LANGLEY RESEARCH CENTER CONTRIBUTIONS IN ADVANCING ACTIVE CONTROL TECHNOLOGY

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ABSTRACT

The application of active control technology to reduce aeroelastic response of aircraft structures offers a potential for significant payoffs in terms of aerodynamic efficiency and weight savings. To reduce technical risks, research was begun at NASA in the early 1970's to advance this concept. This presentation describes some of the contributions of the Langley Research Center in advancing active control technology. Contributions are categorized into the development of appropriate analysis tools, control law synthesis methodology, and experimental investigations aimed at verifying both analysis and synthesis methodology. The work reported herein was either performed in-house or under contract to the Structures Directorate at LaRC.

CONTRIBUTIONS

This chart lists three of the areas to which the LaRC has made contributions advancing active control technology. The following charts will expand on each of these areas.

- ANALYSIS
- CONTROL LAW SYNTHESIS
- EXPERIMENTS

Figure 1

STABILITY ANALYSIS

This chart describes the difficulty in performing a stability calculation for an actively controlled flexible aircraft including the effects of unsteady aerodynamics. The structural quantities are defined in terms of the generalized masses [M], the structural damping coefficients [C], and the structural stiffnesses [K]. The control law is normally expressed as a transfer function which relates control surface motion to aircraft response and is written as a ratio of polynomials in the Laplace variable S. The unsteady aerodynamics are computed for simple harmonic motion at specific values of reduced frequency and can not be cast into the form shown on the chart. The problem facing the analyst is to develop a set of constant coefficient differential equations where the unsteady aerodynamics, the control law, and the structural terms are compatible. Once the equations are cast into this form, a number of synthesis and analysis methods developed for other applications may be utilized.

- EQUATIONS OF MOTION

$$[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} \qquad \text{STRUCTURE}$$

$$+ [C_1]\{\delta\} + [C_2]\{\dot{\delta}\} + [C_3]\{\ddot{\delta}\} \qquad \text{CONTROLS}$$

$$+ [A_0]\{q\} + [A_1]\{\dot{q}\} + [A_2]\{\ddot{q}\} + \ldots = 0 \quad \text{AERODYNAMICS}$$

- STABILITY

CONSTANT COEFFICIENT DIFFERENTIAL EQUATIONS

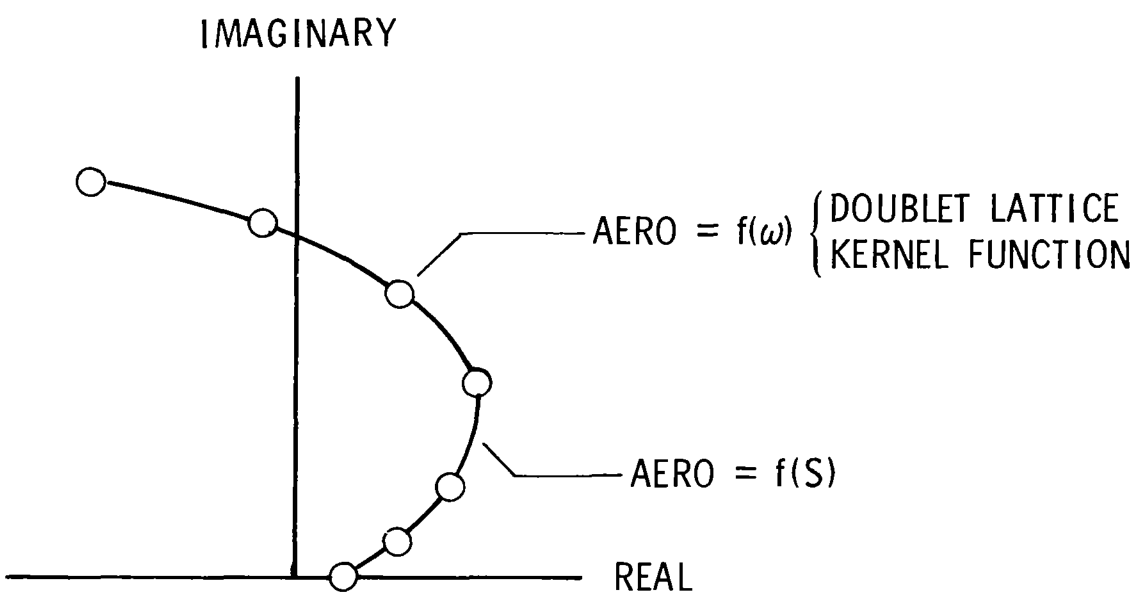
$$\{\dot{q}\} = S\{q\} \qquad \{\ddot{q}\} = S^2\{q\} \ldots$$

- UNSTEADY AERODYNAMICS NOT IN THIS FORM

Figure 2

UNSTEADY AERODYNAMIC APPROXIMATION

In lieu of developing a completely new aerodynamic theory, the approach taken is to allow the variation of the aerodynamic forces with frequency to be approximated by a rational function in the variable S. The form of the function presented permits an approximation of the time delays inherent in unsteady aerodynamics subject to: denominator roots in the left-hand plane, and a good approximation of the complex unsteady aerodynamic terms at $S = j\omega$. The approximating coefficients ($A_0, A_1, \ldots, A_6$) are evaluated by a least-squares curve fit through the values of complex aerodynamic terms at discrete values of frequency. The chart illustrates a typical fit. The solid curve represents the approximating function. This technique is similar to that described in reference 1.



