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OVERVIEW OF LANGLEY ACTIVITIES IN ACTIVE CONTROLS RESEARCH

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ABSTRACT

The application of active controls 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 the NASA in the early 1970's to advance this concept. This presentation describes some of the activities of the Langley Research Center (LaRC) in advancing active controls technology. Activities 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.

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ACTIVITIES

This chart lists three areas in which the LaRC has ongoing activities aimed at advancing active controls technology. The following charts will expand on each of these areas.

- ANALYSIS
- CONTROL LAW SYNTHESIS
- EXPERIMENTAL INVESTIGATIONS

STABILITY ANALYSIS

This chart illustrates 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 cannot 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

$$
\begin{aligned}
&[M]\{\ddot{q}\} + [C]\{\dot{q}\} + [K]\{q\} && \text{STRUCTURE}\\
+\ &[C_1]\{\delta\} + [C_2]\{\dot{\delta}\} + [C_3]\{\ddot{\delta}\} && \text{CONTROLS}\\
+\ &[A_0]\{q\} + [A_1]\{\dot{q}\} + [A_2]\{\ddot{q}\} + \ldots = 0 && \text{AERODYNAMICS}
\end{aligned}
$$

- STABILITY

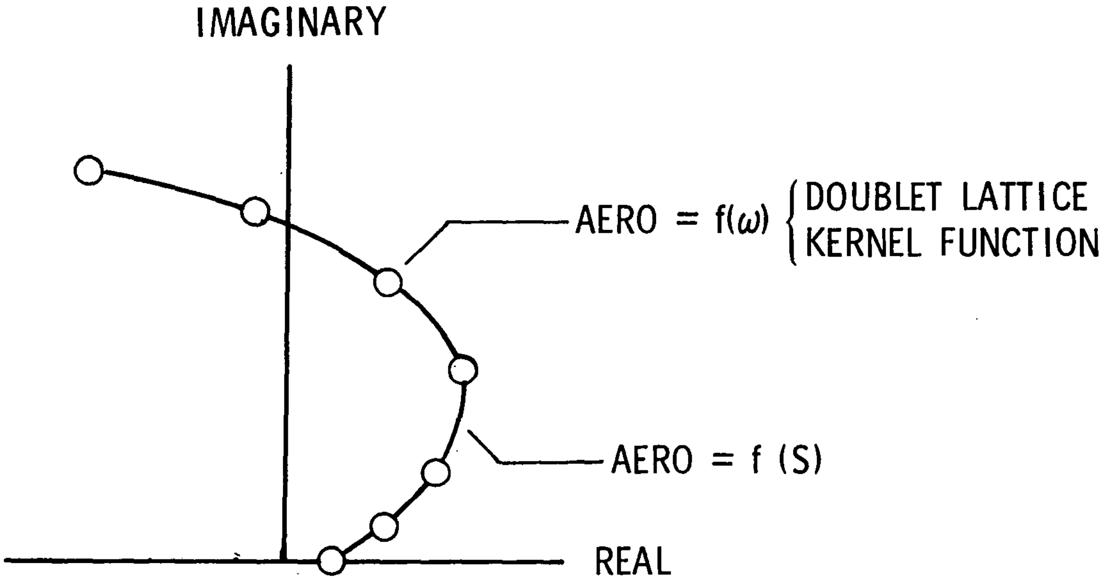
CONSTANT COEFFICIENT DIFFERENTIAL EQUATIONS

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

- UNSTEADY AERODYNAMICS NOT IN THIS FORM

UNSTEADY AERODYNAMIC APPROXIMATION

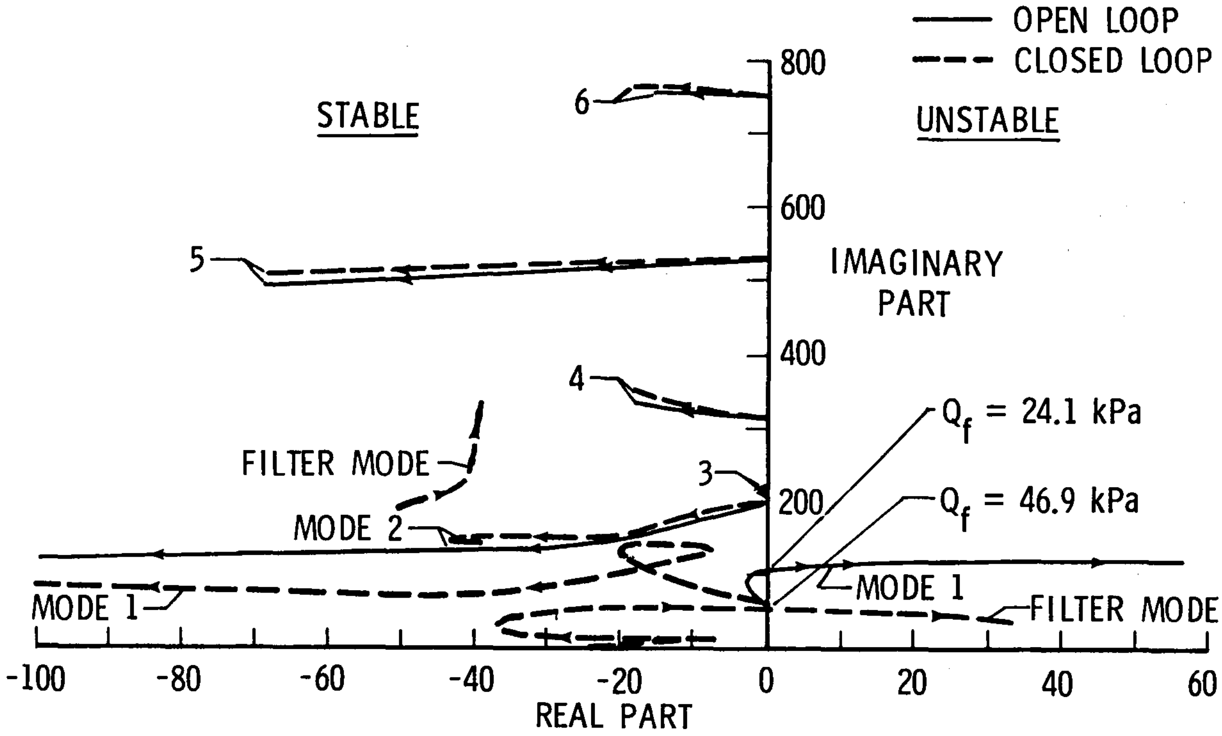
In lieu of developing a completely new aerodynamic theory, the approach taken is to allow the variation of the aerodynamic forces with frequency to be approximated by a rational function in the variable S. The form of the function presented permits an approximation of the time delays inherent in unsteady 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.



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

TYPICAL DYNAMIC PRESSURE ROOT LOCUS

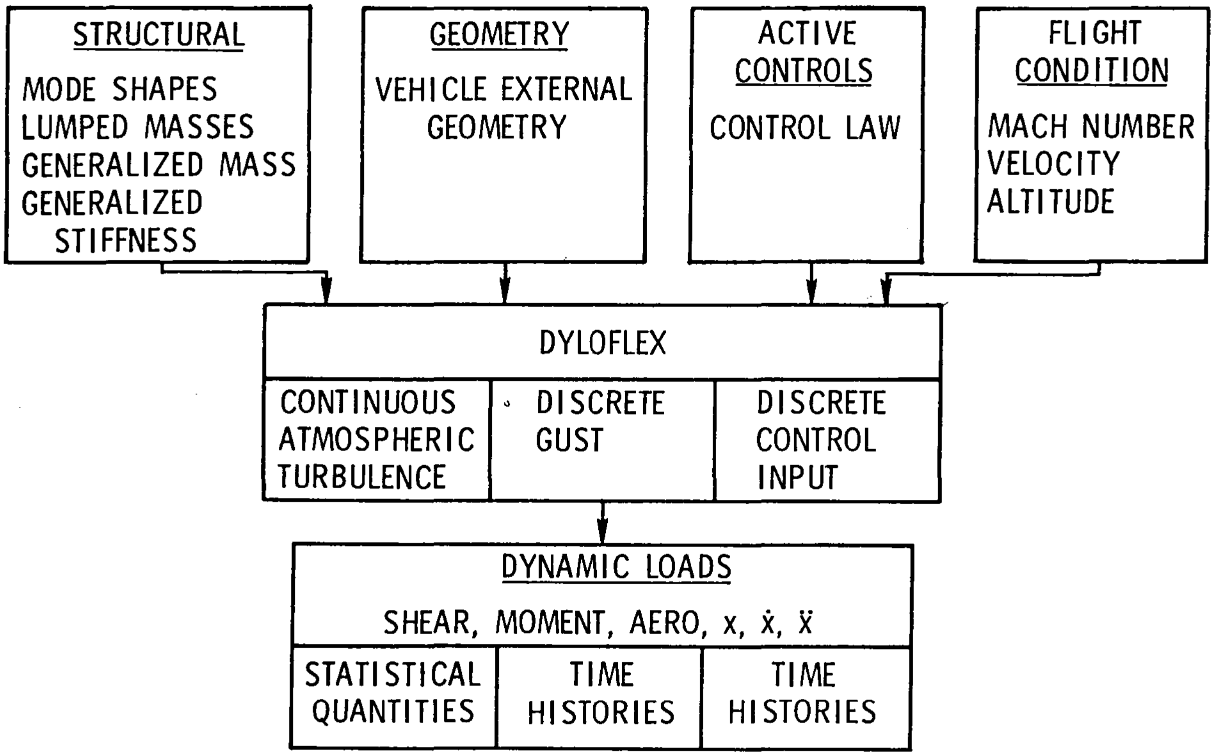
Using the aerodynamic approximating functions, the stability problem is solved by calculating the roots of the characteristic equation. This chart presents a typical root locus of the flexible mode roots as a function of dynamic pressure for a drone test vehicle (arrows indicate increasing dynamic pressure). 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 (Q_f = 24.1 kPa). 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 (Q_f = 46.9 kPa). 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.



