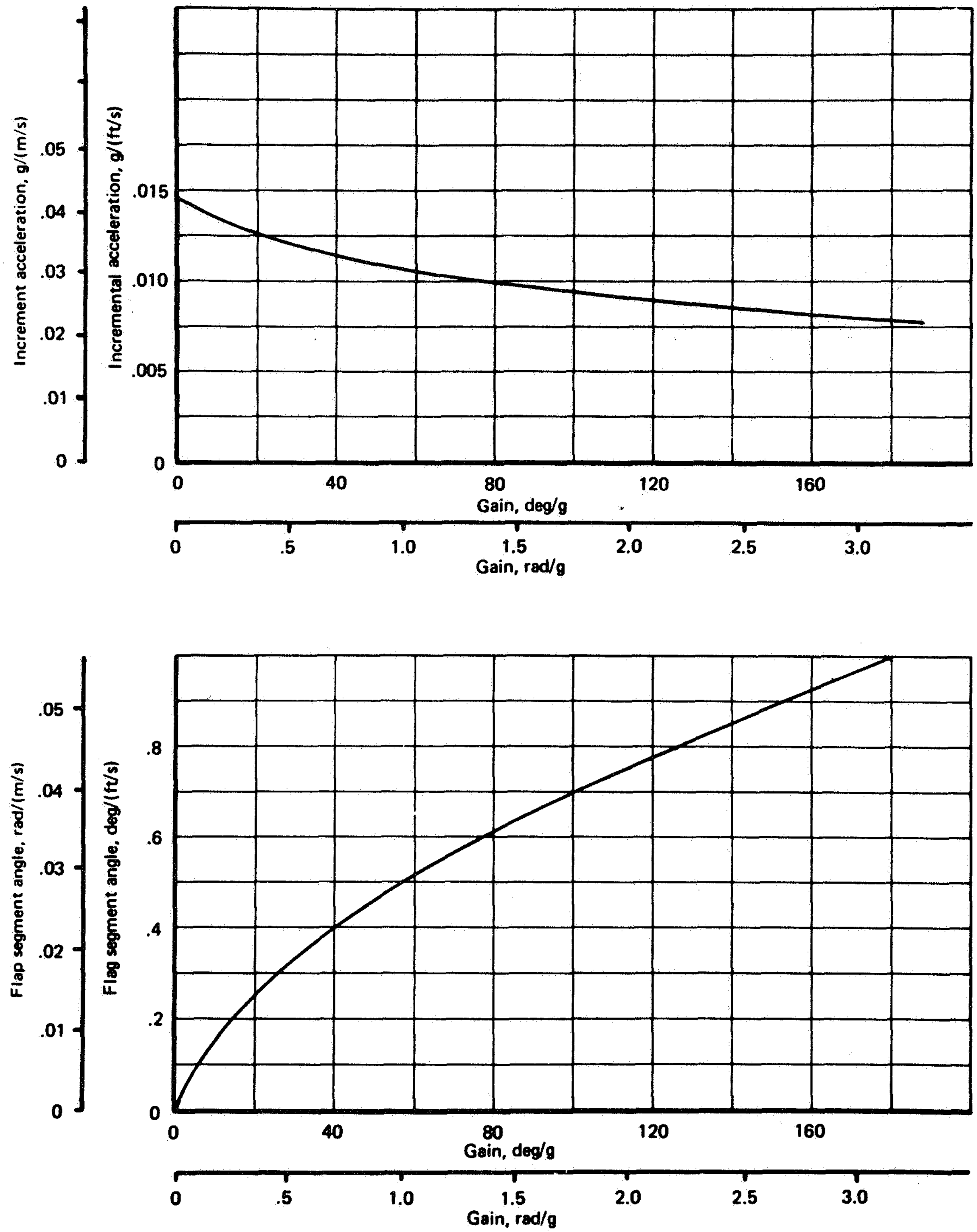


FIGURE 13. AIRPLANE RESPONSE (GLA)
(From ref. 2)