$$AERO(S) = A_0 + A_1 S + A_2 S^2 + \sum_{m=3}^{6} \frac{A_m S}{S + \beta_{m-2}}$$

Figure 3

TYPICAL DYNAMIC PRESSURE ROOT LOCUS

Using the aerodynamic approximating functions, the stability problem is solved by calculating the roots of the characteristic equation. This chart presents a typical root locus of the flexible mode roots as a function of dynamic pressure for the DAST ARW-1 vehicle (arrows indicate increasing dynamic pressure). The solid line represents the no control case. A classical flutter behavior is apparent since the frequency of flexible modes 1 (wing bending) and 2 (wing torsion) tend to coalesce as mode 1 crosses into the unstable region. Calculations performed for the wing with flutter suppression (dashed line) indicate that the flutter can be delayed to dynamic pressures approaching 100 percent above the no control case. Analyses of this type are of extreme value to the designer since he can see graphically the manner in which the control system is modifying the behavior of the flexible mode roots. A description of this analysis method is presented in reference 2.

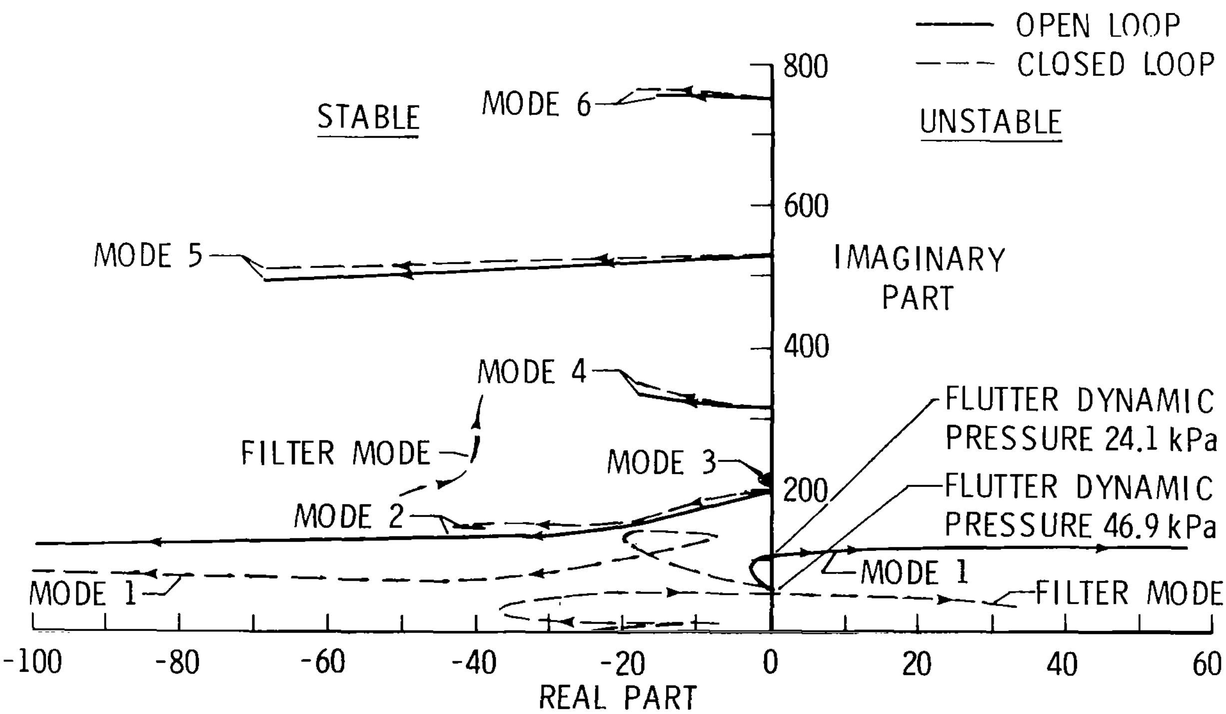


Figure 4

DYLOFLEX

DYLOFLEX is an integrated system of stand-alone computer programs which performs dynamic loads analyses of flexible airplanes with active controls. DYLOFLEX incorporates a wide range of analysis capabilities which include calculating dynamic loads due to (1) continuous atmospheric turbulence, (2) discrete gusts, and (3) discrete control inputs. The input to DYLOFLEX consists of externally generated structural data, vehicle geometry, a transfer function representation of the active control system, and flight condition information. The output consists of either statistical quantities or time histories of the dynamic loads. DYLOFLEX is well documented and available from COSMIC (Computer Software Management and Information Center). It was developed under contract by the Boeing Company, Seattle, Washington. An overview of its capabilities is presented in reference 3.