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.

DYNAMIC LOADS ANALYSES OF FLEXIBLE AIRPLANES WITH ACTIVE CONTROLS



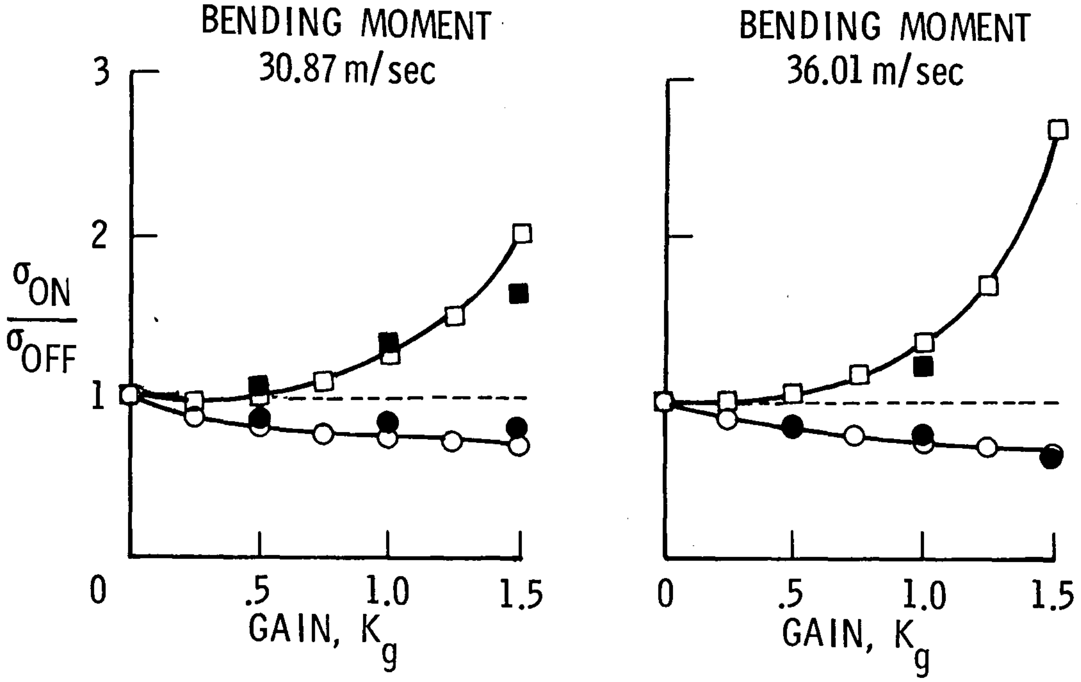
DYLOFLEX RESULTS

An example of DYLOFLEX's capability is presented on this chart. It presents a comparison of analytically predicted and experimentally measured turbulence responses of a wind tunnel model of a DC-10 derivative wing equipped with an active control system. Turbulence was modeled as a Dryden spectrum fitted to measured wind tunnel data. Results are presented in terms of the normalized rms values of wing bending moment as a function of system gain K_g and phase ϕ at two tunnel velocities. Analytical results are plotted as open symbols and experimental results as closed symbols. The comparison between analysis and experiment is quite good. Results of these tests are presented in reference 4.

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.