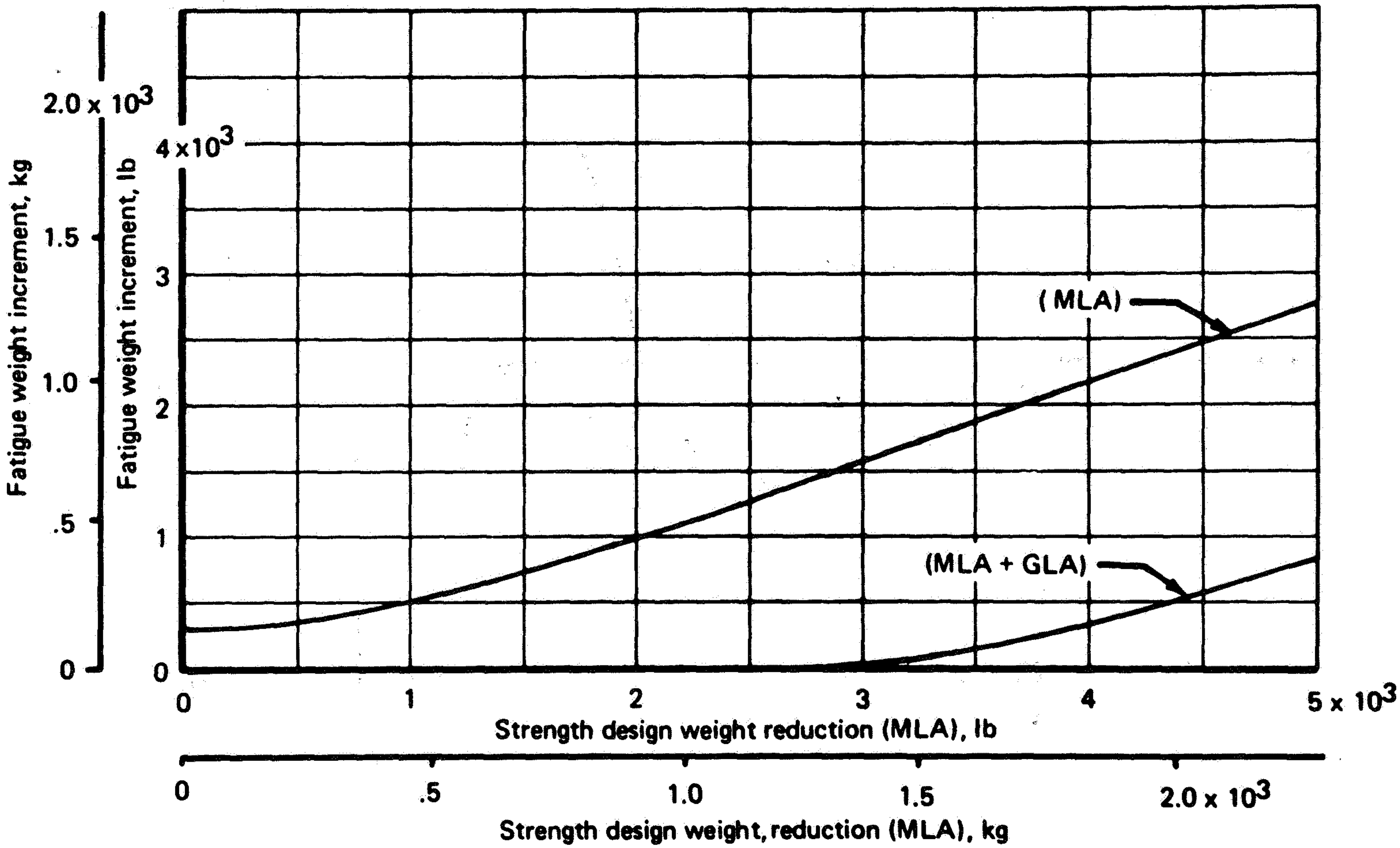


FIGURE 14. GUST LOAD ALLEVIATION POTENTIAL
(From ref. 2)