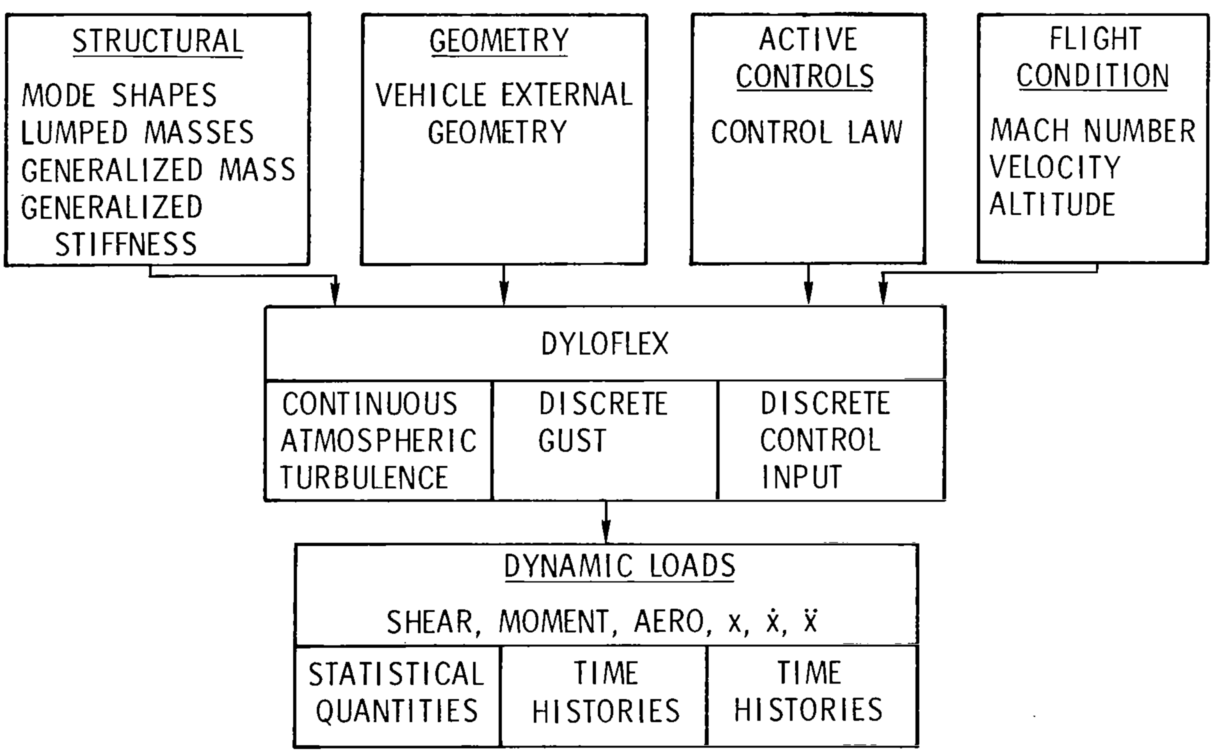


Figure 5

TYPICAL DYLOFLEX RESULTS

A typical example of DYLOFLEX's capability is presented on this chart. A wind-tunnel model of a DC-10 derivative wing was analyzed. Predicted gust loads, both with and without an active control system, were calculated. Structural input data were provided by the Douglas Aircraft Company. Turbulence was modeled as a Dryden spectrum fitted to measured wind-tunnel data. Results are presented in terms of the rms values per unit gust velocity of wing acceleration and wing bending moment as a function of wing semispan.

DYLOFLEX has also been applied to several other aircraft configurations, both at NASA and within the aircraft industry. It has been shown to be suitable for both preliminary and final design studies.