GUST LOADS ON ACTIVE CONTROL WIND-TUNNEL MODEL

	ANALYSIS	EXPERIMENT
$\Phi = 0°$	○	●
$\Phi = 20°$	□	■



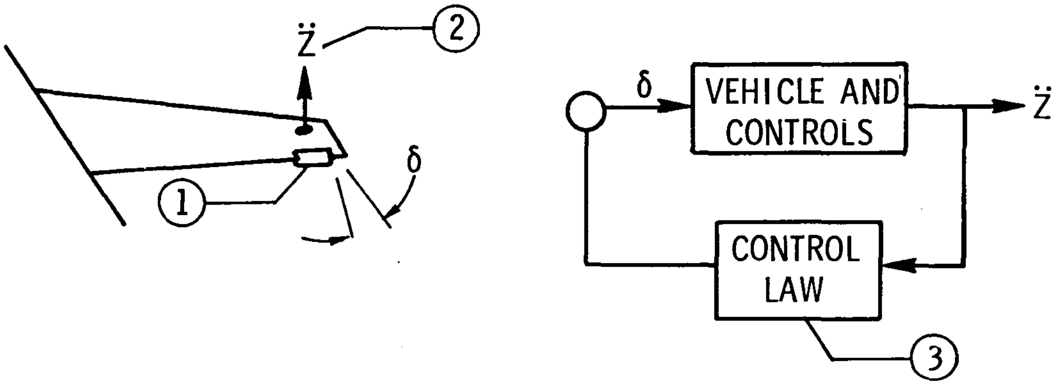
CONTROL LAW SYNTHESIS

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

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

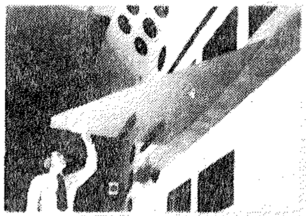
SYNTHESIS METHODS

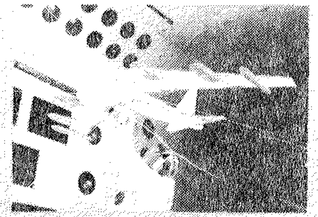
Three methods for synthesizing active control systems that the authors have used and are familiar with are listed on this chart. All three methods have been applied to the flutter suppression problem. References 5 through 11 describe the development and application of both the aerodynamic energy method and the use of optimal control theory as applied to the control of flexible aircraft.

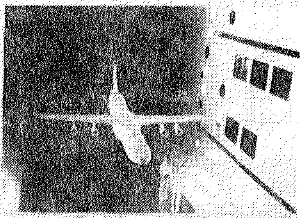
- CLASSICAL
- AERODYNAMIC ENERGY
- OPTIMAL CONTROL THEORY

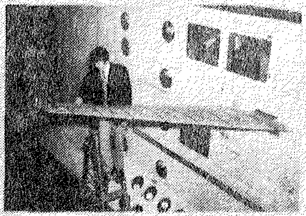
WIND TUNNEL STUDIES

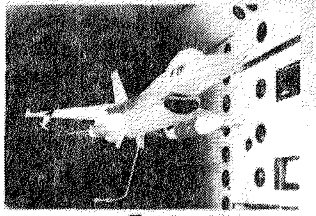
Wind tunnel studies of aeroelastic models have been a cornerstone of the NASA research program. Presented on this chart are a number of models that have been used to demonstrate active control concepts on a variety of configurations. The Delta-wing model was the first experimental demonstration of flutter suppression in this country (ref. 12). The B-52 model was tested in support of a USAF/Boeing flight study on active controls (ref. 13). Wing load alleviation was studied in support of a USAF/Lockheed program using a C-5A model (ref. 14). The DAST ARW-1 model was used for a variety of flutter suppression studies including an evaluation of a control system that would ultimately be tested on a remotely-piloted research flight vehicle. Control laws were synthesized and tested on the model using classical, aerodynamic energy, and optimal methods (ref. 6). 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. 15 and 16). 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. Increases in flutter speeds in excess of 26 percent were demonstrated. These studies are reported in reference 17.

