ACTIVE CONTROLS TECHNOLOGY TO MAXIMIZE STRUCTURAL EFFICIENCY

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ABSTRACT

This paper discusses two programs, being conducted by The Boeing Company, that consider the implication of the dependence on Active Controls Technology (ACT) during the design phase of transport structure: 1) Drones for Aerodynamic and Structural Testing (DAST), and 2) Maximum Benefit of Active Controls Technology (Max Benefit). The purposes of the two programs are compared and then certain aspects of the structural analysis that will be performed on the Max Benefit program are discussed in detail. Critical loading conditions are discussed along with probable ways of alleviating these loads. The paper presents explanations of why fatigue requirements may be critical and can only be partially alleviated. Finally, the significance of certain flutter suppression system criteria are examined.

INTRODUCTION

Although active control technology (ACT) advancements have been increasingly applied to military aircraft, they have not enjoyed the same degree of acceptance in the commercial arena. When they have been applied to commercial transports their use has been limited, usually because of: 1) The need to overcome a problem on a design that has been committed, or 2) The desire to improve an existing transport in the form of a minor model change or a derivative. In both cases the designer and configurator have been constrained by the necessity to make no, or at best, very little, change to the "as-tooled" structure. Reduced structural weight and/or the ability to apply features that would improve aerodynamic performance (i.e., high aspect ratio, engine placement, wing sweep. etc.) with minimum structural weight penalty are the areas of payoff for ACT. Therefore, their full potential has not been exploited. In fact, it seems that a comprehensive evaluation of ACT, when applied during the preliminary design of a commercial transport, has not been completed in an atmosphere that recognizes the effect of Federal Airworthiness Regulations (FAR). Further there are no acceptable operational standards and no detailed examination of the effect of ACT on structural and flight control system design and configuration effects.

Full exploitation of ACT could offer new degrees of freedom for the structural designer, aerodynamist, and configurator. At the same time, the burden of proof will be on the flight control system designer, because his systems will have to perform to reliability standards approaching those of the structure. The cost of owning these systems must be held in check to preserve economic benefits achieved by lower structural weight and high performance. A much greater degree of design team coordination will be needed to achieve the potential.

Two contracts being performed by Boeing under the Energy Efficient Transport (EET) portion of the NASA Aircraft Energy Efficiency (ACEE) program offer the potential for conducting the detailed examination lacking to date. This paper is limited to the structural investigations involved in those two contracts.

DAST

The feasibility of active controls to improve stability and control, flutter, and ride comfort and to reduce structural loads has been demonstrated in flight as described in references 1 through 5. The next logical step is to integrate active controls into the airplane design cycle. To assist in this step, an integrated wing design with active controls is currently being accomplished by NASA under a contract with the Boeing Wichita Company. The program is designated DAST (Drones for Aerodynamic and Structural Testing) and evaluates an integrated design of a high aspect ratio wing with active controls on a Firebee II drone vehicle. The second advanced research wing (ARW-2) being designed under this program has a supercritical airfoil with an aspect ratio of 10.3.

The primary objectives are to develop the interdisciplinary methodologies required to accomplish an integrated ACT design and to apply these methodologies to the design of a wing maximizing structural efficiency. The DAST vehicle will depend on active controls for maneuver load alleviation, gust load alleviation, and flutter mode suppression. The program will have significant value to the aircraft industry which is just starting to apply some of these advanced control concepts to commercial transports. Further benefits will come when DAST is flown and when flight-measured loads and flutter are correlated with those predicted.

INTEGRATED ACT AIRPLANE DESIGN

The typical conventional aircraft design process is shown in figure 1. Even though the figure reflects active control synthesis for structure or stability and control augmentation, it should be emphasized that in this conventional design process such control functions do not significantly impact the configuration. The first step in developing a new airplane configuration is to establish mission requirements, i.e., payload, range, speed, and takeoff and landing distances. Propulsion, aerodynamics, structures, and weight technologies are then combined to obtain a configuration that meets the mission requirements. Its performance is assessed and the process is iterated until the vehicle meets all of the specified mission performance requirements and satisfies the minimum weight, minimum cost, and other specified criteria.

There are examples of conventional configurations that include modest active control functions, e.g., yaw dampers, ride improvement augmentation, or in the case of the C-5, an airload distribution control system. These active control designs began when the configuration was defined or, in some instances, after the airplane had been built and entered service. With this approach, the active control systems are used to augment the airplane dynamics or extend the airplane's life by minimizing structural fatigue damage, rather than to meet mission performance requirements with a more efficient airplane. If active control technology is not considered from the very outset of the configuration cycle, its full benefit will not be realized. In contrast to the conventional design, the integrated active control design approach capitalizes on the potential of integrating ACT concepts during configuration definition trade studies. With this approach, active controls are included in the design on an equal basis with other major technologies of propulsion, aerodynamics, and structures.

DAST INTEGRATED ACT DESIGN

The integrated DAST design approach emphasizes the structural dynamic benefits of active control and considers only secondarily stability and control benefits. Most aerodynamic parameters were specified and were not optimized as a part of the integrated design process. Table I compares the aerodynamic design parameters that are normally fixed and variable for a conventional transport and the DAST ARW-2 wing. Also, relaxed static stability is being used to minimize trim drag but the horizontal stabilizer and empennage structure are not being optimized.

The DAST integrated design process is similar to the transport design process except the propulsion, fuselage, empennage, and most of the wing parameters were constrained and not allowed to change during the design cycle. Figure 2 shows this design cycle. There are several parameters that are unique to the DAST, as compared to a typical fuel conservative transport. They include wing material, flutter within the flight envelope required, limited amount of power to drive control surfaces, and c.g. control (ballast) used to achieve minimum trim drag.

Structural material selected for the wing was aluminum spar with fiberglass honeycomb skins. The mixed material, selected to provide transport similarity within the drone minimum gage constraints, caused problems in using standard preliminary sizing for steady-state loads and weights. Electrical power to drive the control surfaces was a constraint for the DAST program for which a cost-effectiveness study would be conducted on a transport. To achieve minimum trim drag, wing location and ballast were iterated, as opposed to optimizing the empennage structure and surface sizes.

Several aeroelastic requirements also affected the DAST design. The DAST ARW-2 wing was designed to have a ratio of aerodynamic forces to elastic forces in the same range as a full-scale fuel-conservative transport. The goal was to have the outboard ailerons used for active controls exhibit a loss of effectiveness with increasing dynamic pressure. The primary method used to meet the ratio of force requirement was to iterate structural stiffness properties through spar spacing and material stiffness. Flutter occurs within the flight envelope without adverse ballasting so the final DAST configuration is similar in flutter to a fuel-conservative transport.

Once the aeroelastic characteristics are satisfied, the active control system synthesis is initiated. Maneuver and gust requirements are imposed at this point in the design cycle. This differs from the conventional design, where the maneuver and gust effects are determined by the aeroelastic analysis. Gust load alleviation, maneuver load alleviation, and flutter suppression concepts are defined and performance is compared to the design gust, maneuver, and flutter requirements. If these requirements are not met with the initial configuration, revisions are made in control surface size, location, or design loads and a second iteration is initiated. This iterative process is repeated until the design loads and flutter requirements are met and the active control system design requirements are determined to be achievable.

ACT DESIGN CYCLE CHARACTERISTICS

Some major characteristics of the integrated ACT design cycle are as follows:

- A single data base is needed for synthesizing active control functions and predicting ACT benefits such as flutter, loads, and stability and control.
- Active control systems are added to the design cycle on an equal basis with propulsion, aerodynamics, and structures.
- The control system synthesis and analyses must produce the aircraft design loads, flutter, and stability and control characteristics.
- After the active control system is integrated with the aeroelastic model, conventional analysis methods may be used.

The need for a single data base and compatible airplane math models for analysis of stability and control, flutter, structural integrity and ride comfort has been heightened by three factors: the ability to improve performance in each of these areas with active control systems, interaction between ACT functions, and the lack of frequency separation in large airplanes between these areas of concern. This also means that the various performance parameters must be monitored to prevent inadvertent degradation. For the conventional design, these analyses are generally conducted independently, using different data bases and math models. Because of the interaction between ACT functions, the final performance evaluation needs to be with all functions operating simultaneouly even though the synthesis may be accomplished independently.

As shown in figure 2, active control systems are added to the design cycle on an equal basis with propulsion, aerodynamics, and structural dynamics. This approach maximizes the effect of active control technology on the structural design.

MATH MODELS AND ACT DESIGN TECHNIQUES

The math models used for active control system synthesis and analysis must be capable of producing the aircraft design loads, flutter, and stability and control characteristics. It is therefore logical and expedient that the control analyst use the same math model as the loads and flutter analyst. Since the controls engineer normally synthesizes active control systems in the S-plane, it is necessary to formulate the airplane equation in the S-plane.