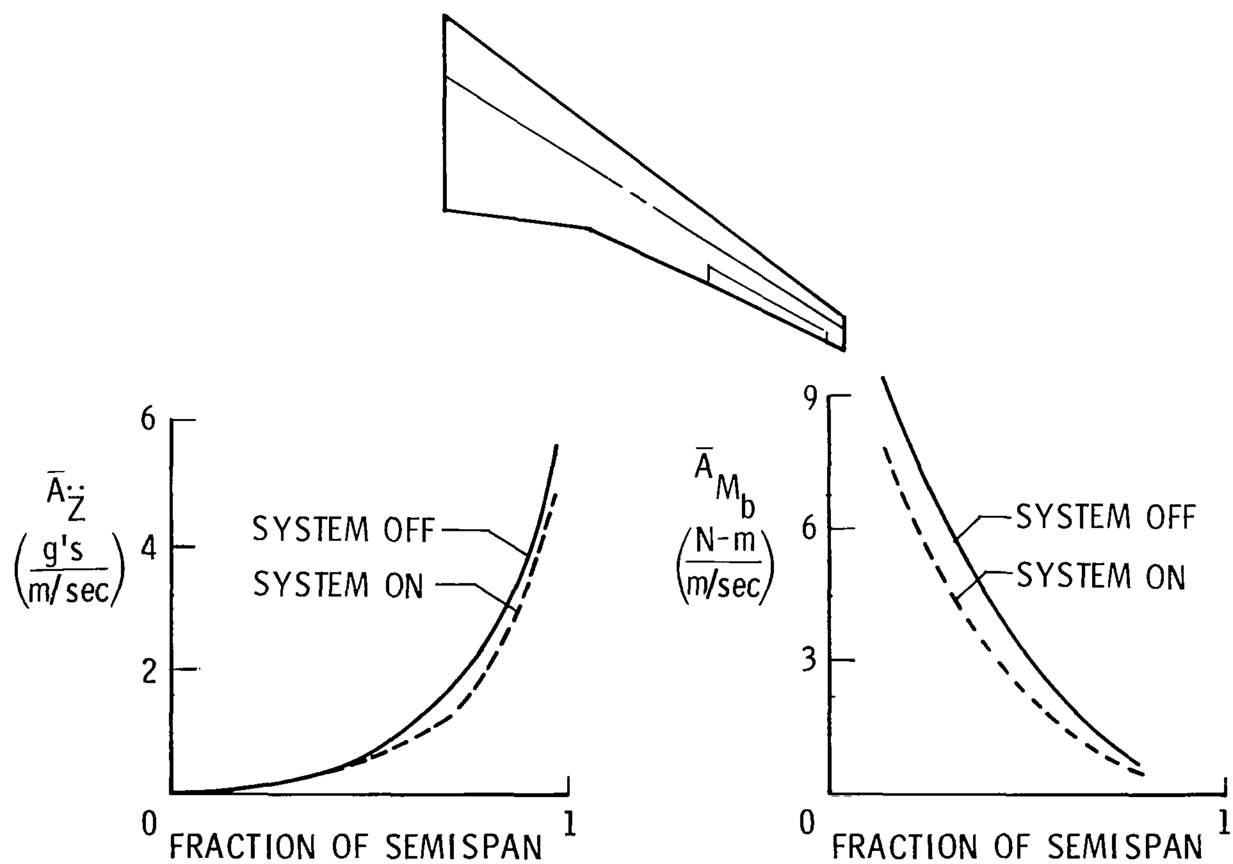


Figure 6

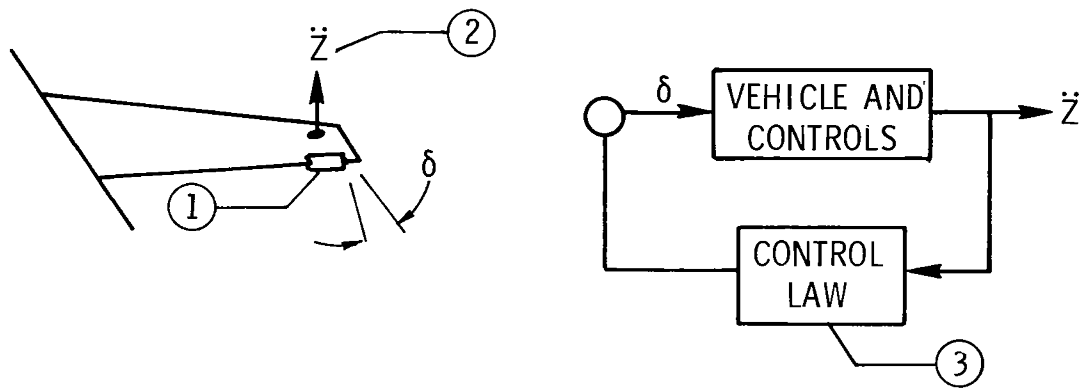
CONTROL LAW SYNTHESIS

Through the proper selection of (1) control surfaces and (2) sensors, (3) control laws can be synthesized to:

- o Increase flutter speed
- o Reduce loads due to gusts
- o Reduce wing loading during maneuvers
- o Reduce acceleration levels within the crew and passenger compartments
- o Augment the basic aircraft stability

Due to its impact on safety of flight, flutter suppression is probably the active control concept furthest from realization and is therefore an area of primary emphasis within NASA. The synthesis methods which will be described deal primarily with active flutter suppression but the methodology can also be extended to other active control functions.

PROBLEM:



FOR:

- FLUTTER SUPPRESSION
- GUST LOAD ALLEVIATION
- MANEUVER LOAD CONTROL
- RIDE QUALITY CONTROL
- RELAXED STATIC STABILITY

Figure 7

SYNTHESIS METHODS

Three methods for synthesizing active control systems that the authors have used and are familiar with are listed on this chart. All three methods have been applied to the flutter suppression problem.

- CLASSICAL
- AERODYNAMIC ENERGY
- OPTIMAL CONTROL THEORY

Figure 8

CLASSICAL CONTROL THEORY

This chart describes the basic steps used when applying classical control theory. The first two steps are common to all three methods and normally begin with a parametric investigation, at a design point, to establish the number and location of control surfaces and sensors needed to provide the increased stability. In many cases, this step is a result of engineering judgment or the constraint that existing control surfaces be used. Once the number and location of control surfaces and sensors are fixed, a control law is designed using a combination of classical techniques including gain root loci, Nyquist diagrams, trial and error, and engineering judgment. The stability of the system is now evaluated over a range of flight conditions. If the system is unstable at off-design conditions, the control law is modified. At this point in the design process, the forced response of the system to a realistic gust environment is evaluated. If the control surface activity is beyond the capability of the actuator, either the control law is modified or the control surface is resized. In this method, stability and forced response analyses are sequential and can lead to time consuming iterations. Once the system meets both stability and gust criteria, the design is complete.

