FLUTTER SUPPRESSION BY ACTIVE CONTROL AND ITS BENEFITS

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SUMMARY

A general discussion of the airplane applications of active flutter suppression systems is presented with focus on supersonic cruise aircraft configurations. Topics addressed include a brief historical review; benefits, risks, and concerns; methods of application; and applicable configurations. Highlight results are presented from previous analytical and wind-tunnel model studies for supersonic cruise aircraft configurations. These results show that significant increases in flutter speed (or flutter dynamic pressure) can be accomplished by using active flutter suppression.

Results of a study are presented where the direct operating costs and performance benefits of an arrow-wing supersonic cruise vehicle equipped with an active flutter suppression system are compared with corresponding costs and performance of the same baseline airplane where the flutter deficiency was corrected by passive methods (increases in structural stiffness). The design, synthesis, and conceptual mechanization of the active flutter suppression system are discussed. The results show that a substantial weight savings can be accomplished by using the active system. For the same payload and range, airplane direct operating costs are reduced by using the active system. The results also indicate that the weight savings can be translated into increased range or payload.

INTRODUCTION

Commercial airplane designers are constantly striving to improve airplane performance. One technique currently being considered is the increased use of active controls. An active control application that is receiving more and more attention is active flutter suppression. The subject of this paper is the application of active flutter suppression to supersonic cruise aircraft.

This paper is divided into four major sections. In the first section, entitled "Background," active flutter suppression is described in general terms, a brief historical review is presented, and reasons for the interest in using an active system for supersonic cruise aircraft are pointed out. In the second section, entitled "General Discussion of Active Flutter Suppression," such topics as benefits, risks, and concerns; methods of application; and applicable configurations are addressed. In the third section, entitled "Past Supersonic

Cruise Airplane Flutter Suppression Studies," highlight results from analytical studies and wind-tunnel model investigations for supersonic cruise airplane configurations are presented. In the fourth section, entitled "Arrow-Wing Active Flutter Suppression System Design and Benefits," results are presented from a study that examines the potential direct-operating-cost (DOC) benefits of an active flutter suppression system for an arrow-wing configuration that required a substantial increase in structural weight to provide sufficient stiffness for satisfactory flutter margins. Direct comparisons are made between the airplane with the active flutter suppression system and the same baseline airplane with a passive flutter solution (increases in structural stiffness). In addition, the design, synthesis, and conceptual mechanization of the active flutter suppression system are described.

BACKGROUND

Supersonic Cruise Airplane Flutter Characteristics

Flutter is an oscillatory instability that must be properly accounted for in aircraft design. In fact, Federal Aviation Administration (FAA) regulations require a commercial transport to be flutter free at speeds 20 percent greater than the design dive speed V_D. Although flutter has caused problems in present-day subsonic jet transport design, and in some instances has impacted engine locations on the wing, satisfactory flutter-free configurations have been realized usually without requiring significant increases in structural stiffness and resulting increases in structural weight. That is, a strength-design structure had sufficient or very nearly adequate stiffness to satisfy flutter requirements. However, studies have shown that if wing aspect ratios for this type of airplane increase to values above about 10, substantial stiffness increases for flutter avoidance may be required.

Although no actual supersonic cruise airplane has been built in the United States, several designs have been taken to sufficient depth to indicate that the flutter deficiency of a strength-design structure may be rather large. This is illustrated in figures 1 and 2, where the flutter boundary relative to the operating boundary is shown for two strength-design supersonic-cruise vehicles, namely, the national program configuration and a version of the NASA arrow-wing configuration. More information on the flutter characteristics of these two configurations is presented in references 1 and 2, respectively. The application of passive flutter solutions (increases in structural stiffness, mass balance, etc.) to increase the flutter speeds to an acceptable level required the addition of over 4536 kg (10 000 lbm) of structural weight in both cases. (Other strength-design arrow-wing configurations, although flutter deficient, have flutter characteristics different from those shown in fig. 2 and consequently required different amounts of increased structural weight. (See refs. 3 and 4.)) Such weight additions, of course, penalize the aircraft by increasing the initial costs, reducing payload and range, and increasing direct operating costs throughout the operational life. Consequently, there is considerable interest in developing better methods of increasing flutter speed which can be used in place of, or in combination with, the traditional passive methods.

Active Flutter Suppression

Active flutter suppression is an alternative to passive flutter solution. An active system offers a means of artificially stiffening and damping the aircraft structure to increase the flutter speed by using aerodynamic control surfaces which are activated by control surface actuators through a feedback system control law (feedback gains) which receives structural motion information from dynamic motion sensors. Although active flutter suppression may eliminate the requirement for added structural weight that just goes along for the ride, so to speak, it may also increase airplane complexity and system maintenance costs. That is, there are both advantages and disadvantages to the use of an active system. The relative margin that the advantages outweigh the disadvantages is undoubtedly a governing factor in whether an active flutter suppression system is considered for implementation in any new airplane design.

Other Active Control Concepts

Active flutter suppression is only one of many active control concepts that are currently being considered to improve the performance of new technology airplanes. (See refs. 5 and 6.) Other concepts are relaxed static stability, gust load alleviation, ride quality control, and maneuver load control. In fact, during the past decade, some of these concepts have already begun to appear in production aircraft although, in most cases, they have been add-on systems that were not included in the preliminary design. A good illustration is the ride quality improvement system that was developed and certified for the Boeing 747 subsonic transport airplane (ref. 7).

Historical Review of Active Flutter Suppression

Active flutter suppression is not a new idea. The concept is suggested in a 1955 classic textbook (ref. 8), and it is a natural outgrowth of a flight flutter testing technique proposed a year earlier (ref. 9). In the late 1950's to mid-1960's very little research was done on active flutter suppression as is evidenced by the lack of published papers for this time period. In the mid to late 1960's, some interest in the subject developed. For example, at Lockheed-Georgia, some analyses and experiments were conducted to demonstrate the use of servo-control to delay flutter onset (ref. 10); Boeing conducted analytical studies of possible flutter suppression systems for the national supersonic transport (SST) configuration (ref. 11); and the NASA initiated some combined analytical and wind-tunnel model studies (ref. 12). In the 1970's interest continued to increase as is evidenced by the increasing number of published papers which describe a variety of analytical and experimental studies (refs. 13 to 39).[1]

A significant development during the early 1970's was the inclusion of active flutter suppression as one of the active control concepts to be demonstrated during the B-52 control configured vehicle (CCV) program (refs. 18, 34, 38, and 40). The successful flight demonstration beyond the basic airplane flutter speed by using the B-52 CCV airplane gave an affirmative answer to the question whether an active flutter suppression system can be designed, built, and demonstrated in flight. Of course, the B-52 system was developed to meet research program objectives and was not designed to meet the requirements of a commercial airplane system. Some wind-tunnel model studies were conducted in conjunction with the flight tests (refs. 28 and 31). Because the model results correlated well with flight-test results, it was confirmed that models can be used to predict accurately flight flutter suppression results. This accomplishment is important because uncertainties in present-day flutter analysis techniques require extensive use of wind-tunnel model testing in developing and validating active flutter suppression systems for commercial transport aircraft.

GENERAL DISCUSSION OF ACTIVE FLUTTER SUPPRESSION

Although other topics are mentioned, the discussion in this section focuses on the benefits, risks, and concerns associated with active flutter suppression. In preparing this section, the authors found very useful the information in two excellent papers (refs. 5 and 6) that describe the prospects for many active control applications including flutter suppression.

The implementation of an active flutter suppression system on a commercial transport airplane will depend on the tip of the scales shown in figure 3 where the potential benefits are shown balanced against the risks. The most often stated benefit is that for an airplane with a flutter deficiency, an active system may require a smaller increase in aircraft weight than that weight increase required by a passive flutter solution. However, this smaller weight increase is only the apparent benefit. A true benefit will only exist if this weight reduction can be translated into a performance, or economic, benefit. It is this performance benefit that must be balanced against the risks. The term "performance benefit" as used herein is consistent with that of reference 6

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[1] Although the reference list in this paper contains numerous papers on active flutter suppression, the list is certainly not all inclusive. It is intended to be only a representative sampling of the many papers available, and with one exception (ref. 27) is limited to papers that are available without restriction. Permission to cite reference 27 and to include material therefrom in this paper was granted by the Department of Transportation, Federal Aviation Administration. Their cooperation in this regard is hereby acknowledged.

where performance was defined as "a productivity increase of sufficient magnitude to provide a reasonable return on investment." This definition is rather broad and is not limited to the usual items such as increased speed and longer range.

Many of the risks and concerns relative to the use of active flutter suppression are because it is a new technology. The manufacturer has little past experience on which to base the certification of such systems. The manufacturer also is concerned about the apparent weaknesses in analytical methods in accurately predicting system performance. The users, primarily the airlines, are concerned about such items as maintenance costs and reliability. Here again lack of previous experience is the key ingredient. Because maintenance costs are a large fraction of the total DOC of commercial transport airplanes, any appreciable growth in these costs could more than offset other economic advantages of using an active flutter suppression system.

Design Cycle Integration

The benefits of active flutter suppression will undoubtedly be a function of when the decision is made to consider its use. If it is considered as an option in the preliminary design stage, the potential benefit may be considerably larger than it would be if it is initially considered after the preliminary design is complete. In the first case, the active system is an integral part of the airplane design, and its requirements for such things as hydraulic system capacity, control surface size and location, and actuator power and frequency response are considered at the outset. In the second case, the active system is a substitute for a passive system. At this stage, the introduction of the active system may require changes in already designed systems such as hydraulic power and control surface actuators. Furthermore, at this stage the active system design will probably be constrained to use existing control surfaces whose size and location were selected without any consideration of active flutter suppression.