Selected analytical methods described in reference 6 are useful in aircraft modeling and active control system design. One of the modeling techniques that provides a means of formulating the equations of motion in the S-plane is summarized below.

Unsteady aerodynamic forces acting on the DAST vehicle were computed using numerical methods to satisfy lifting surface theory. The interfacing of the point frequency unsteady aerodynamic coefficients with Laplace transform equations of motion was done with the use of approximating functions. Figure 3 shows a typical aerodynamic coefficient, plotted as s moves up the imaginary axis, and the "best fit" approximating function. The approximating function chosen was a rational polynominal with denominator roots on the left real axis. It can be considered to be a physically reliable frequency interpolating function for the unsteady aerodynamic coefficients. A function was found for each element in the aerodynamic influence matrix. The resulting functions were generalized and included as part of the equations of motion, raising the order of the differential equations once for each denominator root, typically between two and four.

The useful (accurate) range for Laplace arguments is not obvious, although analytic continuity suggests that leaving the imaginary axis (small positive or negative damping) is comparable to interpolating along the imaginary axis. The region near the imaginary axis is of greatest physical interest.

The success of the integrated design process discussed in previous paragraphs is ultimately dependent on the successful synthesis of active control systems. Active control system synthesis is generally accomplished for each function (i.e., flutter suppression, gust load alleviation, maneuver load alleviation, etc.) separately to meet performance requirements. Then the analysis is expanded to evaluate compatibility of the combined functions. System parameters are adjusted, if required, to meet the performance of the individual systems. This cycle is repeated until a system definition that meets the criteria is achieved.

There are some advantages to synthesizing each ACT function to operate independently with the minimum interaction between functions. This approach will produce a less complex system and fewer parameters will require changes as various systems are engaged. A major advantage of independent operation of each function is that redundancy can be made appropriate for each function. Otherwise redundancy of the entire active control system needs to meet the requirements of that function which has the most severe redundancy requirement.

The integrated ACT airplane design requires an interdiscipline of the various technologies of aerodynamics, structural dynamics, and control dynamics. Figure 4 shows the integration of technologies and analysis programs necessary for active control synthesis.

Flexible airframe equations of motion are generated from the vehicle mass, stiffness, and aerodynamic data. The structural coordinates and mode shapes are obtained from the vibration analysis. The equations are formulated in the Laplace domain to be compatible with the standard S-plane control synthesis techniques. Active control system synthesis is accomplished in the S-plane and uses the linear analysis programs shown in figure 4. The three-dimensional gust load analysis is conducted in the frequency domain because it is more efficient. A simulation is used to evaluate flying qualities, nonlinear effects, and failure effects in support of the ACT synthesis. The ACT synthesis cycle is iterated until a system that maximizes structural benefits is obtained. After the ACT system has been defined, the final step is to evaluate performance and define the design requirements.

ACT BENEFITS FOR DAST

High aspect ratio wing designs show potential for improved fuel efficiency through increased lift-to-drag (L/D) ratios. This is achieved by reducing sweep and/or increasing thickness ratio at the cruise Mach number by use of supercritical airfoils and by reducing induced drag by increasing the aspect ratio. However, these benefits are not easily achieved without increasing wing structural weight. Weight penalties come from additional strength necessary to accommodate larger wing design loads due to increases in span and wing lift curve slope. Penalties also come from increased wing stiffness needed to prevent flutter. Integration of maneuver load alleviation (MLA), gust load alleviation (GLA) and flutter suppression system (FSS) active control concepts into such a wing design offers the potential for maximizing the L/D benefits of the high aspect ratio supercritical wing while minimizing structural weight penalties.

The fuel efficient DAST ARW-2 wing, shown in figure 5, was designed to meet the aerodynamic parameters specified in table I by NASA while using active controls to maximize structural efficiency. The wing has a gross area of 3.25 m^2 (35 ft^2) and a span of 5.79 meters (19 feet). A wingtip control surface is used to suppress flutter while this surface is combined with an inboard control surface for maneuver load alleviation. Gust load alleviation utilizes a surface slightly inboard of the wing midspan as illustrated in figure 5.

The wing vertical bending design loads for gust and maneuver are presented in figure 6. The wing maneuver loads are slightly higher than gust loads without active load alleviation. With MLA and GLA the wing is still maneuver load critical except at the tip where it is slightly gust load critical. The combined effect of maneuver and gust load alleviation brings a reduction in DAST ARW-2 loads of approximately 20 percent. As shown in figure 7 the DAST ARW-2 flutter boundary is approximately 17 percent below the design speed (V_D) for a typical transport. Therefore, the flutter suppression system is required to increase the flutter speed (V_f) approximately 40 percent to meet $1.2V_D$. Initial flutter evaluation with active controls indicates that this amount of improvement in flutter is feasible. If it were not, the structural design would be iterated at increased weight penalty to suppress flutter.

In a transport design where safety is more of a concern, new criteria must be developed to define minimum allowable flutter speed with the flutter suppression system off as well as the usual $1.2V_D$ with the system on. More will be said about this in the last section of this paper.

MAXIMUM BENEFIT OF ACTIVE CONTROLS TECHNOLOGY

Two objectives of the Max Benefit program are to produce a credible assessment of the benefit of ACT on an advanced subsonic commercial transport with ACT integrated into the design process, and to identify technical risk areas and necessary development and test work. The development and test work are needed for reduction of the ACT implementation risks that are excessive by the standards of current commercial practice. The term "benefit of ACT", as used in this program, is a measure of the improvement of airplane fuel use and operational economics.

This program, which has just begun at the Boeing Commercial Airplane Company, is illustrated in figure 8. The major elements of the program are the design of the configuration and ACT system, examination of advanced technology and its application to the synthesis and implementation of the ACT function, and the test and evaluation of the "high risk" elements of a commercially feasible ACT system. The element most significant to this paper is the configuration/ACT system design task.

Figure 9 shows the more significant parts of the configuration task. Since the objective is to identify the benefit due to ACT, the program begins with the selection of a modern conventional (non-ACT) commercial transport and proceeds to design an ACT transport with the same operational characteristics, i.e., passenger/cargo payload, design range, cruise Mach number, etc. The ACT transport is then compared to the conventional transport in terms of fuel use and operational economics.

The credibility of the comparison will depend upon the validity or reality of the reference conventional airplane and the detail and care with which the design and analysis proceed.

The program could be referenced to an existing, in-service, commercial transport; however, it might be argued that any benefit subsequently identified was the result of an outdated reference, i.e., starting point. Therefore, the reference airplane is being selected from recent preliminary designs that incorporate certain technical advances (e.g., advanced airfoil design) but are still conventional with respect to ACT. All technologies (e.g., conventional aluminum skin/stringer structure) will remain fixed throughout the study except as required to incorporate ACT.

A number of configurations will be designed and evaluated. They include synthesis of the appropriate ACT control functions, in the second element of this task, in order to determine how this additional degree of freedom can best be used. The incorporation of ACT in the design process is expected to free the airplane design from a number of constraints that yield the current commercial transport configurations. Changing these constraints will very likely lead to higher aspect ratio wings without the structural penalties that would accompany such design without ACT. Identifying these effects will require careful determination of the airplane structure, weight, and resulting performance. These trades will be used to select a final ACT configuration which will be designed to meet the same mission as the reference conventional airplane. The same mission means that not only the payload (passenger and cargo)/range will be the same, but in addition, the airplane will be designed to operate out of the same length field, with the same noise characteristics, etc.

A very significant aspect of the inclusion of ACT in the design of a commercial transport is the required system reliability, from both a safety and dispatch point of view. In parallel with the configuration trade studies, a series of trades designed to identify the best way to implement the ACT functions will be pursued to identify the definition of the ACT control system that provides those functions necessary for the final ACT configuration.The results of these tasks will then be evaluated from the perspective of fuel requirements and cost of operation. The assessment of the benefits associated with this ACT design will be "strictly" limited to the mission of the reference airplane, but will certainly be indicative of that to be expected on similar design missions. Fully expecting positive results, the work is currently planned to proceed into a test and evaluation phase, which is designed to reduce the risk to a commercially acceptable level. Figure 10 is an illustration of the type of configuration that could result from this study. The principal differences are a higher aspect ratio, a smaller and lighter wing, and a smaller tail.

MAX BENEFITS-STRUCTURAL EVALUATION PLAN

The initial step in this study will reconfigure the reference airplane with reduced longitudinal stability requirements. This will result in a smaller horizontal tail and reduced tail loads. The structural weight saved by this change in empennage and fuselage will be accounted for by conventional loads and weight analysis methods. Subsequent steps will involve changing wing parameters which will result in small, if any, further changes to tail size or loads. For these reasons the major structural analysis effort will be on the wing structure. The following discussions apply to wing only.