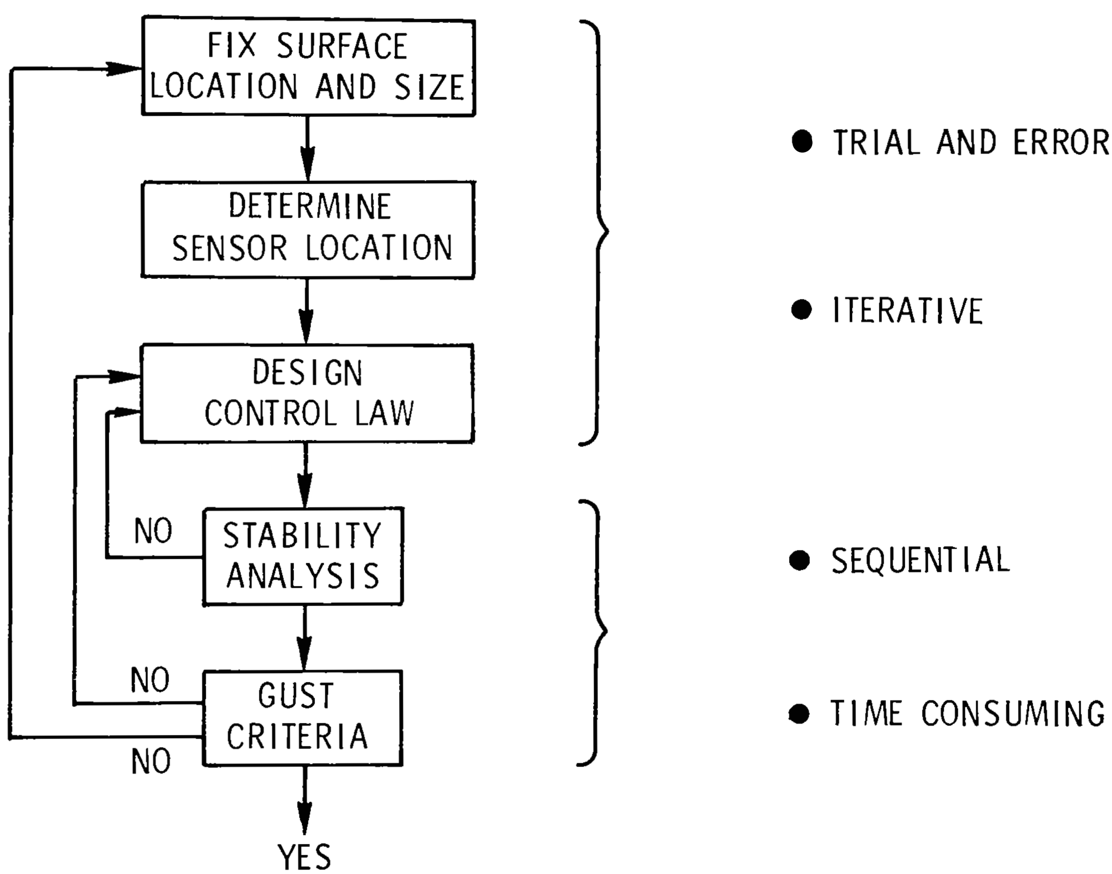
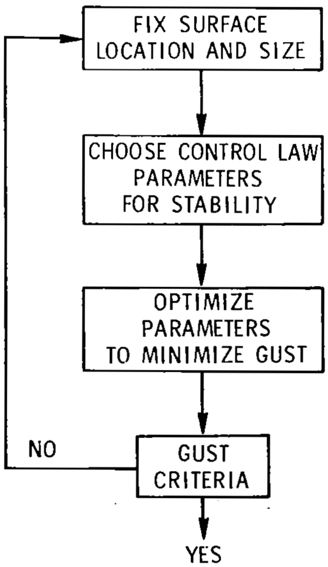


Figure 9

AERODYNAMIC ENERGY PRINCIPLE

This chart presents the steps used when applying the relaxed aerodynamic energy method to the simplest case of a single trailing-edge control surface and a single second-order transfer function. (The most general case uses a pair of leading- and trailing-edge control surfaces, two accelerometers, and two fourth-order transfer functions.) The first step is to fix the control surface location and size. This is normally done using engineering judgment. The location of the accelerometer is fixed with respect to the control surface. The basic form of the control law has "free parameters" a, ζ, and ω which enables it to be tailored to a specific application. This is accomplished by assigning initial values to the free parameters which stabilize the system at the required design point. This step is performed by trial and error. Experience has shown that if the system is initially stable, and the free parameters are changed in a way to reduce stability, the control surface activity in a gust environment increases. Therefore, the final values of the free parameters are determined by minimizing the forced response of the system to a gust input. By placing constraints on the free parameters as shown in reference 4, the resulting control law will be insensitive to changing flight conditions. In this method, the gust response and stability problems are handled simultaneously and the resulting control law is optimal with respect to control surface activity for the given control surface size, location, and order of the control law.

If, after this process is completed, the maximum control surface activity is unacceptable, then the control surface must either be repositioned, increased in size, or more controls added and the process repeated. It has been the author's experience that when this method is combined with classical design techniques, control laws can be synthesized which are near optimal and have excellent stability margins. (See reference 5)



- SENSOR LOCATED BY THEORY
- FORM OF CONTROL LAW SET BY THEORY

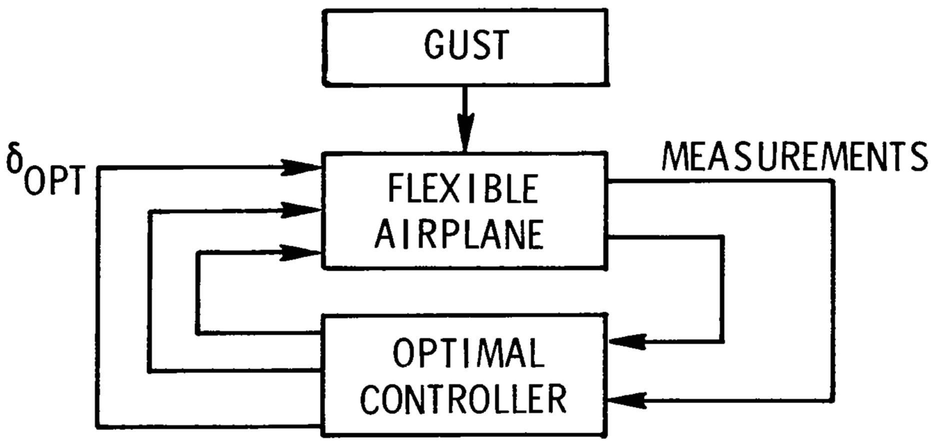
$$\delta = \left(\frac{a}{S^2 + 2\zeta\omega S + \omega^2}\right)\ddot{Z}_{.65C}$$

- CONTROL LAW PARAMETERS DETERMINED BY GUST RESPONSE

Figure 10

OPTIMAL CONTROL THEORY

Optimal control theory provides an excellent basis for a systematic approach to the control law synthesis problem. The theory is based on the design of a controller which minimizes a performance function. Since the performance function can be defined in terms of such quantities as control deflection, bending moment, acceleration, etc., the method can be adapted quite easily to multiple control tasks. The difficult problem of synthesizing control laws that involve multiple sensors and controls can be handled readily with this method. It also provides the very attractive feature of directly synthesizing digital control laws.