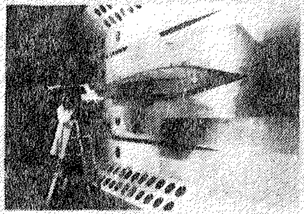

DELTA WING

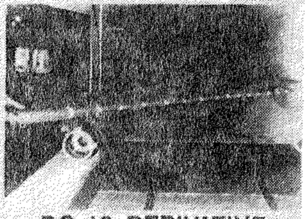

B-52 CCV


C-5A ALDCS


DAST ARW-1

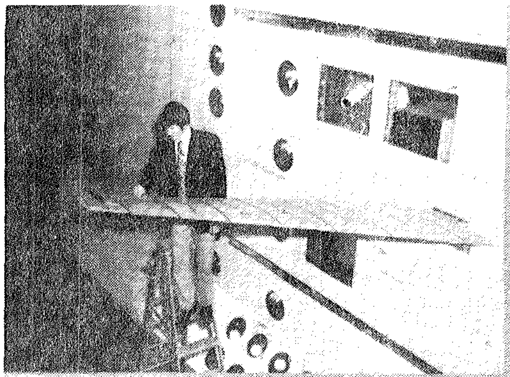

F-16


YF-17


DC-10 DERIVATIVE

FLUTTER SUPPRESSION DESIGN STUDY

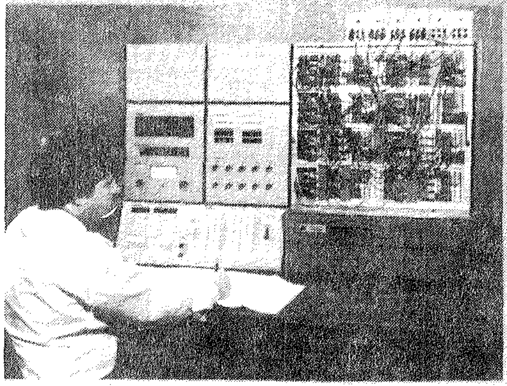
The objective of this wind tunnel study was to provide a 44 percent increase in flutter dynamic pressure for the aeroelastic model shown on the chart through the use of active controls. Two control laws were designed. One control law is based on the aerodynamic energy method, and the other is based on 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 flutter 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 6.