Although the potential benefits may be larger the sooner the decision is made, it can be argued that the earlier the decision, the greater the potential technical risk. This is because a major unforeseen problem may arise after the commitment to active flutter suppression has been made and considerable money and time have been expended. Analytical uncertainties in accurately predicting active system performance may be a critical factor in not identifying a major problem early in the design cycle. Perhaps some reduction in this technical risk can be accomplished by judicious use of wind-tunnel model tests to validate analytical methods as early in the design cycle as possible. Candidate tests would include the measurement of control surface aerodynamic characteristics because, in many instances, existing aerodynamic theories do not predict control surface characteristics to the required accuracy.

Limited Application System

One primary concern about active flutter suppression is that it would be a flight critical system and would have to be as reliable as the passive flutter solution structure that it replaces. This concern is certainly justified in light of the current state of the art if the active system is required to increase the flutter speed from below the design dive speed V_D to the flutter margin requirement $1.2\ V_D$. Presently, it appears that only limited applications of active flutter suppression should be considered. By limited applications is meant that the active system provides only the required flutter margin, V_D to $1.2\ V_D$ (or a portion of the margin). The idea of limited application is illustrated schematically in figure 4. Any flutter deficiency below V_D is corrected by a passive flutter solution. Consequently, the airplane would be flutter free throughout its normal flight envelope and the flutter suppression system would provide the required 20-percent margin of safety.

Considerable precedent exists today for using mode damping systems in commercial airplane operations. Some commercial transports operate with yaw dampers that are flight safety critical. For example, one highly successful subsonic jet transport airplane uses a dual yaw damper system. Although only one system is required to be functional for dispatch, both systems must be working for the airplane to operate throughout its full flight envelope. If one system fails during flight, the airplane operational altitude is restricted to below about 9250 m (30 000 ft). At this altitude and below, the unaugmented Dutch roll characteristics are considered acceptable for commercial airplane operations.

A limited application active flutter suppression system relies on a similar operating restriction (speed reduction rather than altitude reduction) and a fail-operational mechanization. Of course, there are presently no FAA regulations on active flutter suppression. The lack of a specific FAA policy is naturally a concern because the certification requirements and costs represent an unknown risk.

Applicable Configurations

In reference 6, some qualitative indication of the relative benefits of active flutter suppression are presented for several different airplane variables. Some of these results are repeated in figure 5 for speed range, gross weight, and wing aspect ratio. Note that the relative benefits for the ranges of these parameters which are applicable to supersonic cruise airplanes (large speed range, heavy gross weight, and low to moderate aspect ratio) are considered to be moderate to major. It should be recognized that active flutter suppression will not be beneficial for all configurations, and, in some instances, the airplane actually may be penalized if an active system is chosen over a passive system. A case in point is one of the designs generated during the NASA-sponsored Advanced Transport Technology (ATT) Program (see ref. 41) where it was concluded for one of the designs studied that the benefits of an active system would be more than offset by the complexity of such a system.

Interrelation With Other Active Control Concepts

In a new airplane design where the designers attempt to take advantage of as many active control applications as practicable, it may not be possible to make the decision to implement an active flutter suppression system independent of the decision to implement other concepts. For example, a flutter suppression system may be required in order to achieve maximum benefits from a load alleviation system. The interrelation of various active control concepts for supersonic cruise aircraft is discussed in reference 42. If more than one concept is implemented, there may be advantages in common system components. For example, flutter suppression and gust load alleviation systems may use some of the same control surfaces and actuators.

PAST SUPERSONIC CRUISE AIRPLANE SUPPRESSION STUDIES

In this section, highlight results from some flutter suppression studies that have been conducted for supersonic cruise airplane configurations are presented. Remember that flutter suppression studies for other configurations may be applicable to supersonic cruise aircraft. For example, from the results of the B-52 CCV model/airplane studies mentioned previously, it can be concluded that full-scale supersonic cruise aircraft flutter suppression system performance can be accurately simulated by using appropriately scaled wind-tunnel models.

National Configuration Analytical Studies

During the latter stages of the National Program, some analytical studies were made by The Boeing Company to determine whether an active flutter suppression system could be used effectively to increase the flutter speed of the national configuration. As pointed out previously, the strength-design configuration was rather flutter deficient (see fig. 1), and a substantial increase in structural weight was required for a passive flutter solution. During these studies, it was assumed that satisfactory flutter margins would be achieved by a combination of passive and active flutter solutions (the limited application concept mentioned previously). Although the complete results of these studies are not generally available in the literature, some information is contained in reference 11. Various combinations of aerodynamic control surfaces, types and locations of motion sensors, and feedback control laws (feedback gains) were investigated. One combination of control surfaces and motion sensors that yielded a substantial increase in airplane flutter speed is shown in figure 6. Some results obtained at a Mach number M of 0.90 by using this combination are presented in figure 7 as the variation in damping with airspeed for two of the important flutter critical modes, namely, a wing mode and a wing-body mode. The effectiveness of this active system in substantially increasing the flutter speed of the unaugmented basic airplane is readily apparent. For the basic airplane, both modes flutter near the design dive speed V_D. The active system increased the flutter speed for both modes to at least the $1.2\ V_D$ flutter margin requirement. Indeed, at this velocity, both damping trends are toward increasing stability.

DOT Technology Follow-On Model Study

After the cancellation of the National Program, the Department of Transportation (DOT) sponsored a wind-tunnel model active flutter suppression study as part of the SST Technology Follow-On Program. The results of this study are given in reference 27, and only some of the highlights are presented here. The model was a 1/20-scale low-speed model of the national configuration that was modified to include active-control aerodynamic surfaces for flutter suppression and stability augmentation. A photograph of this model is presented in figure 8. During the wind-tunnel tests, the full-span model was mounted on a cable suspension system to simulate the free-flying condition. Three active flutter suppression systems were investigated. The first used the inboard ailerons; the second used the outboard ailerons; the third used both the inboard and outboard ailerons. The locations of these control surfaces are shown in figure 9. The experimental flutter results for all three systems are presented in figure 10. All three systems increased the flutter speed of the unaugmented aircraft. The inboard-outboard aileron system provided the largest increase, about 11 percent. A comparison of the experimental results with analytical results was somewhat contradictory. The analysis accurately predicted the inboard aileron system experimental results. However, the analysis for the outboard aileron system predicted about a 13-percent increase in flutter speed, about four times the experimental value. The reason for this discrepancy is unknown at present.

Incidentally, this model was damaged near the end of the wind-tunnel program. Since that time it has become the property of the NASA and has been repaired. Additional testing is planned in the Langley transonic dynamics tunnel to study different flutter suppression systems as well as other active control applications.

Delta-Wing Flutter Suppression Model Study

For a number of years the Langley Research Center has been sponsoring considerable research activity in active flutter suppression. Both in-house and contractor work have been involved. Much of this activity has utilized a cantilever delta-wing model that was equipped with hydraulically actuated leading-edge and trailing-edge control surfaces for active flutter suppression. Although this model does not scale dynamically any particular airplane configuration, it is representative of a contemporary supersonic cruise airplane design. A photograph of the model mounted in the Langley transonic dynamics tunnel is shown in figure 11. One of the purposes of this model study was to experimentally evaluate and validate the aerodynamic energy approach to active flutter suppression that was developed in reference 15. This goal was successfully accomplished, and the study is described in detail in reference 35.

Some analytical and experimental results from the delta-wing study are presented in figures 12 and 13. These data are presented in terms of dynamic pressure rather than velocity as was the case for the two previous examples. An important point can be made by referring to the calculated results shown in figure 12 for various locations of aerodynamic control surfaces and wing motion sensors — accelerometers in this case. Three possible locations of the pair of leading-edge and trailing-edge control surfaces were investigated with three possible accelerometer locations for each control surface arrangement. The greatest increase in flutter dynamic pressure was obtained for the outboard control-surface location with the accelerometers alined with the outboard edges of the control surfaces. However, on this model the installation of the outboard control surface actuators was not practical without violating the external contour of the airfoil section. For this and other reasons, the control surface arrangement chosen was the midspan strip. The point to be made is that on this model, as undoubtedly will be the case in airplane applications, there were practical considerations that really had nothing to do with the flutter suppression system itself that played an important role in the choice of system that was actually implemented.

The delta-wing model was used over the Mach number range from 0.60 to 0.90 to demonstrate successfully the aerodynamic energy approach. Some experimental and analytical results obtained at a Mach number of 0.90 are shown in figure 13 for the three control laws studied, designated as control laws A, B, and C, respectively. Which control surfaces were used, and whether two-dimensional (2D) or three-dimensional (3D) unsteady aerodynamics were used in determining the feedback gains constituted the differences between the three control laws. These differences are indicated in figure 13. All three control laws were effective in increasing the flutter dynamic pressure of the unaugmented basic model. One word of caution — although the trailing-edge control (law C) indicated the largest increase in flutter dynamic pressure, this does not mean that a trailing-edge control system is better necessarily than a leading-edge trailing-edge control system. Analytical studies (not shown in the figure) indicated just the contrary. See reference 35 for details.

The only direct comparison that can be made between experiment and analysis is for control law A, since this is the only case where the model was actually taken to flutter with the flutter suppression system operational. For law A, the analysis and experiment are in good agreement. However, to obtain the analytical results shown, the theoretical unsteady aerodynamic characteristics of the control surfaces were adjusted by using measured hinge-moment data that had been determined previously for this model. If purely theoretical aerodynamics are used in the calculations, the predicted improvement in flutter dynamic pressure is considerably larger than that shown in the figure.