Figure 11 shows the structural evaluation procedure. All of the structural analyses start with a math model. These models will be developed jointly by the structure and flight controls engineers. The first and simplest model is the static model which will include aeroelastic effects but no airplane pitch or translations. This model will produce good "steady-state" loads such as maneuver and preliminary gust loads. It will also be possible to use it for a preliminary assessment of fatigue criticality.

The static model will then be upgraded to a quasi-static model by the inclusion of the pitch and vertical translation degrees of freedom and must include the longitudinal control system laws. With this model much better dynamic gust loads will be obtained to be used for both design and fatigue analysis.

Finally the full dynamic model will be developed from the quasi-static model which will include all of the required structural degrees of freedom and final controls laws. This model will be used to determine the final gust loads and it will become the basis of the flutter analysis.

The final output of these analyses will be the structural weight that is required for evaluation of the configuration being studied.

GUST AND MANEUVER DESIGN CONSIDERATIONS

The primary structure design load requirements provide the basis for applying active controls technology for load alleviation. A major portion of a transport airplane wing structure is usually designed by symmetrical balanced maneuvers and gusts. The relative criticality of these two design conditions will influence the choice of load alleviation controls, transducers, and system mechanization. Their relative criticality also depends on the configuration characteristics and the mission requirements. Figure 12 compares maneuver and gust sensitivities as a function of wing loading and airplane lift curve slope. For reference, early versions of the 727 and 747 airplanes are shown on the plot. A high wing loading and low lift curve slope leads to a maneuver-critical airplane. Low wing loading and high lift curve slope leads to a gust-critical airplane.

The lift curve slope is dependent upon Mach number, airfoil type, aspect ratio, and sweep, as shown in figure 13. The comparison between the conventional airfoil and the advanced airfoil is made for wings having the same critical Mach number. This means that the wing with the advanced airfoil can have about 3 degrees less sweep than the wing with the conventional airfoil.

A new airplane configured to take advantage of load alleviation (figure 10) will probably have an advanced airfoil. It will probably have a higher aspect ratio and lower sweep angle relative to current airplanes. The probable range of these parameters is shown by the cross-hatched area of figure 13. These changes will lead to an airplane that is significantly more gust critical than current airplanes, as shown by the cross-hatched area of figure 12. The likely result is that gust load alleviation will have greater benefit than maneuver load alleviation.

A maneuver load alleviation system redistributes the wing lift inboard to reduce the bending moments as shown on the left side of figure 14. One method of achieving this is by deflecting an outboard control surface to reduce the lift outboard. Outboard control surfaces tend to lose their effectiveness as dynamic pressure increases.

Elastic wing twist caused by torque due to control surface deflection results in a redistribution of the wing lift. This change in wing lift counteracts the desired change due to the control surface. Loss of control surface effectiveness is aggravated by increases in either aspect ratio or sweep angle.

Design maneuvers tend to be critical at V_A, the speed at which C_{LMAX} is required to achieve a 2.5g maneuver. At higher speeds, the loads due to the 2.5g maneuver are less, because of aeroelastic washout. Thus, an outboard aileron may have considerable effectiveness at V_A, where it is needed, much less effectiveness at maximum operating speed (V_{MO}) and yet be an efficient maneuver load alleviation device. For configurations with reduced sweep angle 2.5g maneuvers tend to become more critical at V_{MO}, however the outboard control surface also will become more effective so that the same trend will be true.

The loads due to a design gust are unlike maneuver loads in that they increase with speed and are usually critical at V_{MO}. Thus, the same outboard aileron that was effective as a maneuver load alleviation device may be ineffective as a gust load alleviation device.

As shown on the right side of figure 14, the gust load alleviation systems should reduce total load on the wing by dumping lift through some device, such as a mid-span aileron, that is effective at high speed. The system should also pitch the airplane into the gust by the augmented longitudinal stability system. Determination of gust loads on an airplane with such a system operation can be accomplished only by use of the quasi-static or dynamic math models previously described.

DISCUSSION OF FATIGUE EVALUATION

Fatigue cracking is a very slow process and, therefore, it is considered to be an economic rather than a safety problem. For this reason the FAA does not have a fatigue requirement for typical aircraft structure. However the major transport manufacturers have learned that they must carefully check all structures against some fatigue criteria to assure customer safisfaction. Boeing, for instance, requires a low probability of cracking during 20 years normal service. Experience has shown that wing surface material will be critical for fatigue on some transports. This is frequently true of the lower surface and sometimes true for the upper and lower surfaces.

Figure 15 illustrates the fatigue criticality of the wing upper and lower surface of a recent model of the Boeing 747. The curves show weight of the bending material required for static strength and the amount and location of additional fatigue material that was added. This kind of data is configuration sensistive and the fatigue criticality of the configurations to be studied undoubtedly will vary. Four-engined configurations (wing mounted) are more apt to be critical on the upper surface than two- or three-engined configurations. Increasing the design range of a configuration by the addition of more center section fuel will probably reduce the fatigue criticality of both the upper and lower surfaces. Fatigue loads can be only partially alleviated, as will be shown in the next paragraph, and therefore a configuration that is fatigue critical will have less potential benefit due to ACT than a configuration that is not fatigue critical.

Before approaching the problem of fatigue load alleviation it is important to understand the types of loads that cause fatigue damage.
The total fatigue damage in wing structure can be divided into two parts: (1) ground-air-ground (GAG) damage and (2) ground and flight maneuver and gust damage.

Figure 16 shows the stresses used for fatigue analysis of a highly loaded segment of a wing lower surface of the same model 747 on a typical flight. The GAG cycle is the change in stress from the maximum compression on the ground to the maximum tension in flight that is expected once per flight. The maximum compression is the 1g taxi stress plus an increment for ground dynamics. The maximum tension is the 1g flight stresses plus an increment due to the peak gust or maneuver. For clarity the figure shows only one cycle of alternating load in each flight segment. The analysis uses the correct number of such loads that will result in the total fatigue damage predicted in that flight segment.

Figure 16 also shows that same data with a hypothetical ACT system incorporated. If a 10 percent weight saving were achieved by application of ACT on the strength design the 1g stresses would be 10 percent higher since the 1g loads would be the same. Because there is no simple way to reduce ground dynamic loads, the alternating stresses on the ground would also be 10 percent higher. ACT can reduce inflight maneuver and gust loads as shown but a net increase in the GAG cycle alternating stresses, and therefore in the GAG fatigue damage will result.

Figure 17 shows percent of total fatigue damage done by the GAG cycle on the upper and lower surface of the 747 model referred to previously. Since the weight saving due to ACT could increase the GAG damage, the total damage may exceed the allowable. This would mean that the weight saving for reduced design loads due to ACT would be limited by the fatigue requirement.

It should be emphasized that the above discussion applies only to a configuration that has no fatigue margin. Most configurations have some fatigue margin on the upper surface and many have fatigue margin on the upper and lower surface. On such configurations a much greater weight saving due to ACT would be achieved.

FLUTTER CRITERIA

Flutter is a definite safety concern and strict FAR criteria must be met to assure that the airplane will never encounter it. Some of the configurations being considered, such as higher aspect ratio wings, will have a flutter speed below the required $1.2V_D$. Since the FAR's do not recognize flutter suppression systems (FSS) as a means of clearing flutter new criteria must be established that include FSS and has reasonable probability of acceptance by the FAA.

Flutter modes can be displayed as a plot of stability vs. speed. Most modern jet transports have critical flutter modes that can be characterized by one of the three plots shown on figure 18. Mode 1 is characterized by a rapid reduction in stability as the flutter speed is approached. It is frequently called "hard" flutter and should never be approached in flight. Mode 2 is "soft" flutter that would be considered safe to approach during flight test. Mode 3 is a "hump" mode that is stable but may exhibit unacceptably low damping. Most critical flutter modes on recent jet transports are similar to mode 2 or 3. Sometimes a "tip" mode occurs like mode 1 but these can usually be fixed for a small structural weight penalty. The above suggests the following as reasonable criteria:

1) With the flutter suppression system off the airplane must be shown by analysis to be free from flutter to:

   (a) $1.2V_D$ for modes which have a rapid reduction in damping as the flutter speed is approached and,

   (b) V_D for all other modes.

2) With the flutter suppression system on, the airplane must be shown by analysis to be free from flutter to $1.2V_D$.

3) The airplane must be shown by flight test to be free from flutter or unacceptably low damping to V_D with FSS on and to V_{D2} with FSS off.

V_{D2} is a "system-off" or "after-failure" dive speed that may be below V_D but must be above V_{MO}. V_{D2} would be defined as the highest speed at which damping is still considered acceptable. There would also be a new reduced operational flight envelope with the usual upset margin provided between this envelope and V_{D2}.