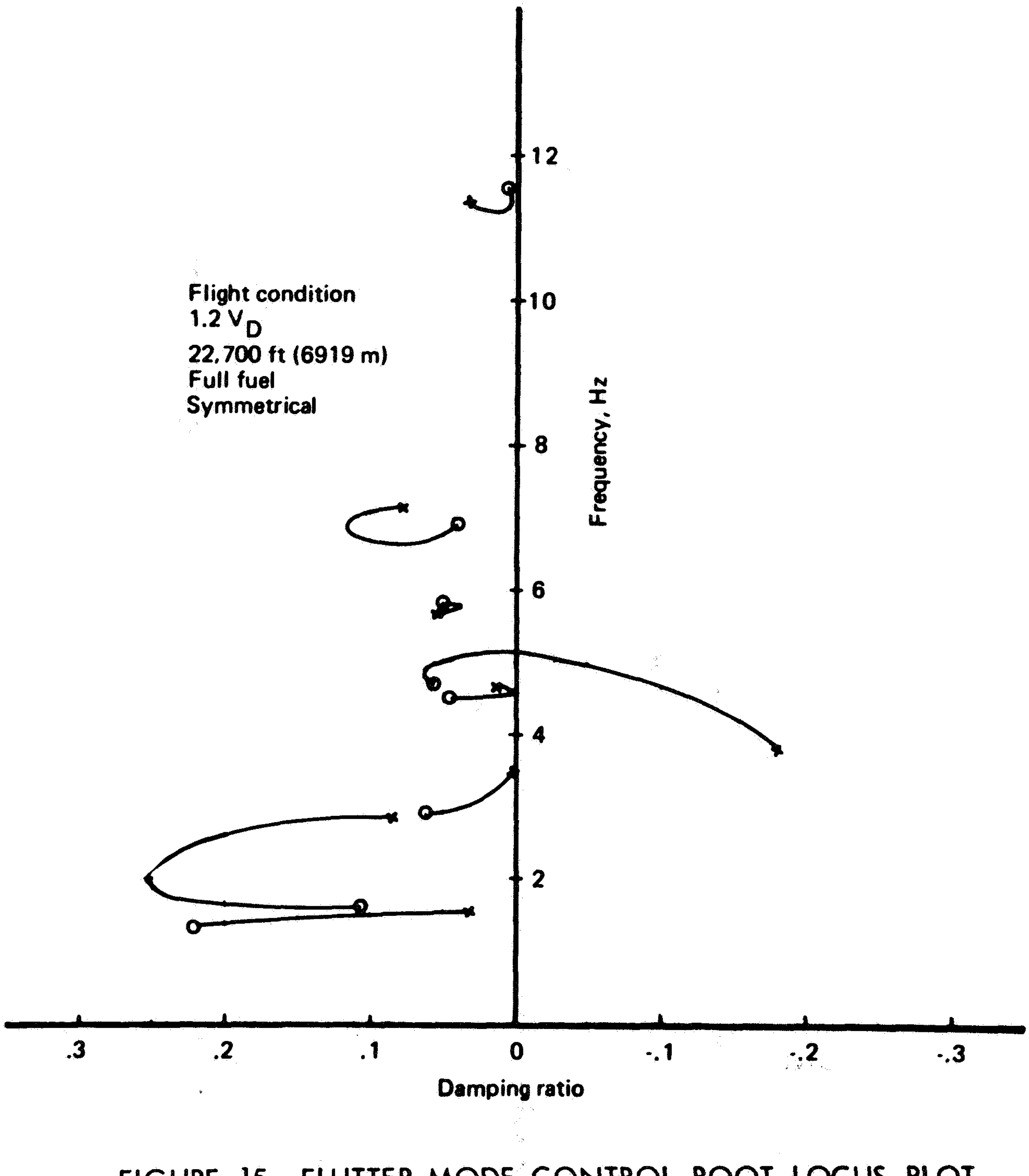


FIGURE 15. FLUTTER MODE CONTROL ROOT LOCUS PLOT
(From ref. 2)