System and Technology Assessment Studies

The NASA has sponsored several system and technology assessment studies for advanced supersonic cruise aircraft. Both in-house and contractor activities have been included. (A bibliography of published reports from these studies is given in ref. 43.)

The system and technology studies, taken as a whole, indicate that a savings in structural weight can be accomplished by using an active flutter suppression system on an advanced supersonic cruise airplane and that this weight saving can be translated into economic benefits, such as a decrease in direct operating costs or an increase in range. The magnitude of the potential benefit, although considerably smaller than that of some other active control applications such as relaxed static stability, will become larger as technology advances occur, will be a function of whether other active control systems are included in the preliminary design, and will be affected by the use of other advanced technologies such as composite structures.

ARROW-WING ACTIVE FLUTTER SUPPRESSION SYSTEM DESIGN AND BENEFITS

Presented in this section are the results obtained to date from a study that compares the relative structural weight, performance, and direct operating costs of an arrow-wing supersonic cruise aircraft configuration that had its flutter deficiency corrected by an active flutter suppression system with the corresponding weight, performance, and DOC of the same baseline airplane where the flutter deficiency was corrected by using a passive system (increased structural stiffness). The baseline airplane was the strength-design configuration developed by The Boeing Commercial Airplane Company during the NASA-sponsored arrow-wing structural design concepts studies. (See ref. 2.) The geometry of this configuration is shown in figure 14. The flutter deficiency of this airplane was large (see fig. 2), and 4627 kg (10 200 lbm) of structural weight was required to increase the flutter speed to the $1.2\ V_D$ requirement. This airplane is referred to as the passive system airplane. The other airplane, referred to as the active system airplane, used the same baseline design, but the flutter deficiency was corrected by a combination of passive and active system applications. A passive solution was used to increase the minimum flutter speed to V_D, and an active flutter suppression system was used to further increase the flutter speed to $1.2\ V_D$. This is the limited application concept described previously. In the following discussion, the design criteria, synthesis, and conceptual mechanization of the active flutter suppression system are described. Finally, the results of an economic analysis are presented where the DOC of the active system airplane are compared directly with the DOC of the passive system airplane. This comparison gives a direct indication of the benefits of using an active flutter suppression system for the arrow-wing configuration studied.

Design Criteria

Basically, the active flutter suppression system design criteria were based on contemporary industry design practices and existing FAA and military regulations and specifications.

Flutter criteria.- The basic flutter requirement, as shown in figure 15, was that the active flutter suppression system would provide a 20-percent increase in the flutter speed, V_D to $1.2\ V_D$. A passive system was to be used to correct any deficiencies below V_D. At speeds less than V_D, the active system was required to provide the equivalent of 3 percent structural damping for all flutter critical modes. In addition, criteria were adopted which required that the damping of other modes could not be significantly reduced. For example, the ride quality of the active system airplane could not be significantly degraded by the active flutter suppression system. Handling qualities were required to remain essentially unchanged, active flutter suppression system on or off. Furthermore, criteria governing repeated loads on the structure were adopted so that fatigue loading in turbulence would be no greater for the active system airplane than for the passive system airplane. Gain and phase margin requirements were adopted also. At V_D, the active system was required to have 6 dB gain and 45° phase margins.

Turbulence criteria.- A significant factor in the design of an active flutter suppression system is to account properly for atmospheric turbulence and gusts because structural responses resulting from turbulence can place additional demands on the flutter suppression system that can cause system saturation. The turbulence criteria are shown in figure 16. Turbulence effects were allowed to degrade system performance but not to levels below those required by the flutter criteria. That is, turbulence effects could produce reductions in the damping in a critical flutter mode to levels below those in smooth air, but not to levels below 3 percent equivalent structural damping.

Flight safety and reliability criteria.- The basic flight safety criteria was that the flutter suppression system remain completely operational following a first failure. That is, a fail-operational system was required. The system was not required to be functional for dispatch nor was it required that a mission be aborted following an in-flight failure. However, should a system failure occur, either on the ground or in flight, the airplane operational envelope would be placarded to insure the 20-percent flutter margin. For example, if an in-flight failure occurs when the airplane is flying at a speed greater than 80 percent of V_D, speed would be reduced to provide the required 20-percent flutter margin in velocity. If only a single failure occurs, the airplane is still flutter free to $1.2\ V_D$. Should a failure be detected on the ground prior to take-off, the airplane could still be dispatched, but its operating envelope would be restricted to provide the flutter margin, that is, lower speed climb and descent schedules. Recall that the passive system provides safety from flutter up to V_D.

In establishing the reliability requirements, the basic consideration was that the chances of a failure or other event occurring that would result in a catastrophe would be extremely remote. In this case, the catastrophic event would be encountering flutter. For flutter to occur, both of the following must occur: (1) the airplane must be at a speed greater than V_D and (2) there must be a total failure of the active flutter suppression system. For system design purposes, the probability of a total failure of the fail-operational system was chosen to be less than 1×10^{-4} which is a value consistent with the state of the art in fail-operational flight control systems, perhaps even on the conservative side. The same probability value was selected for being beyond V_D. Admittedly, this choice was somewhat arbitrary, but it is believed to be a realistic value. The two contributors to flutter were considered to be independent; therefore, the probability of flutter occurring is less than 1×10^{-8}. This value is consistent with values usually quoted for the chances of experiencing primary structural failure.

Analytical Development

In the analytical development of the active flutter suppression system, the airplane equations of motion were expressed in terms of generalized modal coordinates. These equations were transformed to Laplace variable space where the synthesis was accomplished by using root locus analysis methods.

Structural and aerodynamic modeling.- The airplane structure was modeled by a finite-element idealization developed for The Boeing Commercial Airplane Company's ATLAS integrated structural analysis and design system. Although the basic mathematical structural model was already available (see ref. 2), some modifications were necessary to meet the needs of the present study.

The aerodynamic model was developed by using a finite-element solution of the linear, unsteady, compressible flow equations that provide continuous solutions throughout the Mach number range, subsonic, transonic, and supersonic. The technique was developed by Kenneth L. Roger and his associates at Boeing-Wichita, and is currently unpublished. Unpublished results show that the method is as accurate as other similar existing methods, but is computationally more efficient. The technique requires the airplane to be subdivided into an arrangement of trapezoidal boxes, provides a very general modeling capability, and accounts for such things as intersecting surfaces, out-of-plane surfaces, and arbitrary arrangement of control surfaces. For the steady-state case, the method is similar to that described in reference 44; for the subsonic unsteady flow case, it shares certain similarities with the doublet-lattice method (ref. 45).

Since the airplane equations of motion were expressed in the Laplace domain, it was necessary to transform the frequency-dependent (actually reduced frequency) unsteady aerodynamic coefficients into functions of the Laplace variable. This transformation was accomplished by a least-squares curve-fitting procedure which used rational functions of the Laplace variable with fourth-order denominators. This technique has been used previously with good results. (See refs. 14 and 16.)

System synthesis.- During the initial synthesis studies, various combinations of aerodynamic control surfaces and accelerometer locations were investigated in combination with different feedback control laws. The control surfaces and accelerometer locations are shown in figure 17. The midspan control surface and accelerometer location chosen for the final synthesis are shown darkened in figure 17. The accelerometer location chosen was attractive for two reasons. First, because of local stiffening produced by the engine support beams, very little response of the wing is produced at this point by higher frequency modes which are not flutter critical. Second, studies indicated that the precise location of the accelerometer was not critical; thus the conceptual installation of the accelerometer was facilitated.

Although the chosen control surface, accelerometer location, and feedback control law were effective in providing the required flutter speed increase, a nonflutter-critical mode was adversely affected in that the gain and phase margin requirements were not satisfied. This effect was corrected by adding an aft-fuselage accelerometer whose signal was added to the wing accelerometer signal, and by making a small adjustment in the feedback control law.

A block diagram of the final flutter suppression system is presented in figure 18. Note that gain scheduling is provided, both in terms of Mach number M and dynamic pressure q. Scheduling was used because the active flutter suppression system is only required to provide the flutter margin over a portion of the flight envelope, primarily in the transonic regime. At other flight conditions, the passive system provides sufficient stiffness to give the required 20-percent margin.

The calculated variation of damping in the critical flutter mode with equivalent airspeed is shown in figure 19 for the active system on and off. These data are for a Mach number of 0.90. The effectiveness of the active system in increasing the damping is obvious.

System Mechanization

No hardware items were built during this study, but the required hardware was defined in sufficient detail so that realistic estimates could be made of manufacturing costs and weight. Such information was required for the economic analysis. A simplified block diagram of the system mechanization is presented in figure 20. An important part of the mechanization was the modified nonlinear describing function analysis that accounted for such nonlinear effects as system saturation due to turbulence. This analysis determined the control surface physical size (the location was determined during the synthesis), and the position and rate limits. Control surface size and motion limits plus hinge-moment requirements dictated the control surface actuator selection which, in turn, defined the hydraulic system flow-rate requirements. The flow rate essentially specified the hydraulic system power and cooling requirements. In this application, the hydraulic and electrical power requirements of the flutter suppression system were easily handled by the existing baseline airplane hydraulic and electrical power systems. This situation may exist in other applications as well, since design of these systems is normally based on peak requirements which occur at lower speeds. At the higher speeds, where the active flutter suppression system has substantial power requirements, the baseline airplane had surplus hydraulic and electrical power available beyond expected airplane requirements.

Of course, during the conceptual mechanization the reliability requirements had to be taken into account. For example, triple tandem actuators were required for each control surface.