The above represents only a "skeleton" for building flutter criteria. Many details such as redundancy, warning systems, and speed tolerances must be addressed.

These criteria would allow flight testing above V_{MO} with FSS off to V_D or until unacceptably low damping occurs. If V_D is attained, consideration should be given to deleting the FSS from the certificated airplanes.

The selection of reasonable FSS criteria is a very important task in the Max Benefits program. It will play a major role in determining the benefits due to the FSS, which may be a significant part of the total benefit of ACT.

CONCLUSIONS

Configuration optimization, including ACT functions, is expected to result in significantly greater benefits than could be achieved by applying the ACT functions to existing airplanes. However, this kind of configuration optimization complicates the design process. Analysis methods used by the aerodynamics, flight controls and structures technologies must be integrated. Most of the elements of this integrated design process will be verified during the DAST program. The process will be broadened for the Max Benefit program in order to perform what is believed to be the first credible assessment of the potential of ACT as applied to a new airplane.

Another difference between the ACT functions applied to a new configuration and those applied to an existing airplane is in the application of design load alleviation techniques. Most existing airplanes are maneuver critical whereas a new configuration optimized including ACT functions is expected to be gust critical. Emphasizing gust-load alleviation will probably lead to a more comprehensive control system in terms of transducer inputs, frequency response and actuator rates.

Fatigue is important in structural design because of its potential economic impact. Structural evaluation of the configurations developed during the Max Benefit program will include a fatigue analysis. Many of the configurations will have some of the primary wing structure critical for fatigue. Past experience has shown that the GAG portion of the fatigue damage is frequently a major portion of the total damage. Since this portion cannot be alleviated, those configurations that are fatigue critical will show less benefit from ACT than those that are not.

The present FARs do not consider flutter suppression systems as a method of clearing flutter. A very important task in the early portion of the Max Benefit program will be to establish criteria that allow use of a FSS and ıd yet retains the required level of safety.

Applications of the lessons learned in these two studies should result in significantly improved efficiency of future transports.

REFERENCES

1. AFFDL TR-74-92 Volume I, "B-52 CCV Program Summary", March 1975, The Boeing Company, Wichita Division.
2. AFFDL TR-74-92, Volume II, "B-52CCV Control System Synthesis" Janury 1975 The Boeing Company, Wichita Division
3. AFFDL TR-74-92 Volume III, "B-52 CCV System Design and Aircraft Modification", October 1974, The Boeing Company, Wichita Division.
4. AFFDL TR-74-92 Volume IV, "B-52 CCV Component and Aircraft Ground Test", September 1974, The Boeing Company, Wichita Division.
5. AFFDL TR-74-92 Volume V, "B-52 CCV Control System Flight Test Validation", December 1974, The Boeing Company, Wichita Division.
6. Roger, Kenneth L., "Airplane Math Modeling Methods for Active Control Design", AGARD-CP-228, Structural Aspects of Active Controls, 21 April 1977.

TABLE 1.- AERODYNAMIC WING DESIGN PARAMETER

TYPE OF DESIGN	VARIABLE	FIXED
TRANSPORT -	WING AREA INCIDENCE DIHEDERAL THICKNESS RATIO ASPECT RATIO WING SWEEP TAPER RATIO TAIL AREA	PAYLOAD - RANGE - SPEED TAKEOFF AND LANDING DISTANCE
DAST ARW-2- INTEGRATED ACT	WING AREA INCIDENCE DIHEDERAL	TAPER RATIO ASPECT RATIO WING SWEEP TAPER RATIO TAIL AREA SPEED

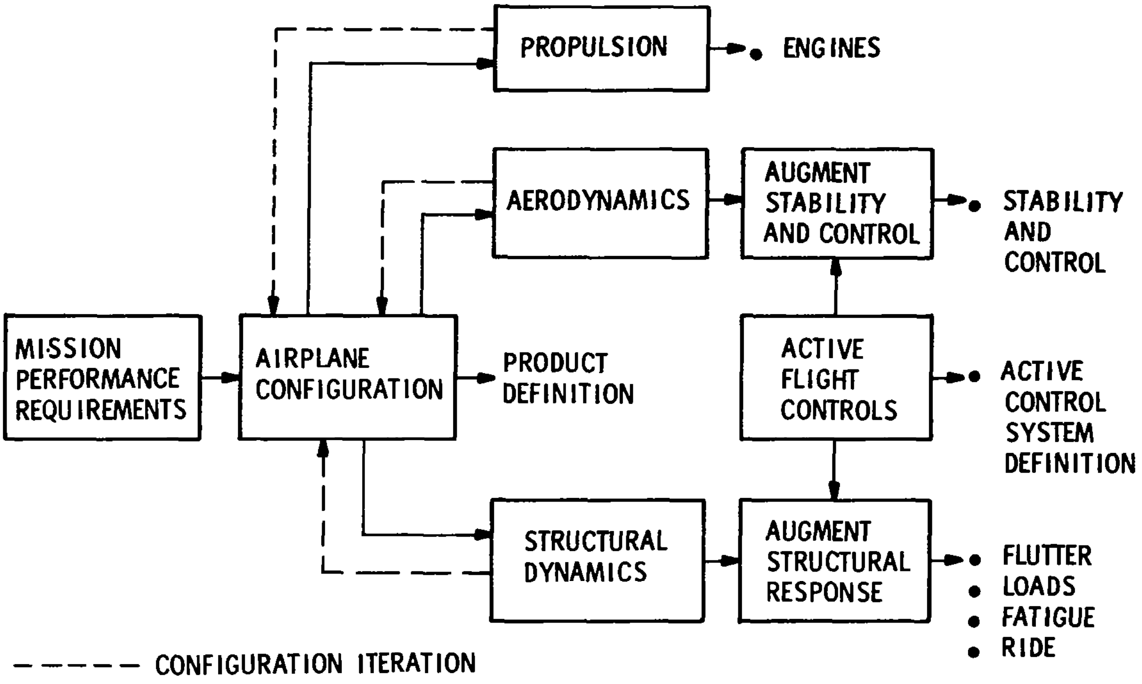


Figure 1.- Conventional aircraft design.

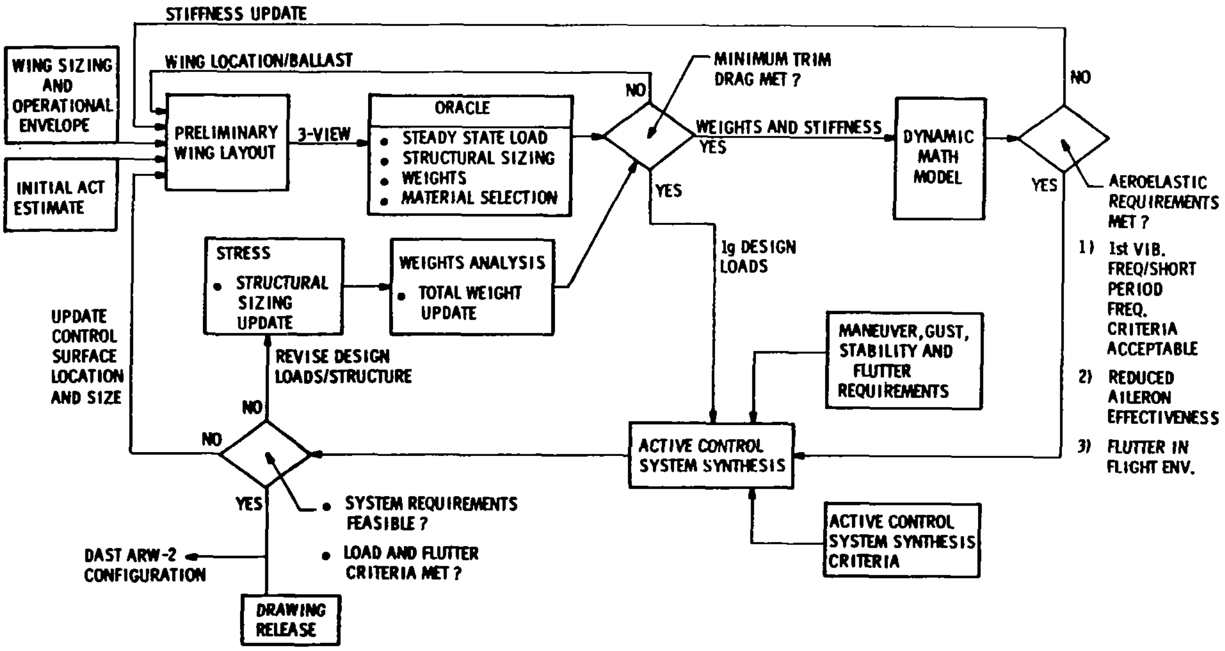


Figure 2.- DAST integrated ACT design.