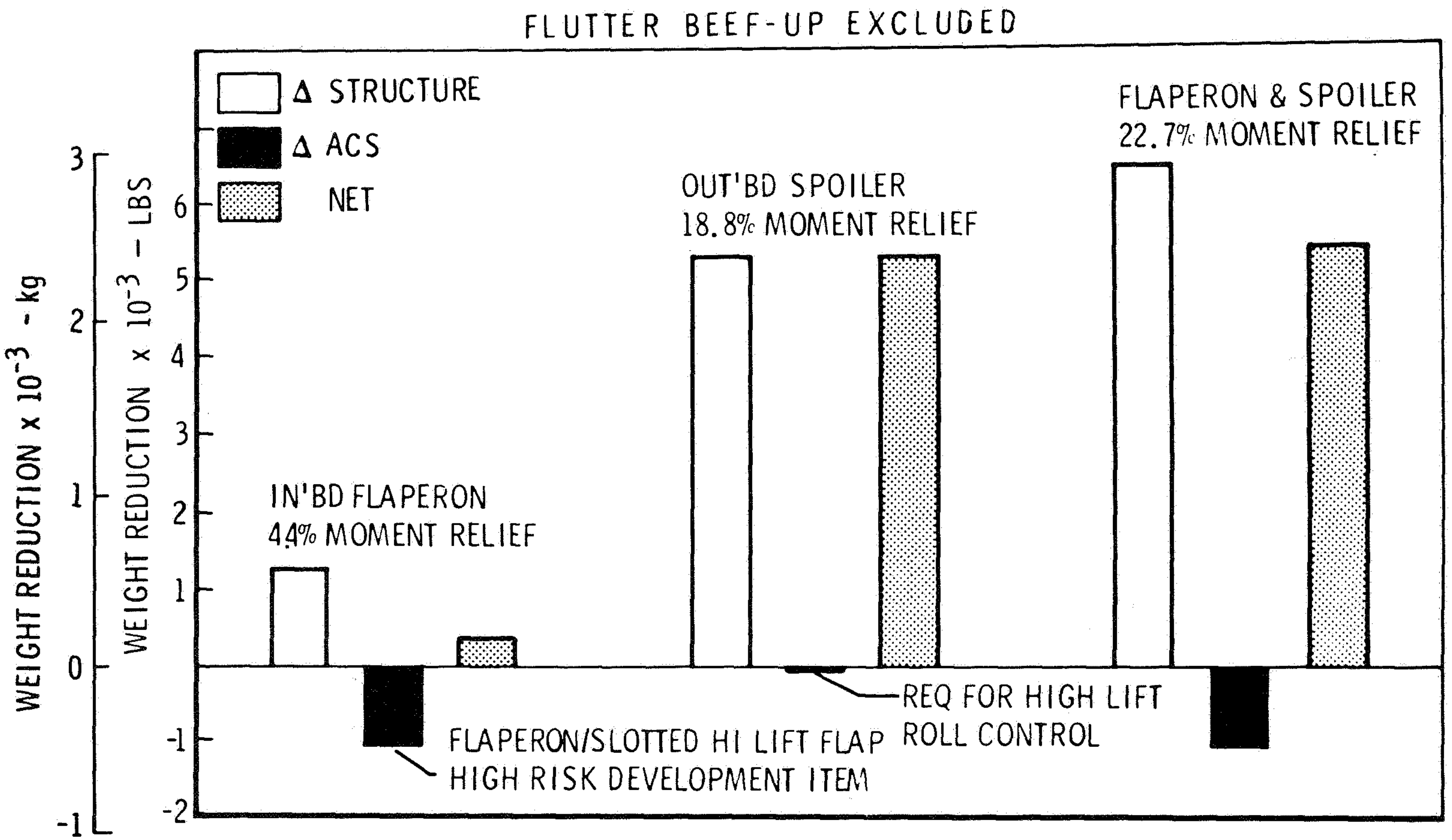


FIGURE 16. WING DESIGN LOAD CONTROL
(From ref. 4)