The estimated weight of the active flutter suppression system was 159 kg (350 lbm). This weight estimate includes all system components such as actuators and electronics. The weight of the passive system part of the limited application flutter suppression system was about 317 kg (700 lbm). Therefore, the total weight of the flutter suppression system for the active system airplane was 476 kg (1050 lbm). When compared with the 4627 kg (10 200 lbm) of structure that was needed for the passive system airplane, there is a net weight savings of about 4151 kg (9150 lbm).

Economic Evaluation

An economic evaluation study was made to obtain a direct comparison of the DOC of the active system airplane with the DOC of the passive system airplane. Although this economic study has not been completed, it is believed that the final results may indicate only changes in detail, but no changes in substance.

The criteria used in the economic comparison are (1) direct comparison of active system airplane with passive system airplane, (2) performance evaluated at constant payload, and (3) cost analysis based on procurement and maintenance costs of similar complex equipment. The basic criterion was that the comparison would be made for the two airplanes where the only differences between them would be in the type of flutter improvement system employed. Some airplane characteristics used in the economic analyses are presented in table I. Of course, for the same payload and fuel loading the take-off gross weights of the two airplanes are different because of the 4151 kg (9150 lbm) weight saving benefit realized by using the active flutter suppression system. The specific methodology used in the economic analysis is described in reference 46. Crew costs, fuel, depreciation, and insurance were calculated by the conventional ATA formula, using 1976 coefficients. Procurement and maintenance costs of the flutter control system were estimated separately based on a comparison with contemporary complex systems of a similar nature.

Some DOC results for the two airplanes are presented in figure 23 as a function of stage length. The DOC of the active system airplane are lower throughout the range shown. For example, for a 3000-nautical-mile trip, the reduction is about 2 percent, \$9.54 per nautical mile (active) versus \$9.73 per nautical mile (passive). These data were obtained by using the same payload for both airplanes. The take-off gross weights were different. The fuel cost used was 10.83 cents per liter (41 cents per U.S. gallon).

The items which contributed to the DOC savings are shown in figure 24. The fuel, depreciation, and insurance costs were less whereas a slight increase in airframe maintenance cost was indicated. DOC items such as crew costs and engine maintenance were unchanged. About 71 percent of the DOC savings obtained by using the active flutter suppression system were produced from fuel savings, which correlate with the lower take-off gross weight. The other major contributor was depreciation (about 25 percent of the total savings). This was due primarily to the fact that the estimated purchase price of the active system airplane was about 2-1/4 percent less than that of the passive system airplane.

The net weight savings gained by using the active flutter suppression system can be translated into an increase in range or payload. For example, if both airplanes are assumed to have the same take-off gross weights and equal payloads, the range of the active system airplane may be increased by about 186 n. mi. This is accomplished by absorbing the weight savings as additional fuel. For the same take-off gross weight and equal range, a payload increase of several thousand pounds is another possible option. In this case, additional payload is carried, instead of additional fuel.

CONCLUDING REMARKS

A general discussion of the application of active flutter suppression systems for increasing airplane flutter speeds has been presented. The discussion focused on applications to supersonic cruise aircraft. In addition to the presentation of some general background information concerning active flutter suppression, such topics as benefits, risks, and concerns; methods of application; and applicable configurations have been discussed.

Highlight results obtained during previous analytical and wind-tunnel model experimental studies made for supersonic cruise airplane configurations have been presented and discussed. These results show that substantial increases in flutter speed (or flutter dynamic pressure) can be obtained by using an active system for the configurations studied.

Results obtained to date in a study to determine the direct operating costs and performance benefits of applying an active flutter suppression system to an arrow-wing supersonic cruise vehicle have been presented. In this study, a direct comparison was made between a baseline airplane equipped with an active system to correct the flutter deficiency and the same baseline airplane with a passive system (increases in structural stiffness). The design, synthesis, and conceptual mechanization of the active system have been described. Results of this study indicate the following:

1. A substantial airplane weight saving can be accomplished by using the active flutter suppression system rather than the passive system. This weight saving is about 4151 kg (9150 lbm).

2. For the same payload and range, the use of the active flutter suppression system decreases the direct operating costs as compared with the passive system airplane. For a 3000-nautical-mile trip, this saving is about 2 percent. The major factors contributing to this reduction are lower fuel costs and depreciation.

3. For the same payload, the range of the active system airplane can be increased about 186 n. mi. over that of the passive system airplane by absorbing the weight savings as additional fuel.

4. For the same range, the payload of the active system airplane can be increased over that of the passive system airplane by absorbing the weight savings as additional payload.

REFERENCES

1. Turner, M. J.; and Bartley, J. B.: Flutter Prevention in Design of the SST. Symposium on Dynamic Response of Structures, Stanford University, Stanford, California, June 28-29, 1971.

2. Robinson, James C.; Yates, E. Carson, Jr.; Turner, M. Jonathan; and Grande, Donald L.: Application of an Advanced Computerized Structural Design System to an Arrow-Wing Supersonic Cruise Aircraft. AIAA Paper No. 75-1038, Aug. 1975.

3. Sakata, I. F.; and Davis, G. W.: Substantiating Data for Arrow-Wing Supersonic Cruise Aircraft Structural Design Concepts Evaluation. Volume 2. (Lockheed-California Co.; NASA Contract NAS1-12288) NASA CR-132575-2, 1976.

4. Sobieszczanski, Jaroslaw; McCullers, L. Arnold; Ricketts, Rodney H.; Santoro, Nick J.; Beskenis, Sharon D.; and Kurtze, William L.: Structural Design Studies of a Supersonic Cruise Arrow-Wing Configuration. Proceedings of the SCAR Conference, NASA CP-001, 1977. (Paper no. 31 of this compilation.)

5. Shomber, Henry A.; and Hollaway, Richard B.: Advanced Controls for Commercial Transport Aircraft. SAE Paper No. 740453, April-May 1974.

6. Schoenman, R. L.; and Shomber, H. A.: Impact of Active Controls on Future Transport Design, Performance, and Operation. SAE Paper No. 751051, Nov. 1975.

7. Cohen, Gerald C.; Cotter, Clifford J.; and Taylor, Donald L.: Use of Active Control Technology to Improve Ride Qualities of Large Transport Aircraft. Advanced Control Technology and Its Potential for Future Transport Aircraft. NASA TM X-3409, Aug. 1976, pp. 373-407.

8. Bisplinghoff, Raymond L.; Ashley, Holt; and Halfman, Robert L.: Aeroelasticity. Addison-Wesley Pub. Co., Inc., c. 1955.

9. Pepping, R. A.: A Theoretical Investigation of the Oscillating Control Surface Frequency Response Technique of Flight Flutter Testing. J. Aeronaut. Sci., Vol. 21, No. 8, Aug. 1954, pp. 533-542.

10. Theisen, J. G.; and Robinette, W. C.: Servo Control of Flutter. ASME/AIAA 10th Structures, Structural Dynamics, and Materials Conf., New Orleans, Louisiana, April 1969.

11. Thompson, G. O.; and Kass, G. J.: Active Flutter Suppression — An Emerging Technology. J. Aircraft, Vol. 9, No. 3, March 1972, pp. 230-235.

12. Rainey, A. Gerald; Ruhlin, Charles L.; and Sandford, Maynard C.: Active Control of Aeroelastic Response. Stability and Control, AGARD CP-119, 1972, pp. 16-1 — 16-5.

13. Topp, L. J.: Potential Performance Gains by Use of a Flutter Suppression System. Paper No. 7-B3, 1971 Joint Automatic Control Conference, St. Louis, Missouri, Aug. 1971.

14. Sevart, Frank D.: Analysis of Aeroelastic Model Stability Augmentation Systems. Doc. D3-8390-4, Boeing Co., Mar. 1971. (Available as NASA CR-132354.)

15. Nissim, E.: Flutter Suppression Using Active Controls Based on the Concept of Aerodynamic Energy. NASA TN D-6199, 1971.

16. Sevart, F. D.; Patel, S. M.; and Wattman, W. J.: Analysis and Testing of Stability Augmentation Systems — Final Report. Doc. D3-8884, Boeing Co., June 1972. (Available as NASA CR-132349.)

17. Triplett, William E.: A Feasibility Study of Active Wing/Store Flutter Control. J. Aircraft, Vol. 9, No. 6, June 1972, pp. 438-444.

18. Hodges, Garold E.: Active Flutter Suppression — B-52 Controls Configured Vehicle. AIAA Paper No. 73-322, Mar. 1973.

19. Noll, Thomas E.; and Felt, Larry R.: Active Flutter Suppression — A Practical Application. Proceedings of National Aerospace Electronics Conference 1973, IEEE, May 1973, pp. 329-334.

20. Lyons, M. G.; Vepa, R.; McIntosh, S. C., Jr.; and DeBra, D. B.: Control Law Synthesis and Sensor Design for Active Flutter Suppression. AIAA Paper No. 73-832, Aug. 1973.

21. Sevart, Francis D.; and Patel, Suresh M.: Analysis and Testing of Aeroelastic Model Stability Augmentation Systems — Final Report. Doc. D3-9245, Boeing Co., Oct. 1973. (Available as NASA CR-132345.)

22. Triplett, W. E.; Kappus, H. P. F.; and Landy, R. J.: Active Flutter Control — An Adaptable Application to Wing/Store Flutter. J. Aircraft, Vol. 10, No. 11, Nov. 1973, pp. 669-678.

23. Abel, Irving; and Sandford, Maynard C.: Status of Two Studies on Active Control of Aeroelastic Response. NASA TM X-2909, 1973.

24. Buchek, Philip M.: Modern Control Techniques in Active Flutter Suppression Using a Control Moment Gyro. SUDAAR No. 474, Stanford Univ., Mar. 1974. (Available as NASA CR-138494.)