- OPTIMIZATION CRITERIA
  - CONTROL DEFLECTION
  - BENDING MOMENT
- MULTIPLE SENSORS/CONTROLS SIMULTANEOUSLY
- MULTIPLE CONTROL TASKS
- ADAPTABLE TO DIGITAL DESIGN/ANALYSIS

Figure 11

OPTIMAL CONTROLLER DESIGN

The Linear-Quadratic-Gaussian (LQG) method has become the most widely accepted means of synthesizing optimal controllers (ref. 6). However a shortcoming of this method, in particular for high-order systems (characteristic of flexible airplanes), is the requirement that the control law be of the same order as the system being modeled. That is, all states of the system must be estimated. Not only is this unnecessarily complex, but this full-order control law is often sensitive to small changes in the system parameters and very difficult to implement in a flight computer. The usual method for designing a low-order control law from optimal control theory is to approximate the full-order control law through order reduction techniques such as truncation, residualization, and transfer function matching (refs. 7, 8, and 9). These techniques all result in low-order control laws that are not optimal.

A new approach has been developed for designing low-order optimal control laws (ref. 10). The basic concept is to begin with a full-order controller. Using engineering judgment, a few key states and their associated design variables and initial values are selected from the full-order solution. A nonlinear programming algorithm is then used to search for the values of the control law variables which minimize the performance function. The resulting low-order control law is optimal for the states selected. The method is direct and results in a control law that is much easier to implement in a flight computer. Comparative features of the new method to the LQG method are given in the chart.

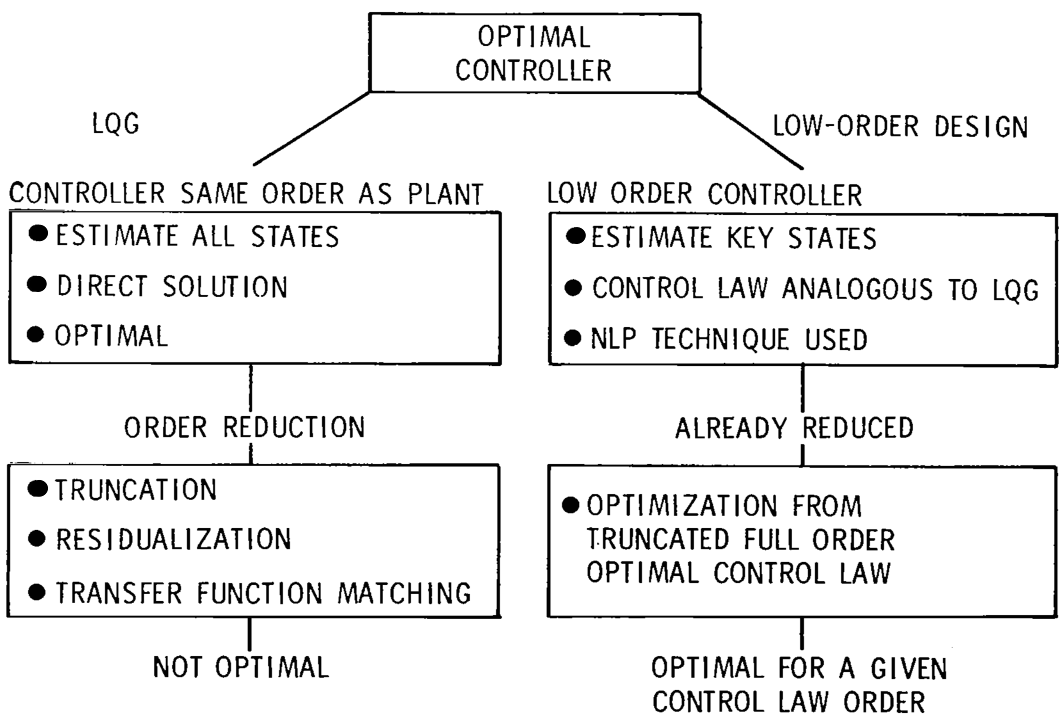


Figure 12

WIND-TUNNEL STUDIES

Wind-tunnel studies of aeroelastic models are a cornerstone of the NASA research program. Presented on this chart are a number of models that have been used to demonstrate active control concepts on a variety of configurations. The Delta-wing model was the first experimental demonstration of flutter suppression in this country (ref. 11). The B-52 model was tested in support of a USAF/Boeing flight study on active controls (ref. 12). Wing load alleviation was studied in support of a USAF/Lockheed program using a C-5A model (ref. 13). The DAST ARW-1 model was used for a variety of flutter suppression studies including an evaluation of the control system that would ultimately be tested on the DAST flight vehicle. Control laws were synthesized and tested on the model using classical, aerodynamic energy, and optimal methods (ref. 5). The F-16 and YF-17 model tests have shown active flutter suppression to be a promising method for preventing wing/external store flutter (refs. 14 and 15). Active controls is especially attractive for fighters because of the multitude of possible store configurations. These studies are part of a cooperative effort with the Air Force Flight Dynamics Laboratory/General Dynamics/Northrop/NASA. The last study was a cooperative effort with the McDonnell Douglas Corporation on a DC-10 derivative wing. The broad objectives were to allow NASA the opportunity to apply in-house control law synthesis methods to a realistic transport configuration with engines on the wing and at the same time provide a rapid transfer of research technology to industry. Increases in flutter speeds in excess of 26 percent were demonstrated. These studies are an extension of those reported in reference 16.