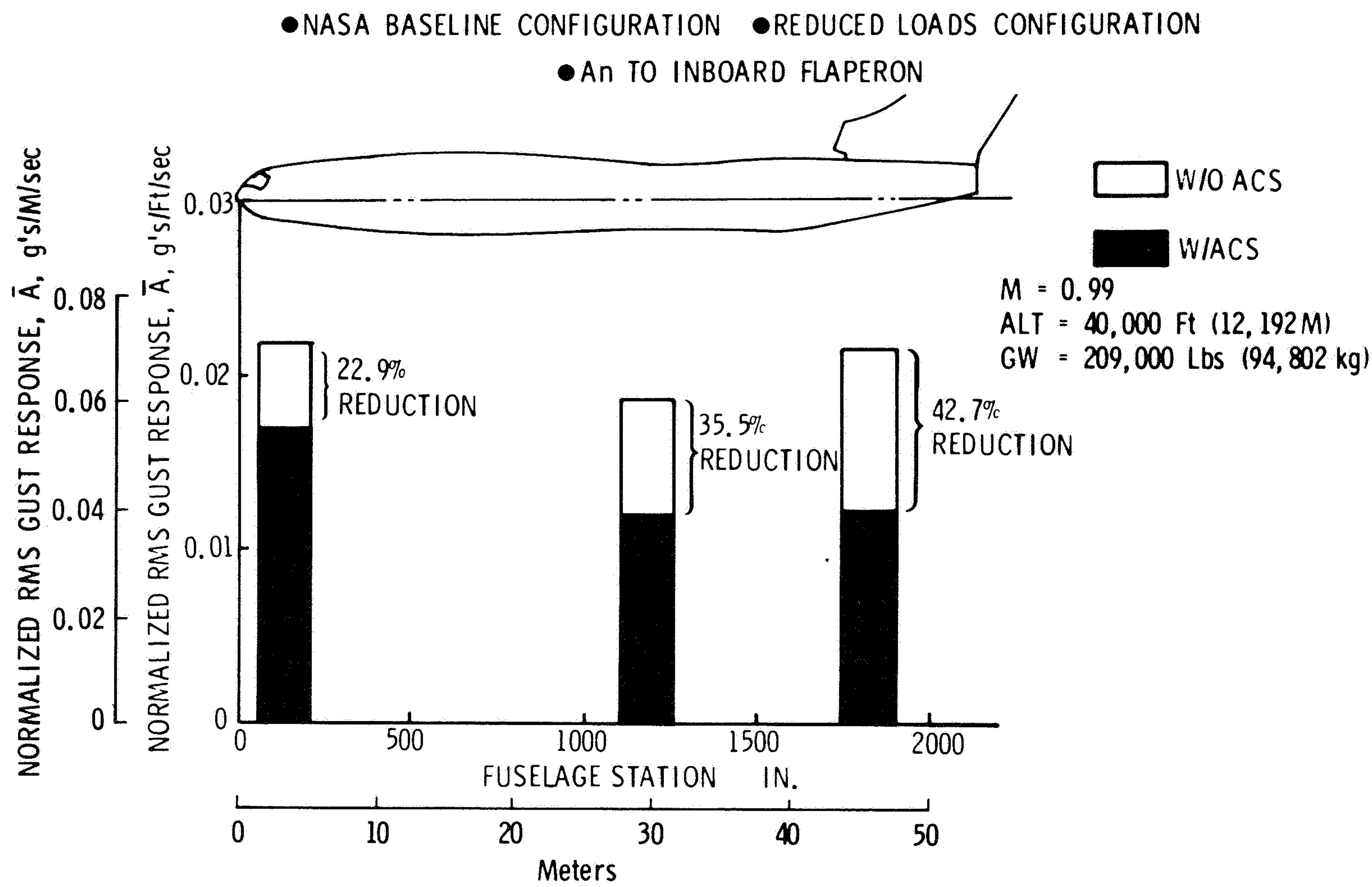


FIGURE 17. RIDE QUALITY BENEFITS OF GUST ALLEVIATION
(From ref. 4)