25. Cwach, Emil; and Stearman, Ronald O.: Suppression of Flutter on Interfering Lifting Surfaces by the Use of Active Controls. AIAA Paper No. 74-404, April 1974.

26. Roger, Kenneth L.; Hodges, Garold E.; and Felt, Larry.: Active Flutter Suppression — A Flight Test Demonstration. AIAA Paper No. 74-402, April 1974.

27. Gregory, R. A.; Ryneveld, A. D.; and Imes, R. S.: A Low Speed Model Analysis and Demonstration of Active Control Systems for Rigid-Body and Flexible Mode Stability. Fed. Aviation Adm. Report FAA-SS-73-18, June 1974.

28. Redd, L. T.; Gilman, J., Jr.; Cooley, D. E.; and Sevart, F. D.: Wind-Tunnel Investigation of a B-52 Model Flutter Suppression System. J. Aircraft, Vol. 11, No. 11, Nov. 1974, pp. 659-663.

29. Nissim, E.: Flutter Suppression and Gust Alleviation Using Active Controls. TAE Rep. No. 198, Technion-Israle Inst. Technol., 1974. (Available as NASA CR-138658.)

30. Turner, M. R.: Active Flutter Suppression. AGARD CP-175, April 1975, pp. 2-1 — 2-14.

31. Thompson, G. O.; and Sevart, F. D.: Wind Tunnel Investigation of Control Configured Vehicle Systems. Flutter Suppression and Structural Load Alleviation, AGARD CP-175, April 1975, pp. 4-1 — 4-8.

32. Destuynader, Roger: Essai en Soufflerie d'un Suppresseur de Flottement sur une Aile Droite Flutter Suppression and Structural Load Alleviation. AGARD CP-175, April 1975, pp. 6-1 — 6-3.

33. Nissim, E.: Active Flutter Suppression Using Trailing-Edge and Tab Control Surfaces. AIAA Paper No. 75-822, May 1975.

34. Roger, Kenneth L.; Hodges, Garold, E.; and Felt, Larry: Active Flutter Suppression — A Flight Test Demonstration. J. of Aircraft, Vol. 12, No. , June 1975, pp. 551-556.

35. Sandford, Maynard C.; Abel, Irving; and Gray, David L.: Development and Demonstration of a Flutter-Suppression System Using Active Controls. NASA TR-450, 1975.

36. Noll, R. B.; and Marino, L.: Flutter and Gust Response Analysis of Flexible Aircraft With Active Control. Proceedings of AIAA/ASME/SAE 17th Structures, Structural Dynamics, and Materials Conference, King of Prussia, Pennsylvania, May 5-7, 1976, pp. 389-397.

37. Doggett, Robert V., Jr.; Abel, Irving; and Ruhlin, Charles L.: Some Experiences Using Wind-Tunnel Models in Active Control Studies. Advanced Control Technology and Its Potential for Future Transport Aircraft. NASA TM X-3409, Aug. 1976, pp. 831-892.

38. Arnold, James I.; and Murphy, Frank B.: B-52 Control Configured Vehicles: Flight Test Results. Advanced Control Technology and Its Potential for Future Transport Aircraft. NASA TM X-3409, Aug. 1976, pp. 75-89.

39. Nissim, E.; Caspi, A.; and Lottati, I.: Application of the Aerodynamic Energy Concept to Flutter Suppression and Gust Alleviation by Use of Active Controls. NASA TN D-8212, 1976.

40. Johannes, R. P.: Active Flutter Control — Flight Test System Synthesis. Paper No. 7-B1, 1971 Joint Automatic Control Conference, St. Louis, Missouri, Aug. 1971.

41. Hood, R. V.: A Summary of the Application of Active Controls Technology in the ATT System Studies. Advanced Control Technology and Its Potential for Future Transport Aircraft. NASA TM X-3409, Aug. 1976, pp. 603-637.

42. Pratt, Kermit G.: A Survey of Active Controls Benefits to Supersonic Transports. Advanced Control Technology and Its Potential for Future Transport Aircraft. NASA TM X-3409, Aug. 1976, pp. 639-659.

43. Hoffman, Sherwood: Supersonic Cruise Aircraft Research (SCAR) Program Bibliography. NASA TM X-73950, 1976.

44. Woodward, Frank A.: Analysis and Design of Wing-Body Combinations at Subsonic and Supersonic Speeds. J. Aircraft, Vol. 5, No. 6, Nov.-Dec. 1968, pp. 528-534.

45. Albano, E.; and Rodden, W. P.: A Doublet-Lattice Method for Calculating Lift Distributions on Oscillating Surfaces in Subsonic Flows. AIAA Journal, Vol. 7, No. 2, Feb. 1969, pp. 279-285. (Errata, Vol. 7, No. 11, Nov. 1969, p. 2192.)

46. Fuel Conservation Possibilities for Terminal Area Compatible Aircraft. (Boeing Commercial Airplane Company; NASA Contract NAS1-12018), NASA CR-132608, 1975.

TABLE I.- SOME CHARACTERISTICS OF ARROW-WING CONFIGURATION

CRUISE MACH NUMBER	2.7
NUMBER OF CREW MEMBERS	3
NUMBER OF ENGINES	4
THRUST PER ENGINE	235 756 N (53 000 lbf)
MAXIMUM TAKEOFF GROSS WEIGHT	339 287 kg (748 000 lbm)
NUMBER OF FIRST CLASS SEATS	0
NUMBER OF TOURIST SEATS	234
PAYLOAD	22 226 kg (49 000 lbm)
MAXIMUM LANDING WEIGHT	217 724 kg (480 000 lbm)
AIRFRAME STRUCTURAL WEIGHT	
PASSIVE SYSTEM AIRPLANE	101 605 kg (224 000 lbm)
ACTIVE SYSTEM AIRPLANE	97 454 kg (214 850 lbm)
DIFFERENCE	4 151 kg (9 150 lbm)

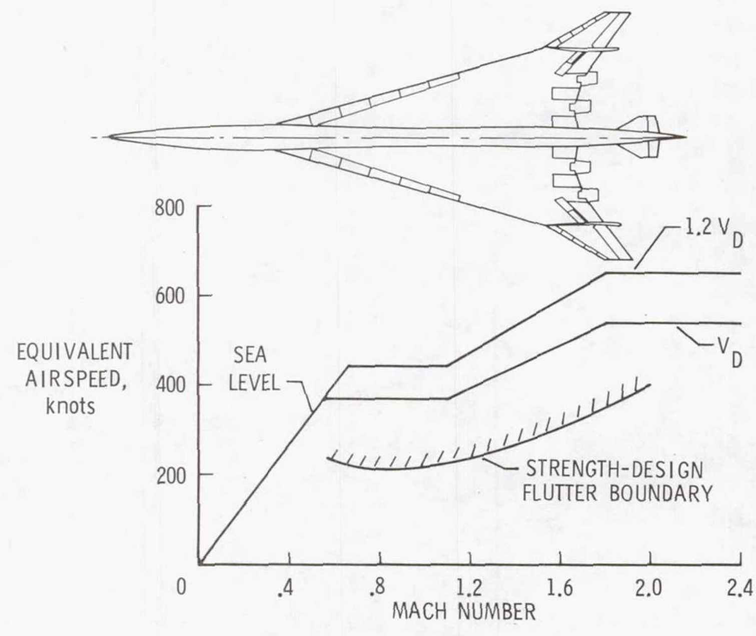

Figure 1.- Strength-design national configuration flutter boundary.

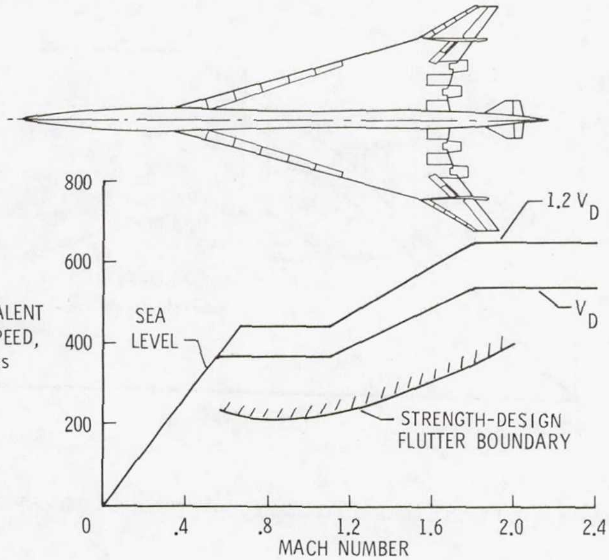

Figure 2.- Strength-design arrow-wing flutter boundary.

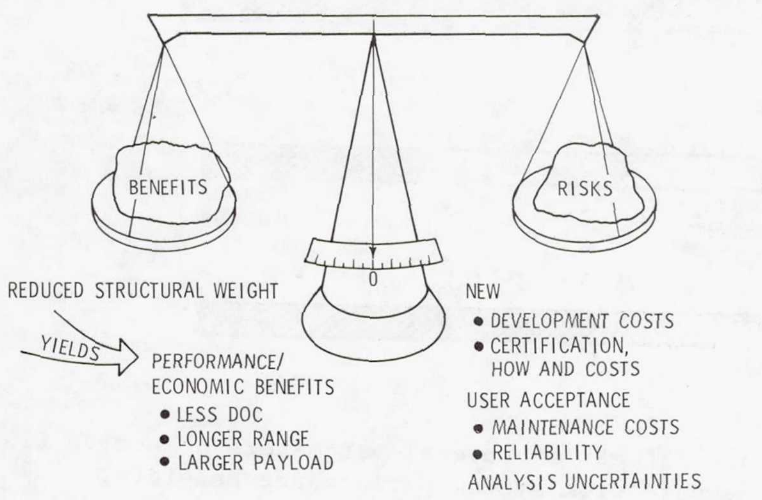

Figure 3.- Benefits and risks of active flutter suppression.