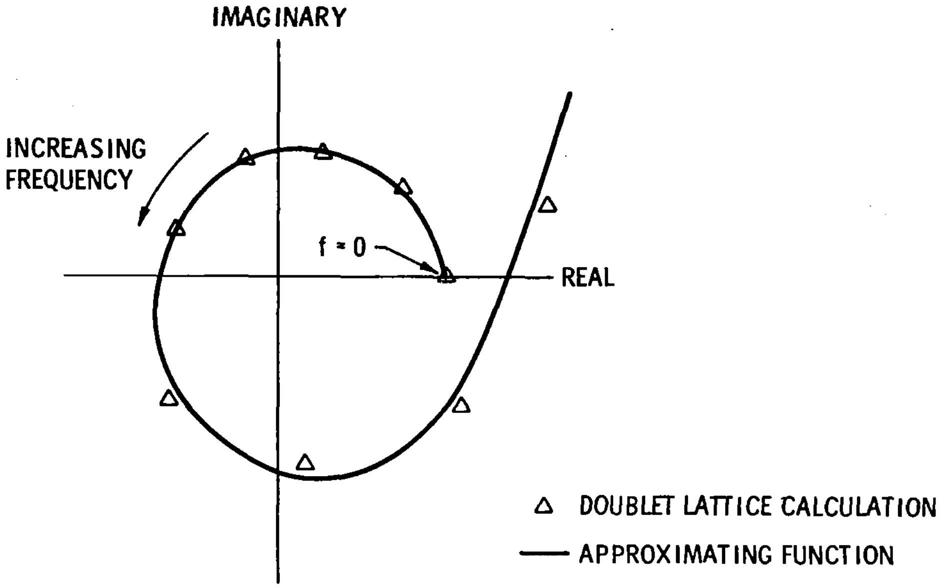


Figure 3.- Aerodynamic coefficient approximating function.

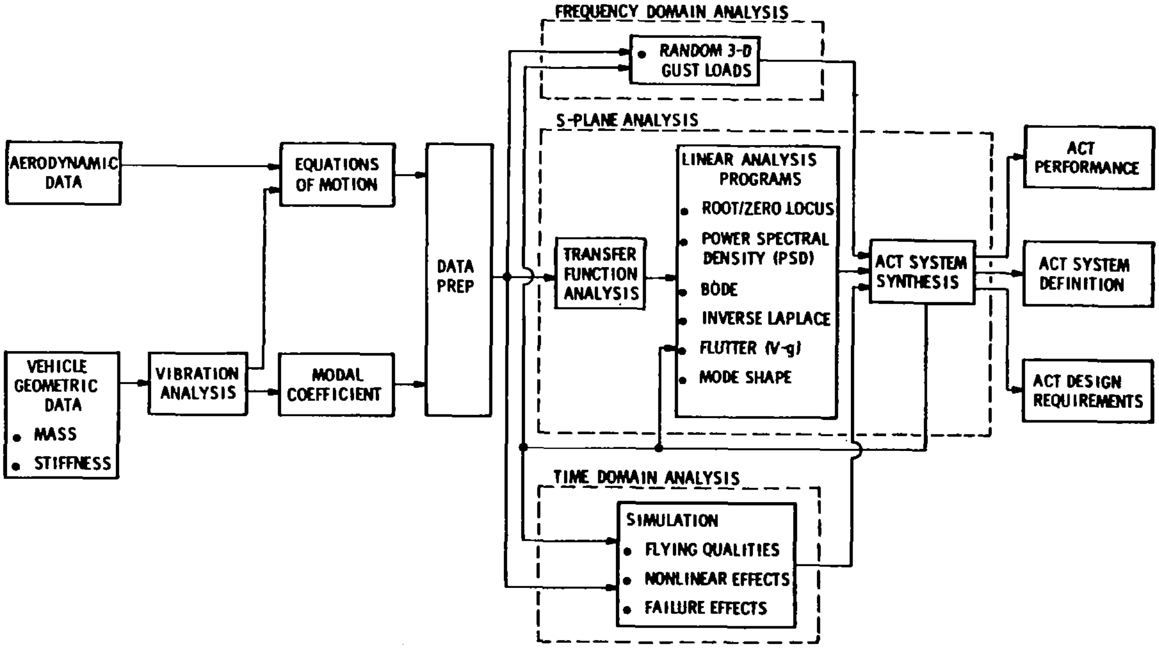


Figure 4.- ACT technology and analysis program integration.

WING

DESIGN C_L	0.53
GROSS AREA	3.25 m^2 (35 FT^2)
ASPECT RATIO	10.3
SPAN	5.79 m (19 FT)
TAPER RATIO (BASIC WING)	.4
SWEEP - 50% BASIC WING CHORD	25°

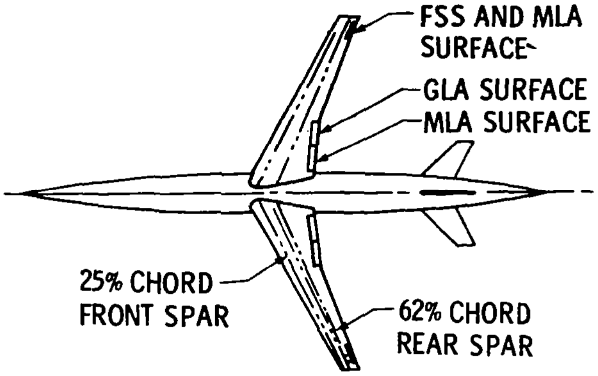


Figure 5.- DAST ARW-2 general arrangement.

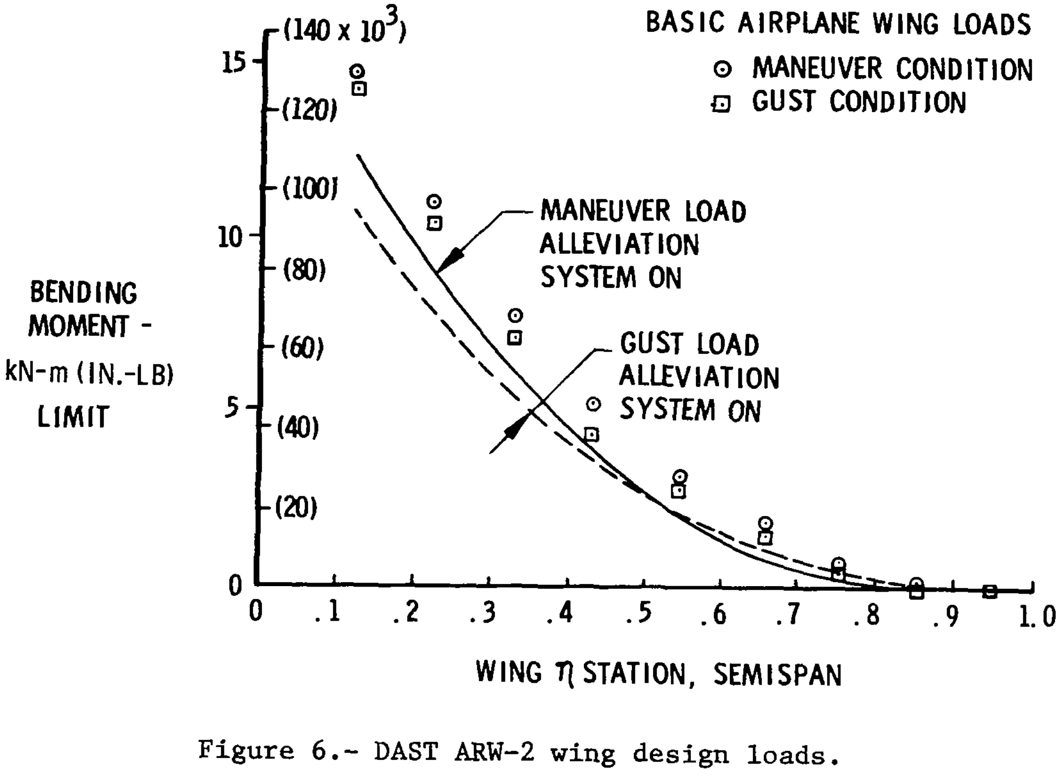


Figure 6.- DAST ARW-2 wing design loads.