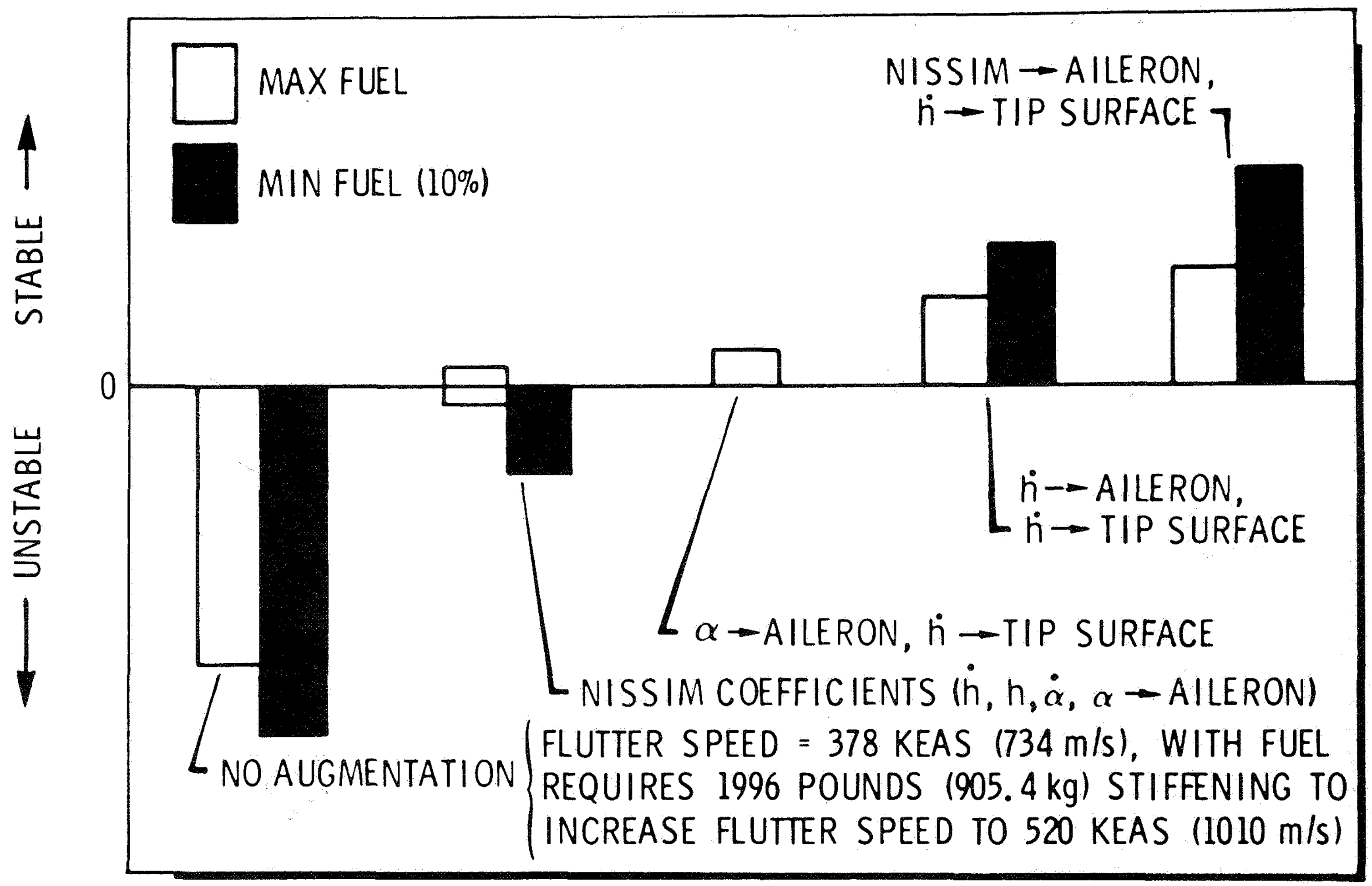


FIGURE 18. FLUTTER SUPPRESSION - REDUCED DESIGN LOADS WING
(From ref. 4)