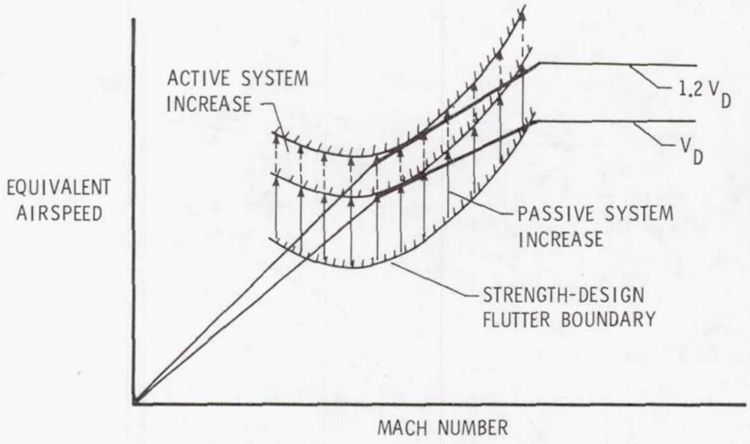

Figure 4.- Limited application flutter suppression system concept.

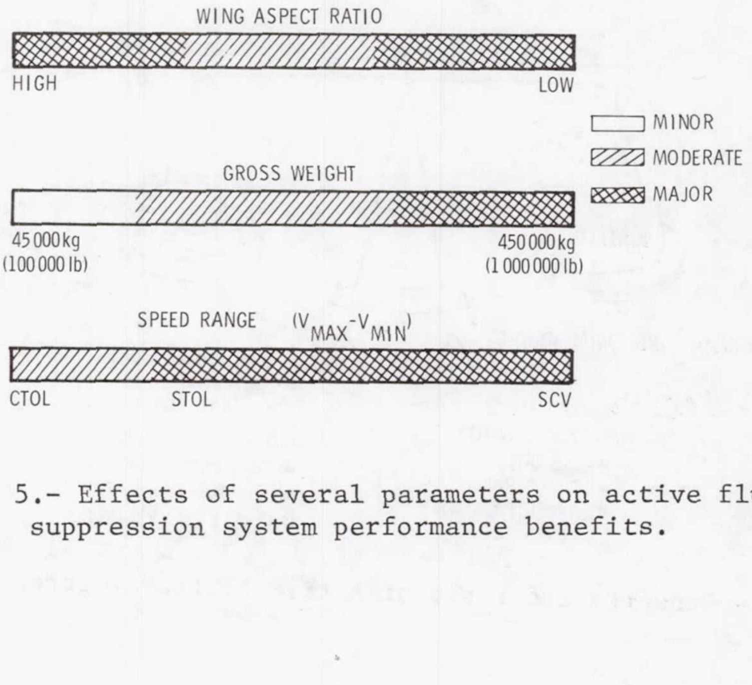

Figure 5.- Effects of several parameters on active flutter suppression system performance benefits.

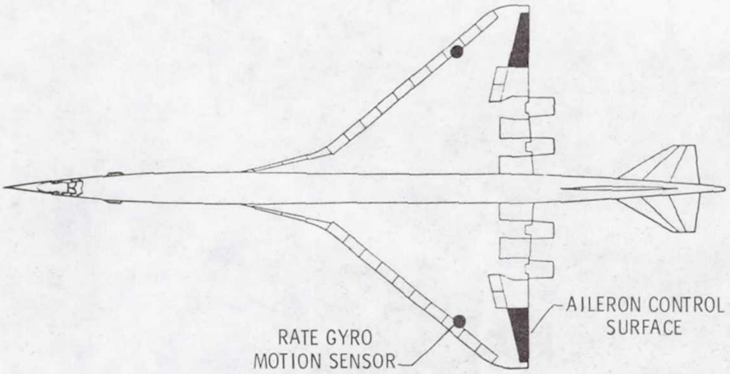

Figure 6.- National configuration active flutter suppression system.

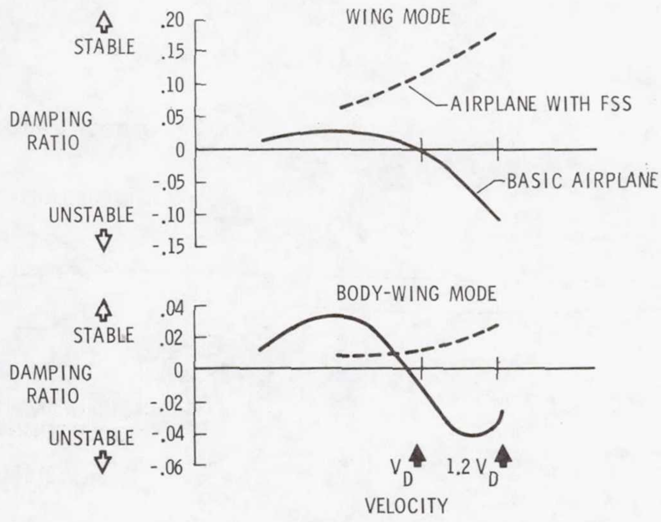

Figure 7.- Calculated active flutter suppression system results for national configuration (M = 0.90).

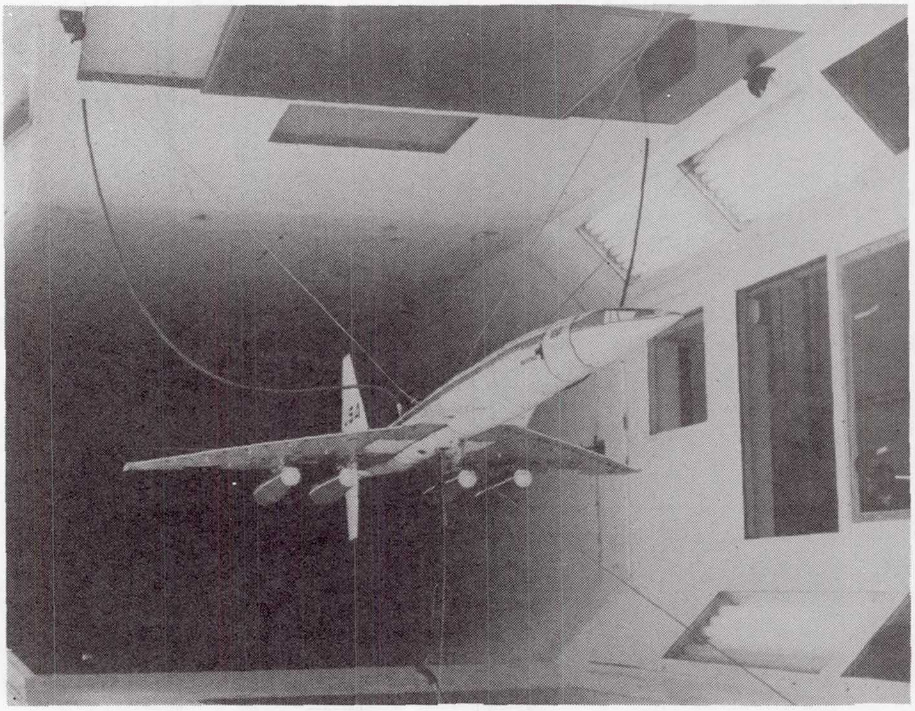

Figure 8.- Low-speed active flutter suppression model mounted in wind tunnel.

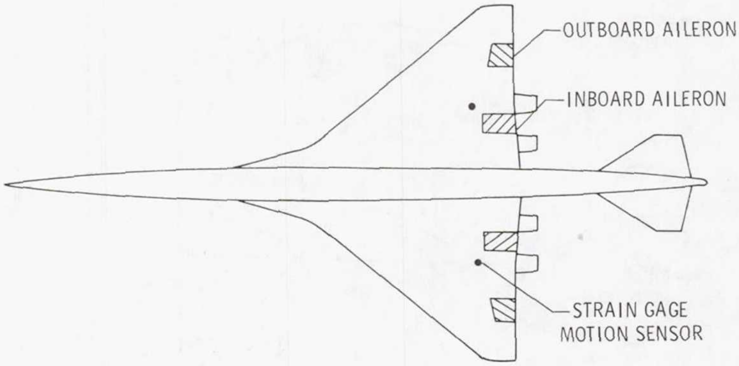

Figure 9.- Low-speed model active flutter suppression systems.

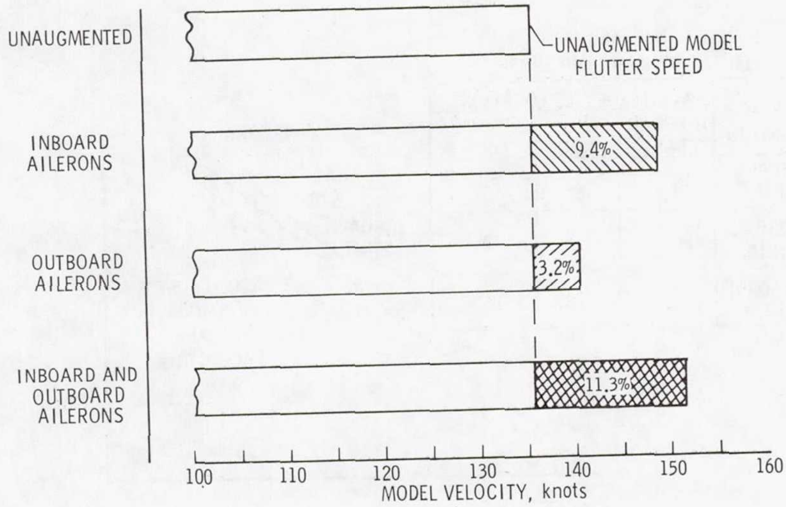

Figure 10.- Experimental results for low-speed active flutter suppression model.