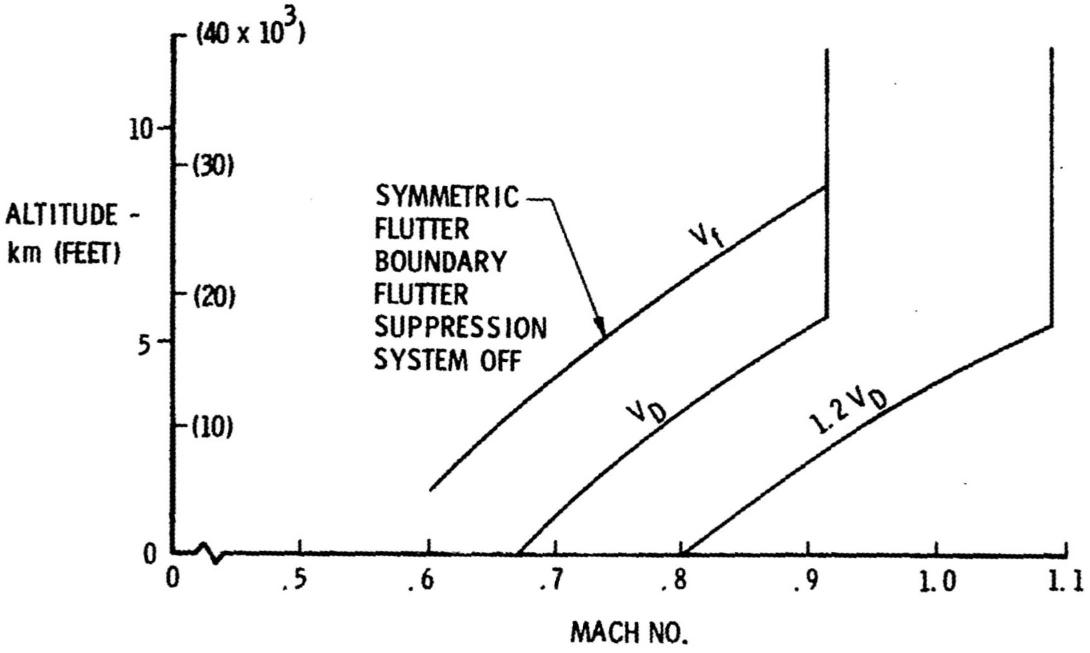


Figure 7.- DAST ARW-2 flutter boundary.

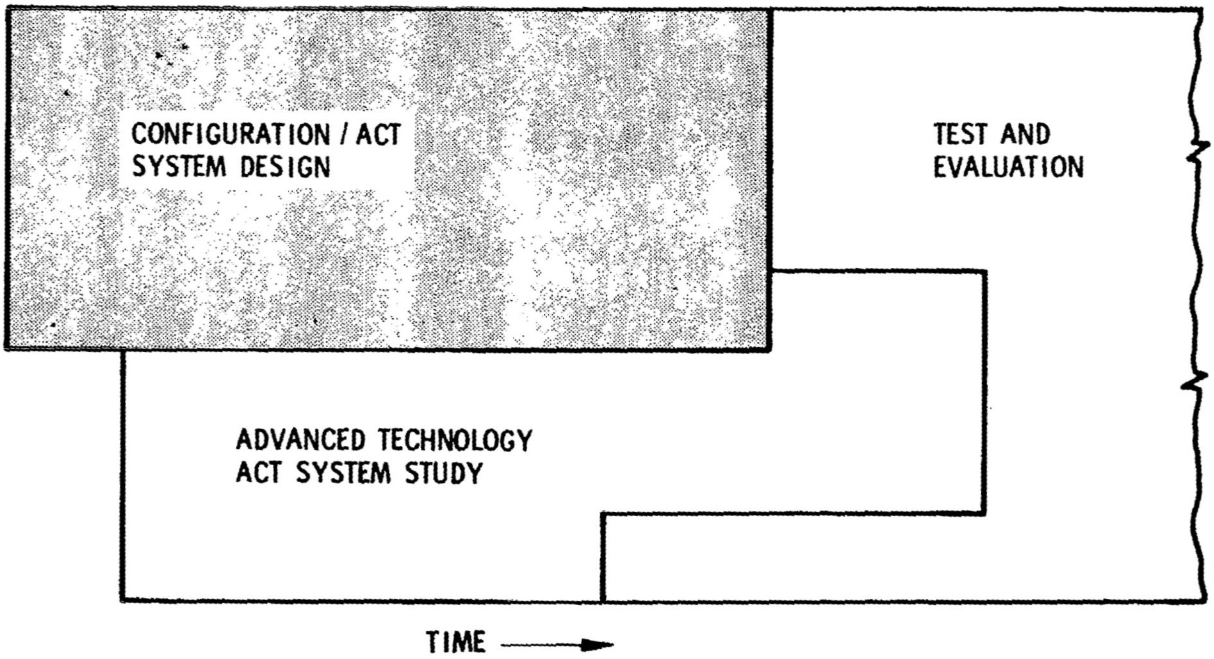


Figure 8.- Major elements of maximum benefit of ACT program plan.

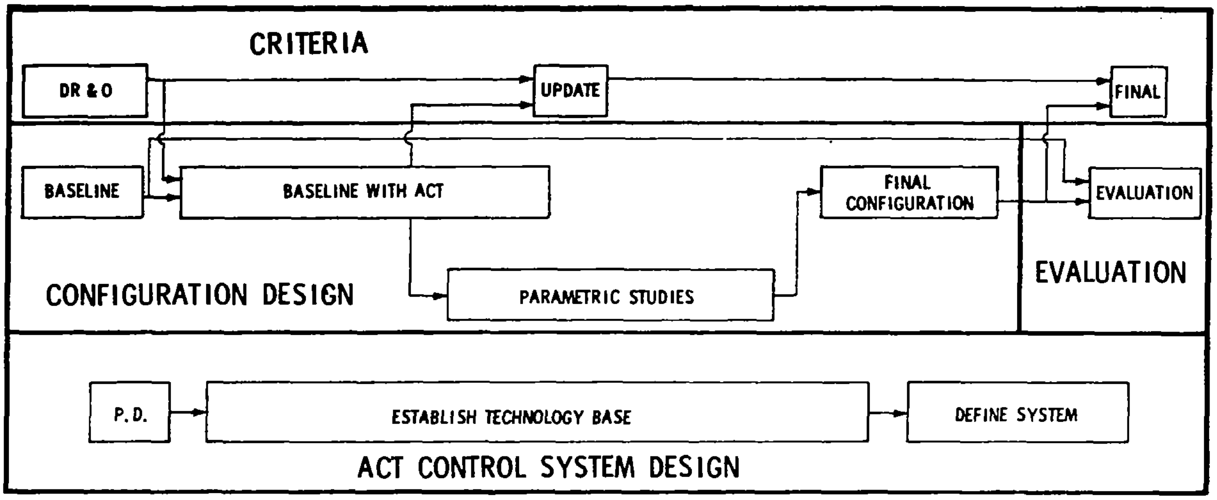


Figure 9.- Configuration/ACT system design task.

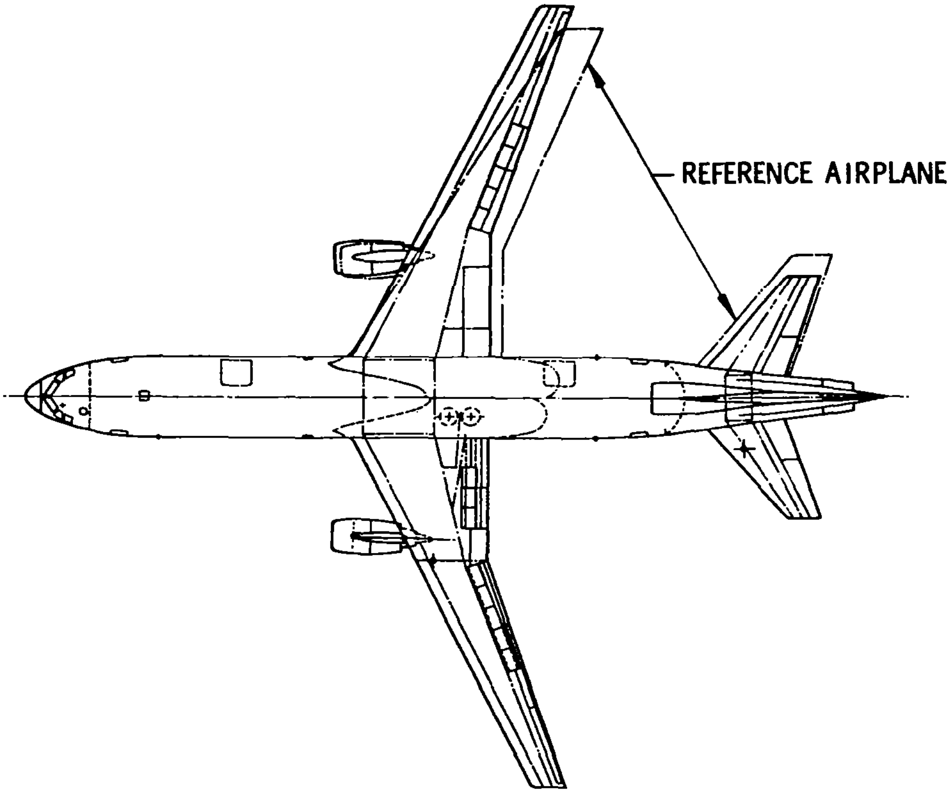


Figure 10.- Possible final ACT airplane.