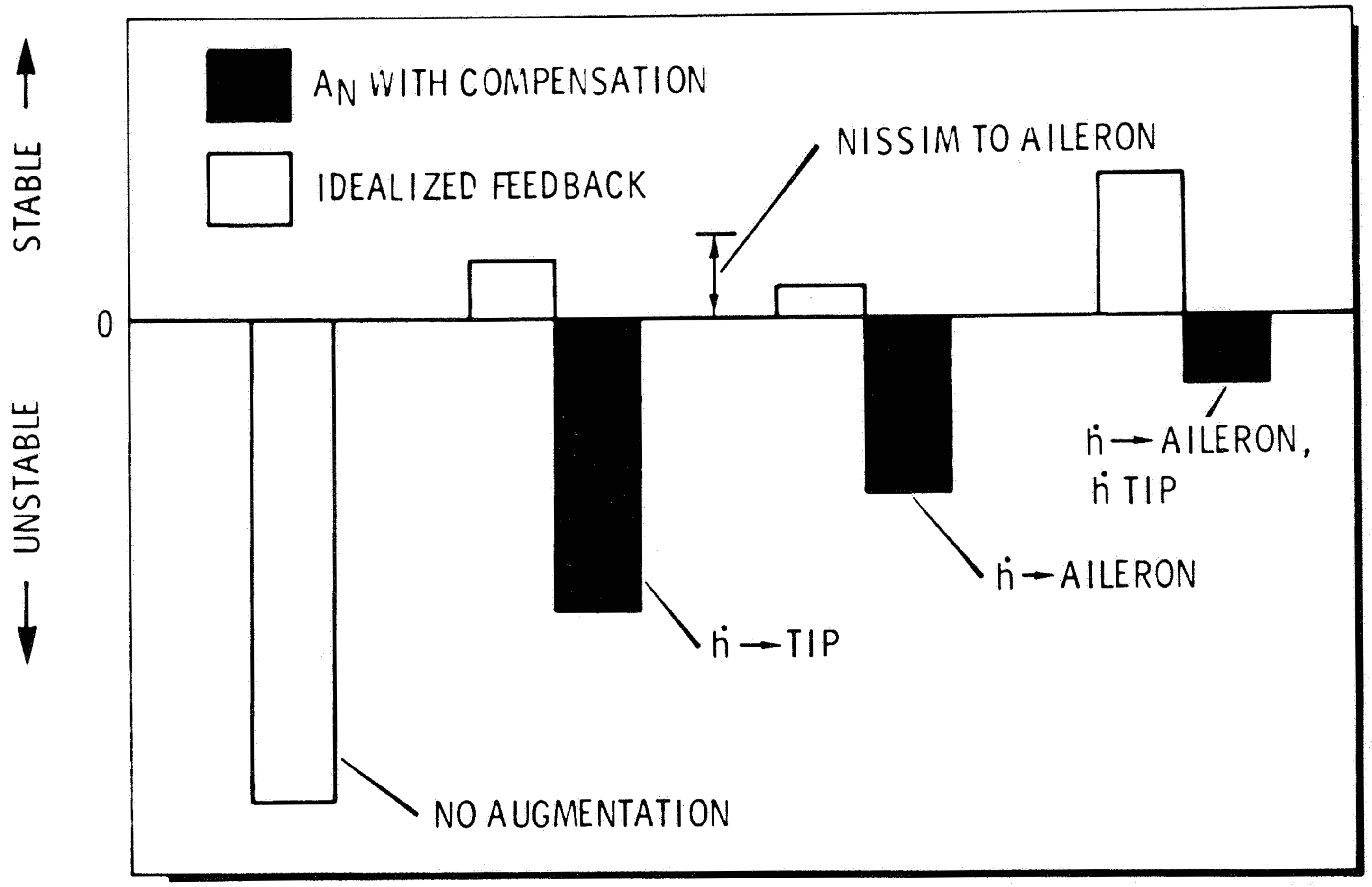
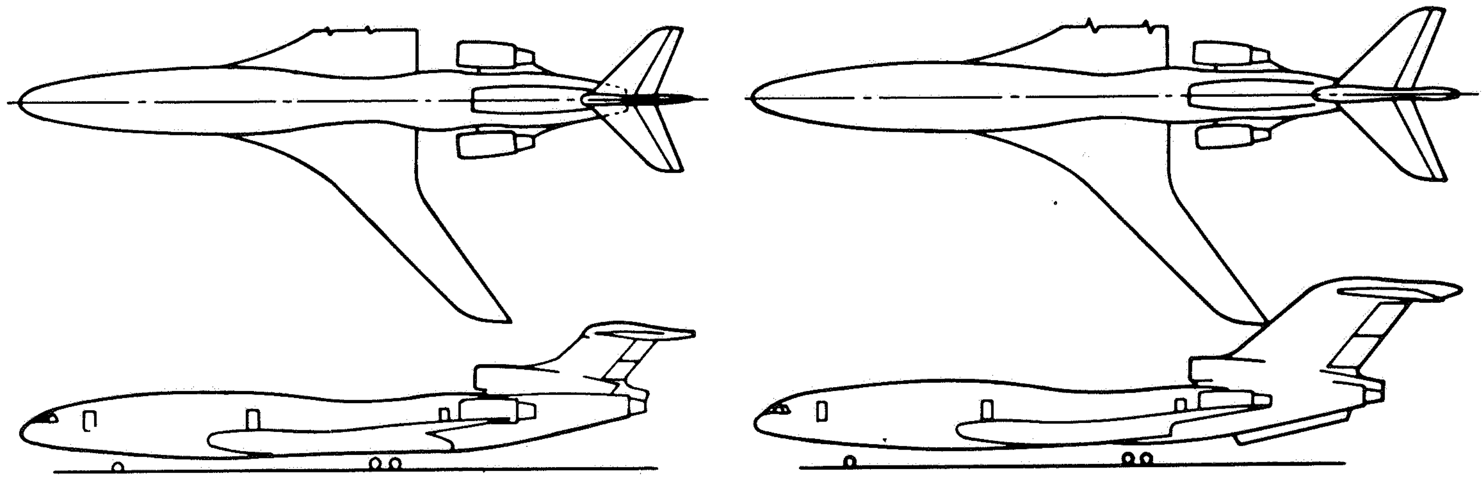