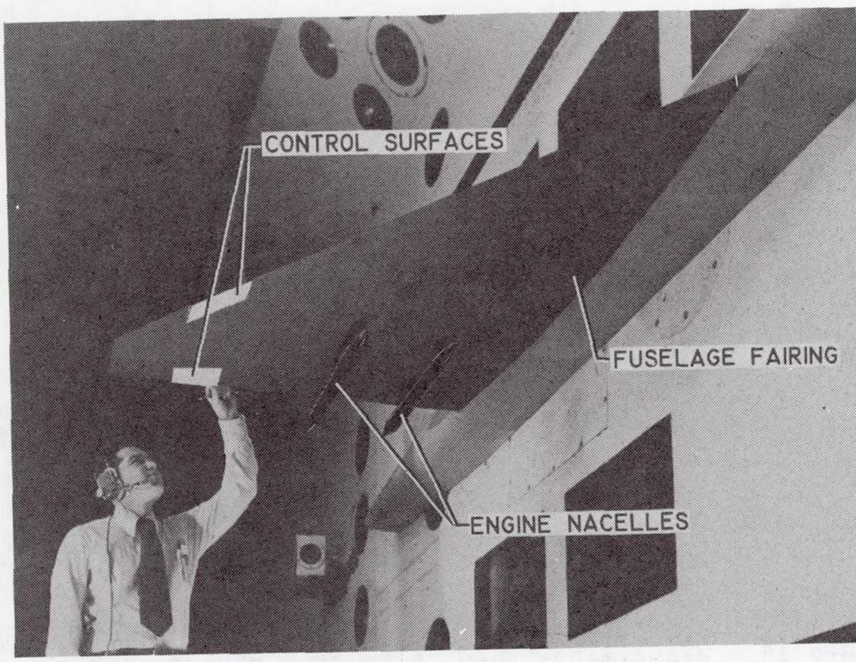

Figure 11.- Delta-wing active flutter suppression model mounted in wind tunnel.

PERCENT INCREASE IN FLUTTER DYNAMIC PRESSURE

SURFACE LOCATION	ACCELEROMETER LOCATION		
	INBOARD EDGE	CENTER LINE	OUTBOARD EDGE
INBOARD STRIP	18	22	21
MIDSPAN STRIP	26	17	8
OUTBOARD STRIP	6	25	36

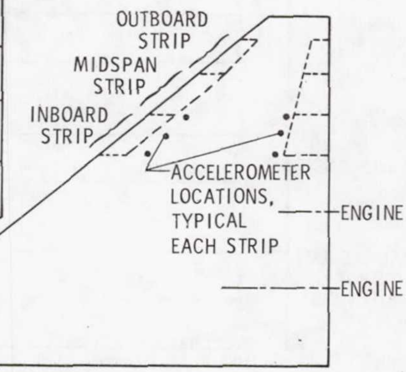

Figure 12.- Calculated effects of control surface and accelerometer locations on delta-wing model flutter dynamic pressure.

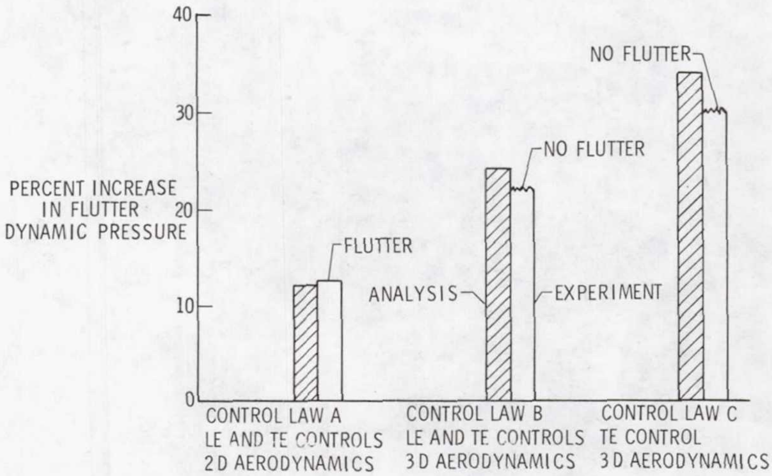

Figure 13.- Experimental and calculated active flutter suppression results for delta-wing model (M = 0.90).

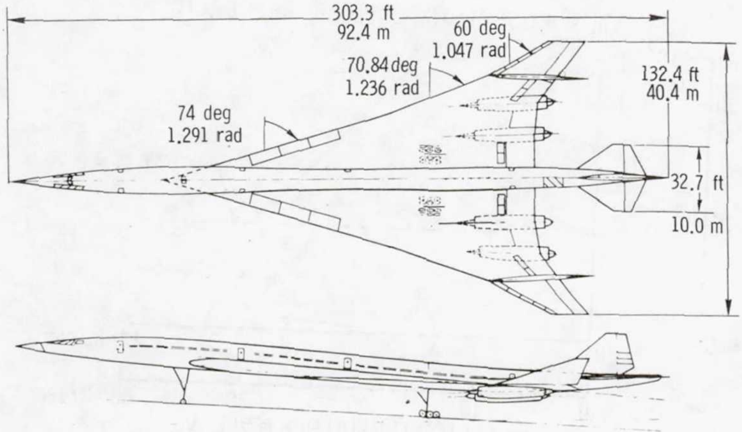

Figure 14.- Arrow-wing configuration.

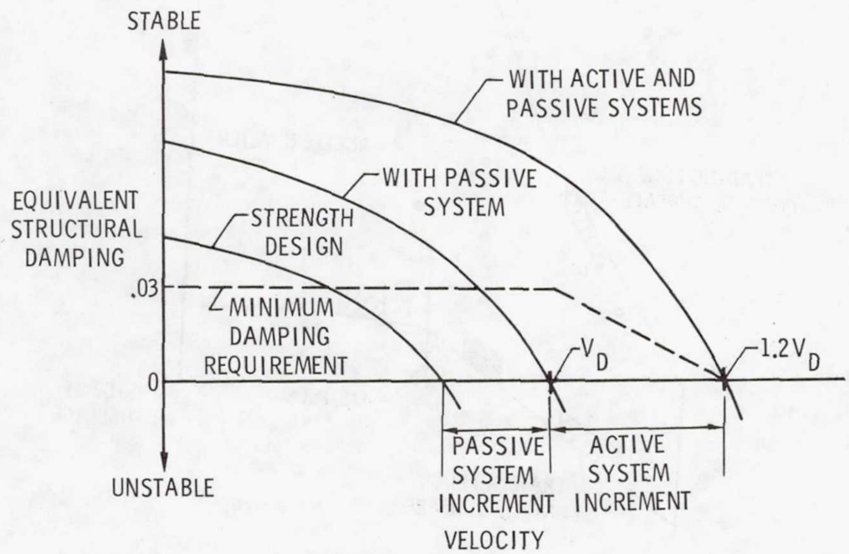

Figure 15.- Flutter design criteria for arrow-wing active flutter suppression system.

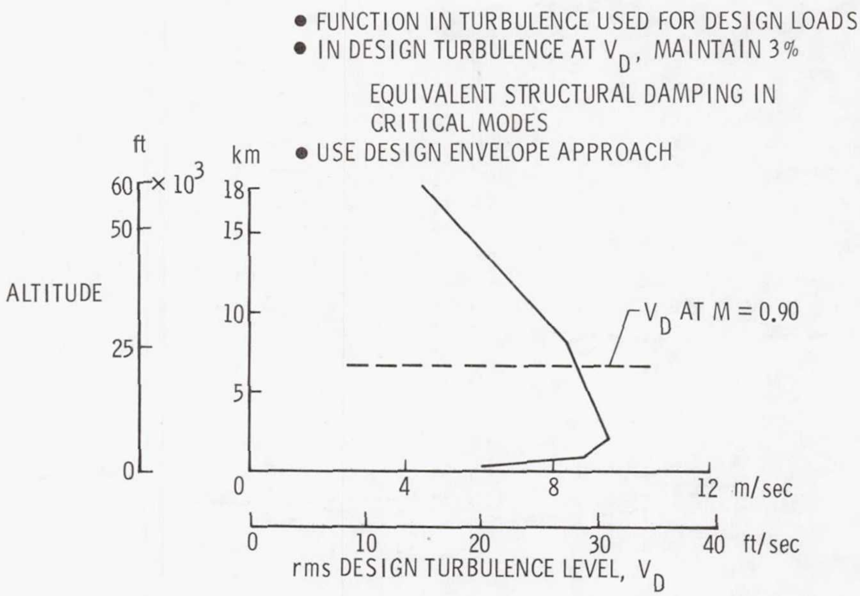

Figure 16.- Turbulence design criteria for arrow-wing active flutter suppression system.