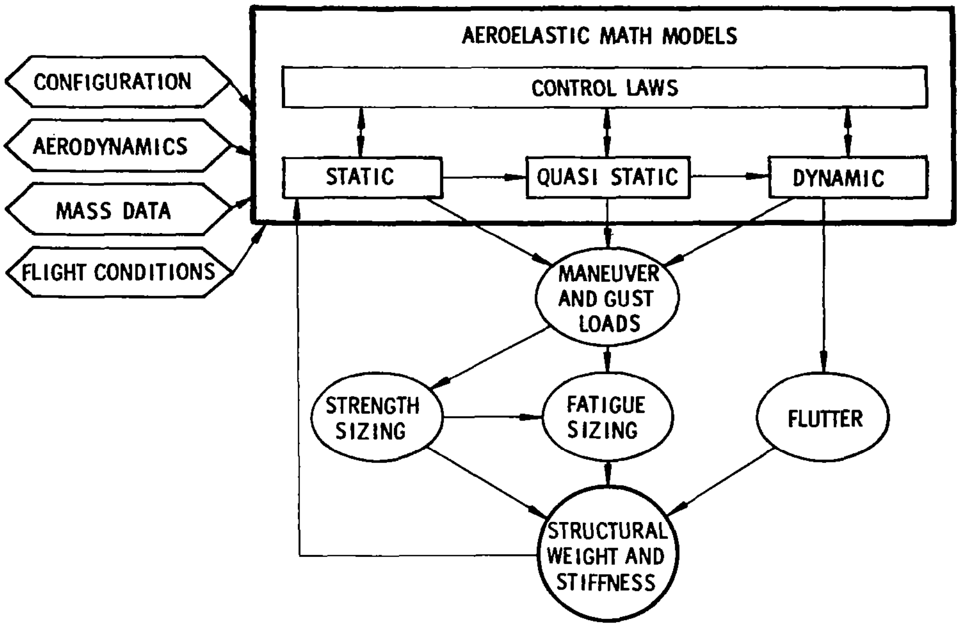


Figure 11.- Maximum benefits structural evaluation plan.

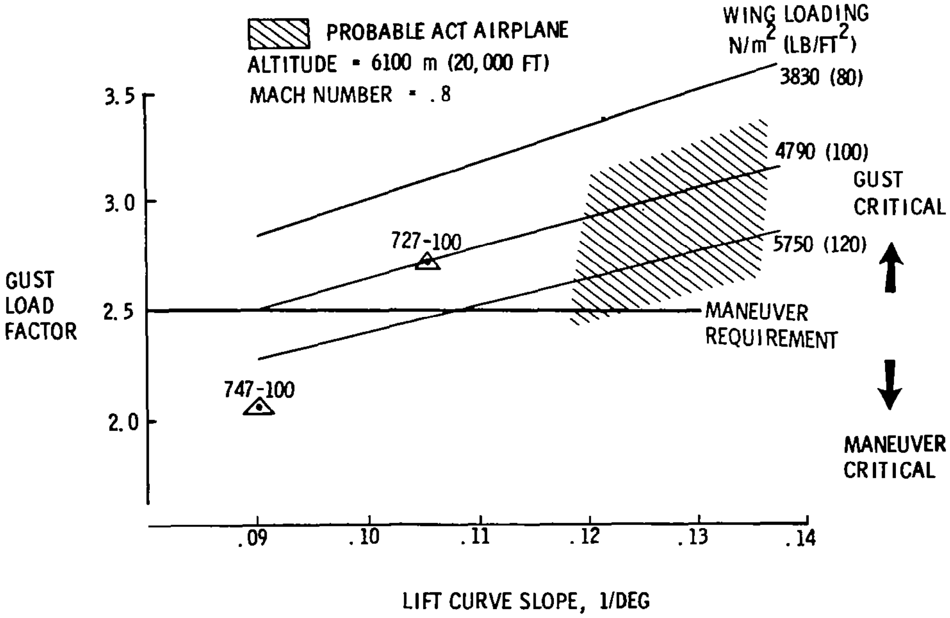


Figure 12.- Gust load factor sensitivity.

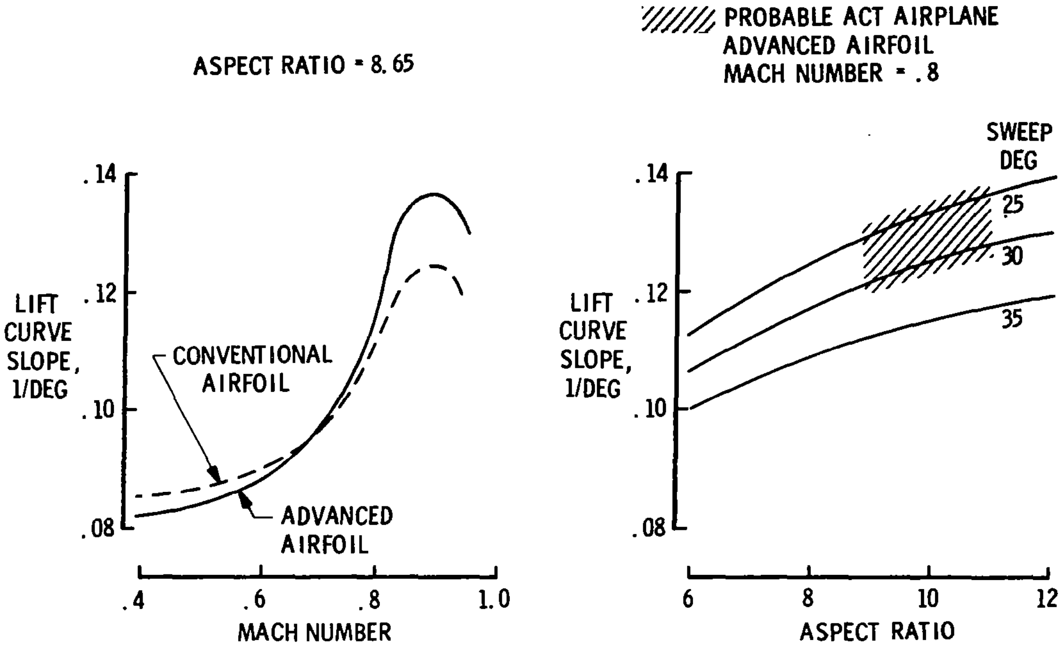
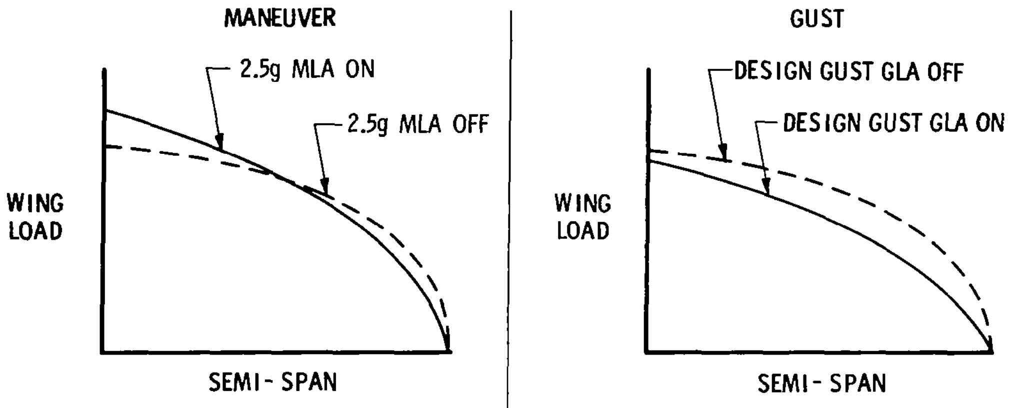


Figure 13.- Lift curve slope sensitivity.



- CRITICAL AT V_A
- OUTBOARD AILERON EFFECTIVE
- TAIL LOAD REDUCTION FURTHER REDUCES WING LOAD

- CRITICAL AT V_{MO}
- OUTBOARD AILERON LESS EFFECTIVE
- MID-SPAN AILERON "DUMPS" LIFT
- ELEVATOR INPUT PITCHES AIRPLANE
- IMPROVES RIDE COMFORT

Figure 14.- Load alleviation.