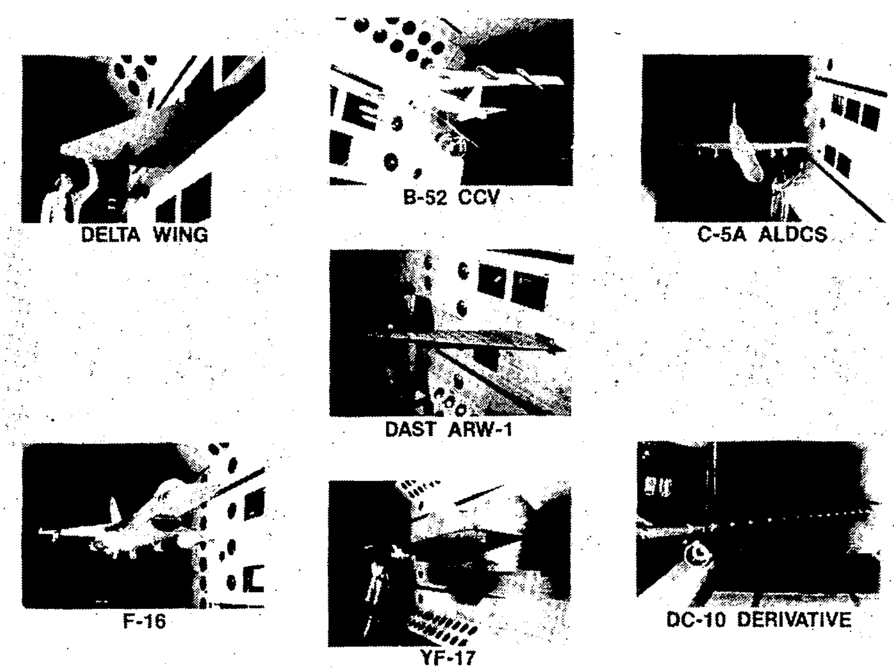


Figure 13

FLUTTER SUPPRESSION DESIGN STUDY

The objective of the wind-tunnel study was to provide a 44 percent increase in flutter dynamic pressure for the aeroelastic model shown on the chart through the use of active controls. Two control laws were designed. One control law is based on the aerodynamic energy method, and the other is based on the results of optimal control theory. Tests were performed in the Langley Transonic Dynamics Tunnel. Both control laws were implemented on an analog computer. The performance of the flutter suppression systems is illustrated by the oscillograph records of wing acceleration and control surface position presented on the chart. The test condition was a dynamic pressure 10 percent above the system-off boundary at M = 0.90. The trace begins with the system turned on. The system was then turned off for approximately 4.5 seconds and then turned on again. During the time the system was turned off, the wing began to flutter as evidenced by the rapid buildup of acceleration. The effect of turning the system on again was a rapid suppression of the oscillatory motion. Results of these tests are reported in reference 5.