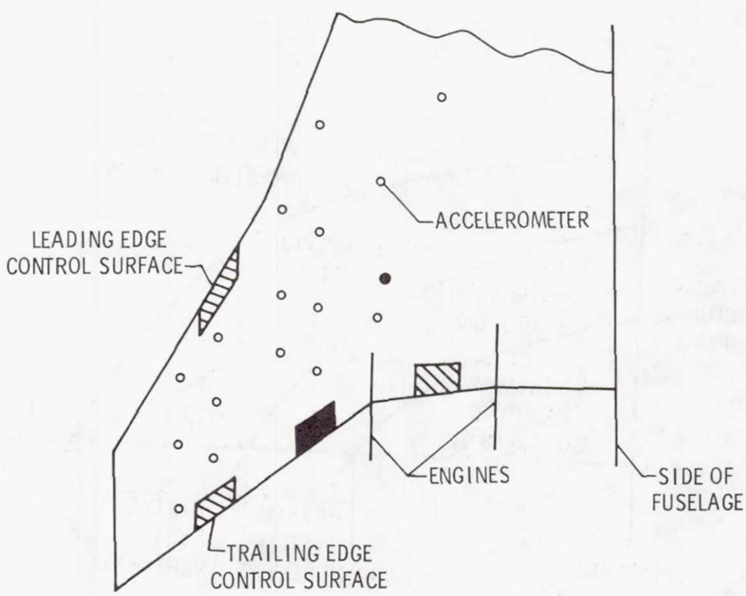

Figure 17.- Control surface and accelerometer locations surveyed during synthesis of arrow-wing active flutter suppression system.

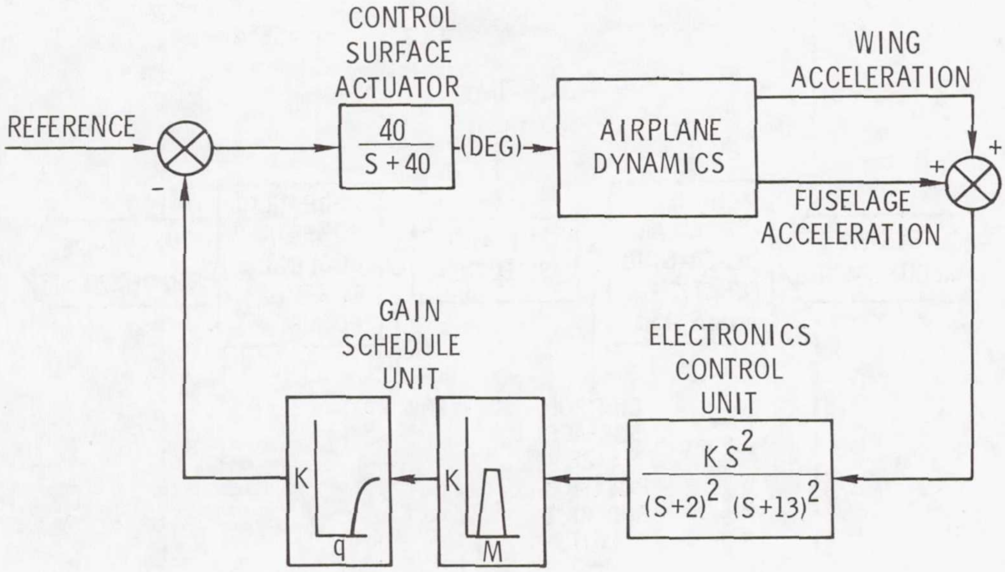

Figure 18.- Block diagram of arrow-wing active flutter suppression system. K denotes gain and S is the Laplace variable.

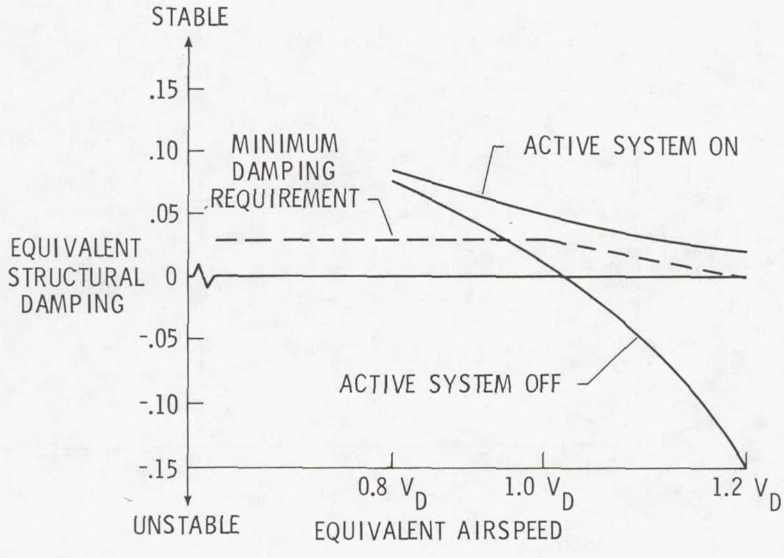

Figure 19.- Calculated variation of damping in critical flutter mode with equivalent airspeed for arrow-wing flutter suppression system on and off (M = 0.90).

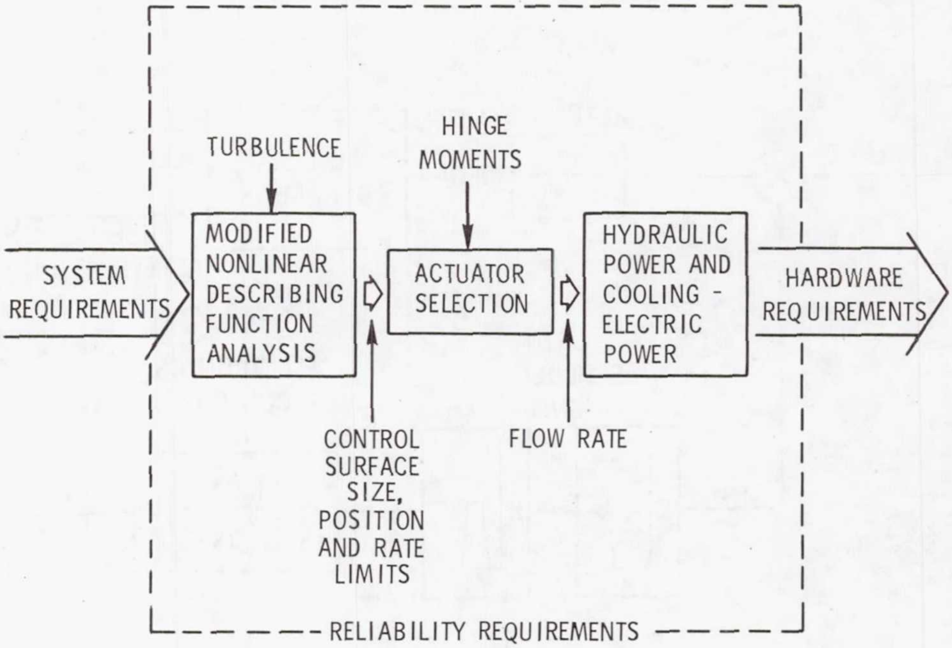

Figure 20.- Mechanization of arrow-wing active flutter suppression system.

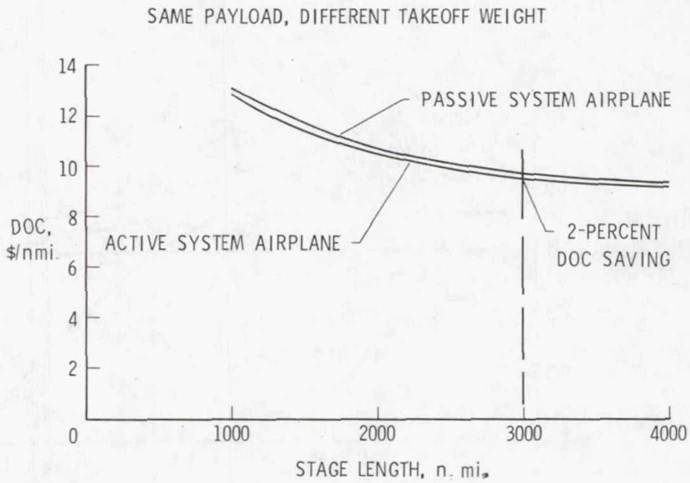

Figure 21.- Variation of direct operating costs (DOC) with stage length for active system airplane and passive system airplane.

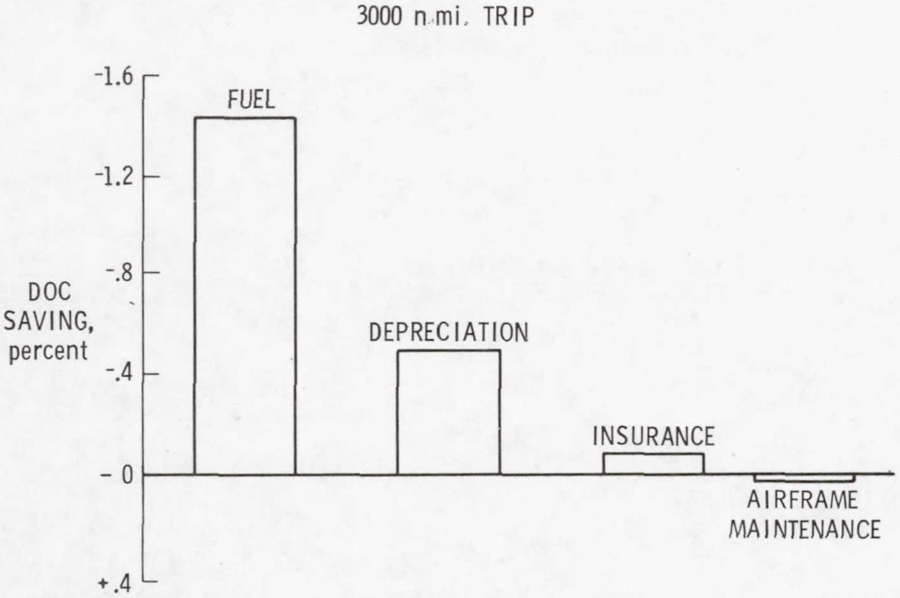

Figure 22.- Contributions of fuel, depreciation, insurance, and airframe maintenance costs to change in direct operating costs (DOC).