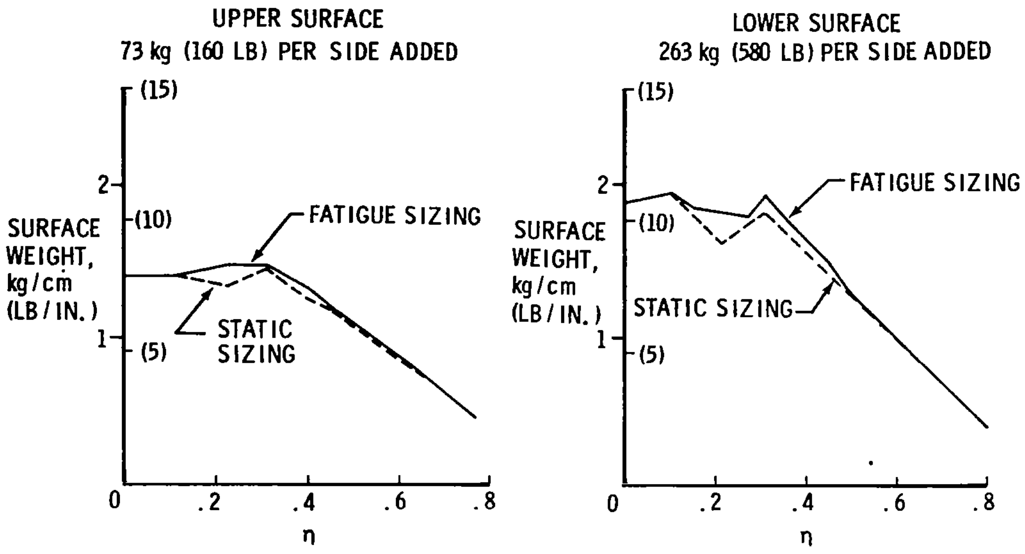


Figure 15.- 747 wing box surface areas.

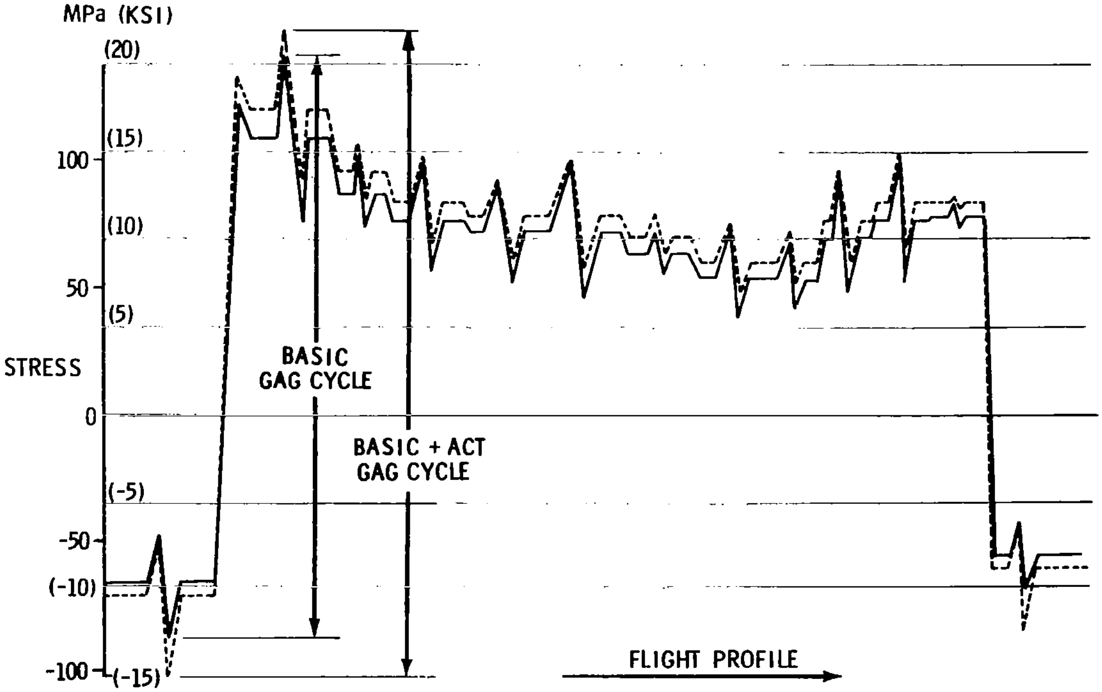


Figure 16.- Typical wing lower surface stress for fatigue analysis.

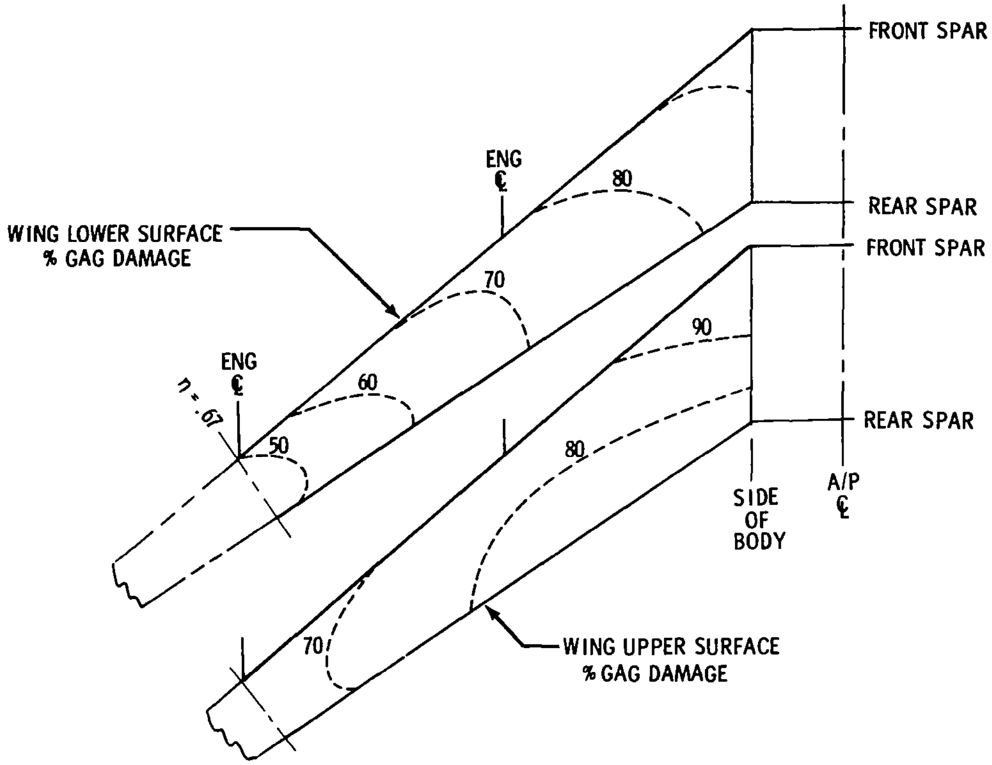


Figure 17.- Percent GAG damage.

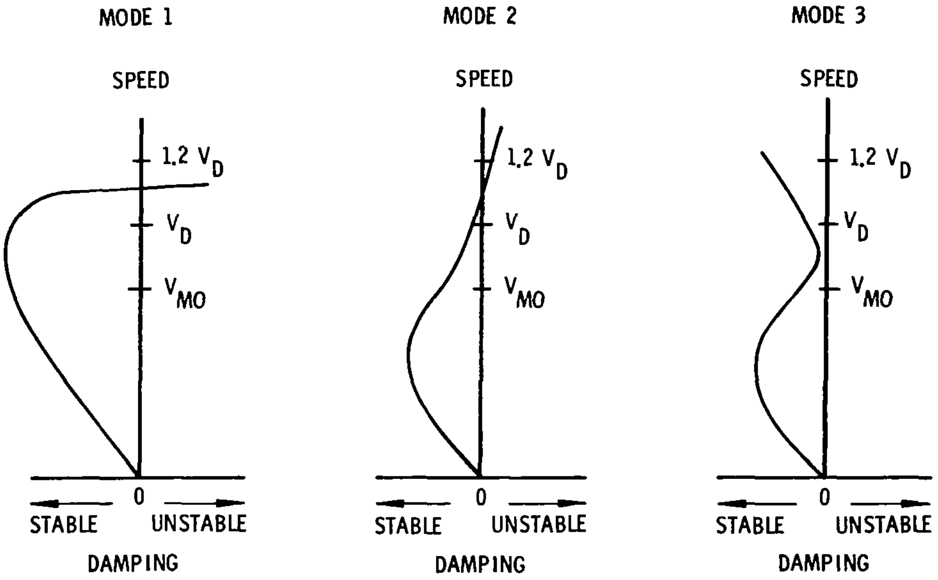


Figure 18.- Flutter stability.