FIGURE 19. FLUTTER SUPPRESSION - CURRENT TECHNOLOGY IMPLEMENTATION
(From ref. 4)

FIGURE 20. FATIGUE DAMAGE RESULTS
(From ref. 4)

Control Point	Relative* Fatigue Damage		
	Study Configuration		
	100% Strength without ACS	100% Strength with ACS	Reduced Strength with ACS
Wing @ η = 0.187			
Gust	1.00	.39	.65
Maneuver	1.00	.09	.64
G.A.G.	1.00	.65	1.10
Wing @ η = 0.702			
Gust	1.00	.25	.55
Maneuver	1.00	.50	.50
G.A.G.	1.00	.90	1.16
Fuselage Sta 957 (24.2 m)			
Gust	1.00	.37	.49
Maneuver	1.00	.42	.58
G.A.G.	1.00	.82	1.08
Fuselage Sta 1196 (30.4 m)			
Gust	1.00	.29	.42
Maneuver	1.00	.13	.27
G.A.G.	1.00	.75	1.29

* Data normalized on 100% strength without ACS configuration.



Advanced Technology
- Flight Critical Stability Augmentation
- Maneuver Load Alleviation
- Gust Load Alleviation
- Optimum Cruise C.G. and Reduced C. G. Range

Conventional Technology
- Statically Stable
- Fail-Safe Yaw Damper
- Inherent Acceptable Stall

FIGURE 21. ACTIVE CONTROLS TECHNOLOGY APPLICATION
(From ref. 2)

CONTRACTOR	RELAXED STABILITY	MLA & GLA	F. S.	TOTAL
BOEING (REF. 2)	11.0% T. O. G. W.	1.4-3.0%	STRUCTURAL WEIGHT	11.0%+ T. O. G. W.
GENERAL DYNAMICS (REF. 4)	1.9% T. O. G. W. (TRIM DRAG EFFECT)	2.4% T. O. G. W.	2.8% T. O. G. W.	7.1% T. O. G. W.
LOCKHEED (REF. 6)	16% O. W. E.	-0-	-0-	16% O. W. E.

FIGURE 22. PERCENT WEIGHT SAVINGS

CONTRACTOR	RELAXED STABILITY	MLA & GLA	F. S.	TOTAL
BOEING (REF. 2)	N. A.	N. A.	N. A.	N. A.
GENERAL DYNAMICS (REF. 4)	4.0% (TRIM DRAG EFFECT)	4.7%	2.8%	11.5%
LOCKHEED (REF. 6)	8.0%	-0-	-0-	8.0%

FIGURE 23. PERCENT IMPROVEMENT IN RETURN ON INVESTMENT

CONTRACTOR	RELAXED STABILITY	MLA & GLA	F. S.	TOTAL
BOEING (REF. 2)	N. A.	N. A.	N. A.	N. A.
GENERAL DYNAMICS (REF. 4)	1.5% (TRIM DRAG EFFECT)	1.9%	1.1%	4.5%
LOCKHEED (REF. 6)	8.7%	-0-	-0-	8.7%

FIGURE 24. PERCENT IMPROVEMENT IN DIRECT OPERATING COSTS