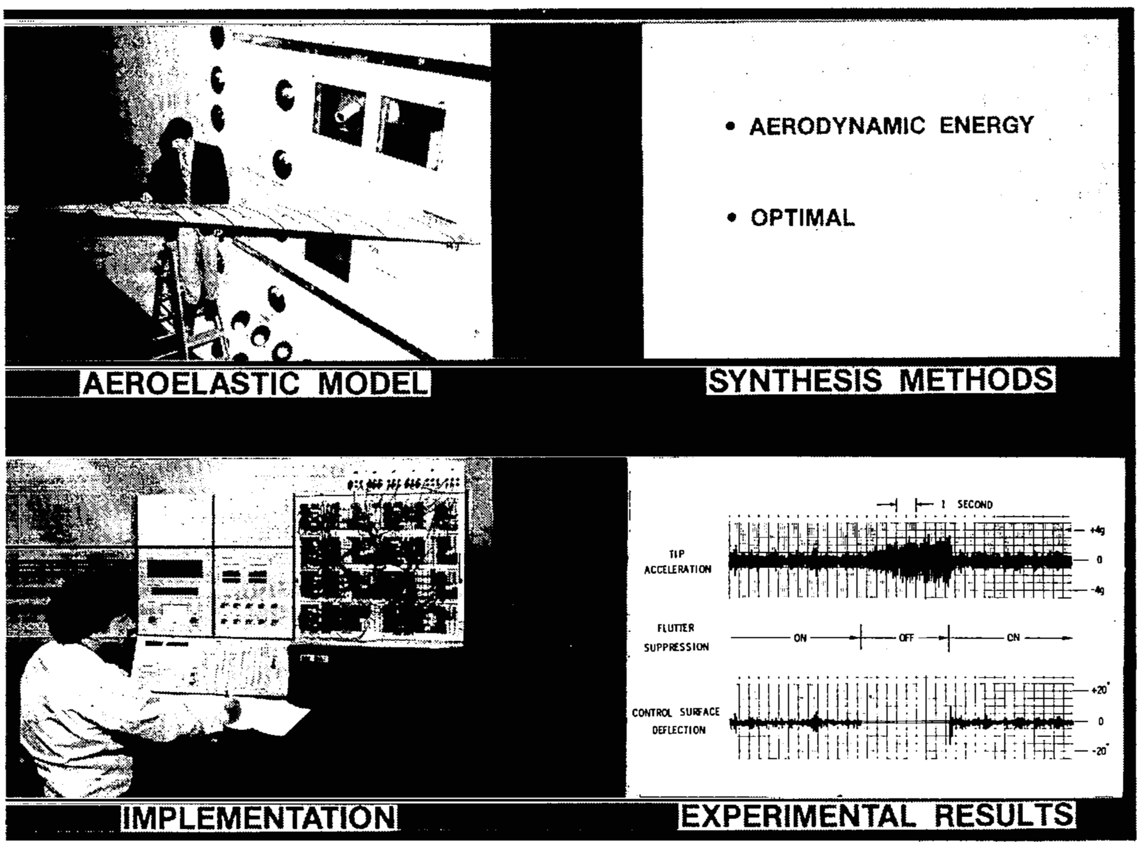


Figure 14

TRANSONIC AIRLOADS

The application of active control technology to advanced airplane designs, such as energy efficient transports, requires the understanding of both steady and unsteady transonic aerodynamics. No theory has yet been developed that can accurately predict unsteady aerodynamic characteristics at transonic speeds. Consequently, a wind-tunnel program has been initiated at the Langley Research Center to experimentally determine the transonic aerodynamic characteristics of a representative energy efficient transport wing with emphasis on oscillating control surfaces. This test is part of a much larger experimental program to acquire unsteady pressure measurements for a wide range of aircraft configurations. The results from this study will serve two purposes. One purpose is to provide a comprehensive data base of measured pressure data that can be used in airplane design; the other purpose is to provide high quality data that can be used to validate theoretical methods being developed in companion programs.

A photograph of the aspect-ratio-10.76 model mounted in the Transonic Dynamics Tunnel is shown on the chart. The model has a supercritical airfoil section and is equipped with ten control surfaces, five along the trailing-edge and five along the leading-edge. Some representative results obtained by oscillating an inboard trailing-edge control surface are shown on the right in the chart. Both steady and unsteady chordwise lifting pressure distributions are presented for two spanwise locations. The data show that the unsteady pressures produced by oscillating the control surface are relatively large when compared to the steady pressures (no control surface oscillation). Even though the outboard station is far removed from the control surface, significant unsteady pressures are produced forward of the midchord at this station. Results of this investigation are presented in reference 17.

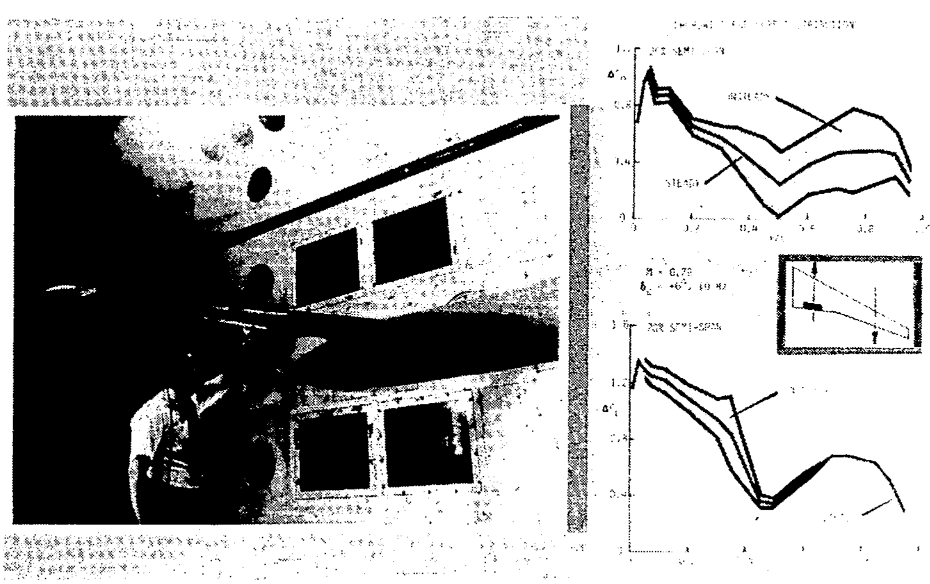


Figure 15

CONCLUSIONS

LESSONS LEARNED	FUTURE THRUSTS
● UNSTEADY AERO THEORY NEEDS ● CONTROL SURFACE ● ARBITRARY MOTION	● TRANSONIC TIME PLANE UNSTEADY AERO
● ACCURATE DEFINITION OF ACTUATOR DYNAMICS	● SYSTEMATIC METHODS FOR LOCATING CONTROL SURFACES AND SENSORS
● ACCURATE TURBULENCE MODEL	● APPLY FLUTTER SUPPRESSION METHODOLOGY TO OTHER ACTIVE CONTROL FUNCTIONS
● CLOSER COOPERATION BETWEEN AEROELASTICIAN AND CONTROLS ANALYST	● SYNTHESIS OF MULTIPLE ACTIVE CONTROL SYSTEMS
	● CONTROL CONFIGURED VEHICLES

Figure 16

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