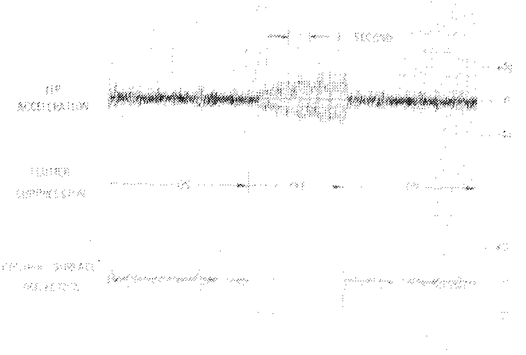
AEROELASTIC MODEL

- AERODYNAMIC ENERGY
- OPTIMAL

SYNTHESIS METHODS



IMPLEMENTATION

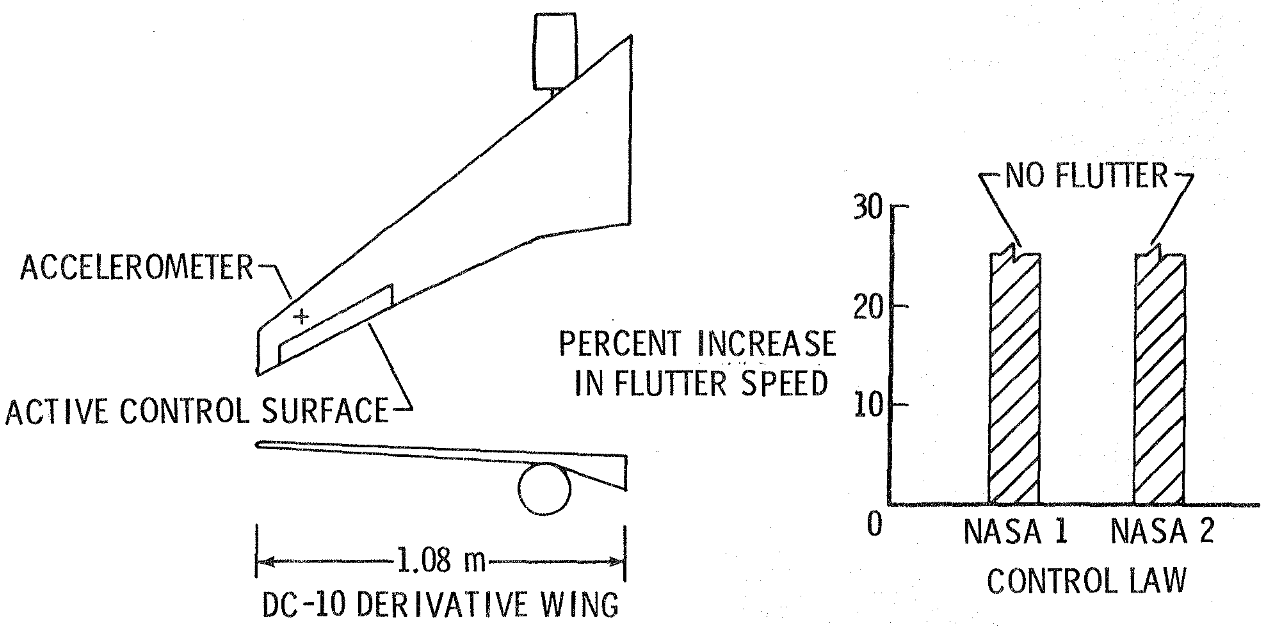


EXPERIMENTAL RESULTS

NASA DEVELOPED CONTROL LAWS DEMONSTRATE FLUTTER SPEED INCREASES IN EXCESS OF 25 PERCENT ON DC-10 DERIVATIVE WING

The aeroelastic model, shown schematically on the chart, is representative of a wing which has a 4.27 m span increase over the standard DC-10 wing. The semispan model is cantilevered from the tunnel wall and has an extended outboard aileron which is used as an active control surface. The purpose of this cooperative study with the Douglas Aircraft Company was to apply control law design methods developed by NASA to a realistic transport configuration with engines on the wing and to provide a rapid transfer of research technology to industry. These studies were an extension of previous wind tunnel tests performed by Douglas (ref. 18).

Two control laws were designed at NASA Langley using different design methods. As indicated on the chart, each control law demonstrated increases in flutter speed in excess of 25 percent during the wind tunnel tests. Other significant results from these tests (see ref. 17) indicated that: (1) analytically derived control laws were capable of demonstrating large increases in flutter speed; (2) calculations performed prior to wind tunnel testing predicted flutter mode trends; and (3) good correlation between measured and predicted characteristics as a function of system gain and phase.



DAST

(Drones for Aerodynamic and Structural Testing)

The concept of the DAST program (ref. 19) is to provide a focus for evaluation and improvement of synthesis and analysis procedures for aerodynamic loads prediction and design of active control systems on wings with significant aeroelastic effects. Major challenges include applications to wings with supercritical airfoil, and tests emphasizing the transonic speed range. The program requires complete solutions to real-world problems since research wings are fabricated and flight tested. Because of the risky nature of the flight testing, especially with regard to flutter, target drone aircraft are modified for use as test bed aircraft.

PRINCIPAL RESEARCH AREAS

- ACTIVE CONTROL SYSTEMS EVALUATIONS
- AERODYNAMIC LOADS MEASUREMENT
- STRUCTURAL INVESTIGATIONS
- STABILITY AND PERFORMANCE STUDIES

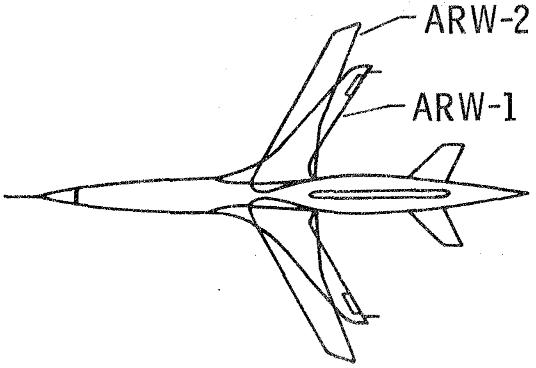
EMPHASIS

- TRANSONIC REGION
- AEROELASTIC EFFECTS

DAST RESEARCH WINGS

Two transport-type research wings are currently in the approved program. The first wing, Aeroelastic Research Wing No. 1 (ARW-1), was designed for M = 0.98 cruise and 2.5 g maneuver, and was purposely designed to flutter within the flight envelope. Flights are aimed at acquiring data emphasizing validation of a flutter suppression system (FSS) design and aeroelastic effects on aerodynamic loads.

The wing fabrication and tests for the second research wing (ARW-2) are sponsored by the NASA Aircraft Energy Efficiency program. This design involved what is believed to be the first exercise of an iterative procedure integrating aerodynamics, structures, and controls technologies in a design loop resulting in flight hardware. Evaluation of multiple active controls systems operating simultaneously, the operation of which is necessary to preserve structural integrity for various flight conditions, is the primary objective of the flight tests on this fuel-conservative-type wing.



ARW-1

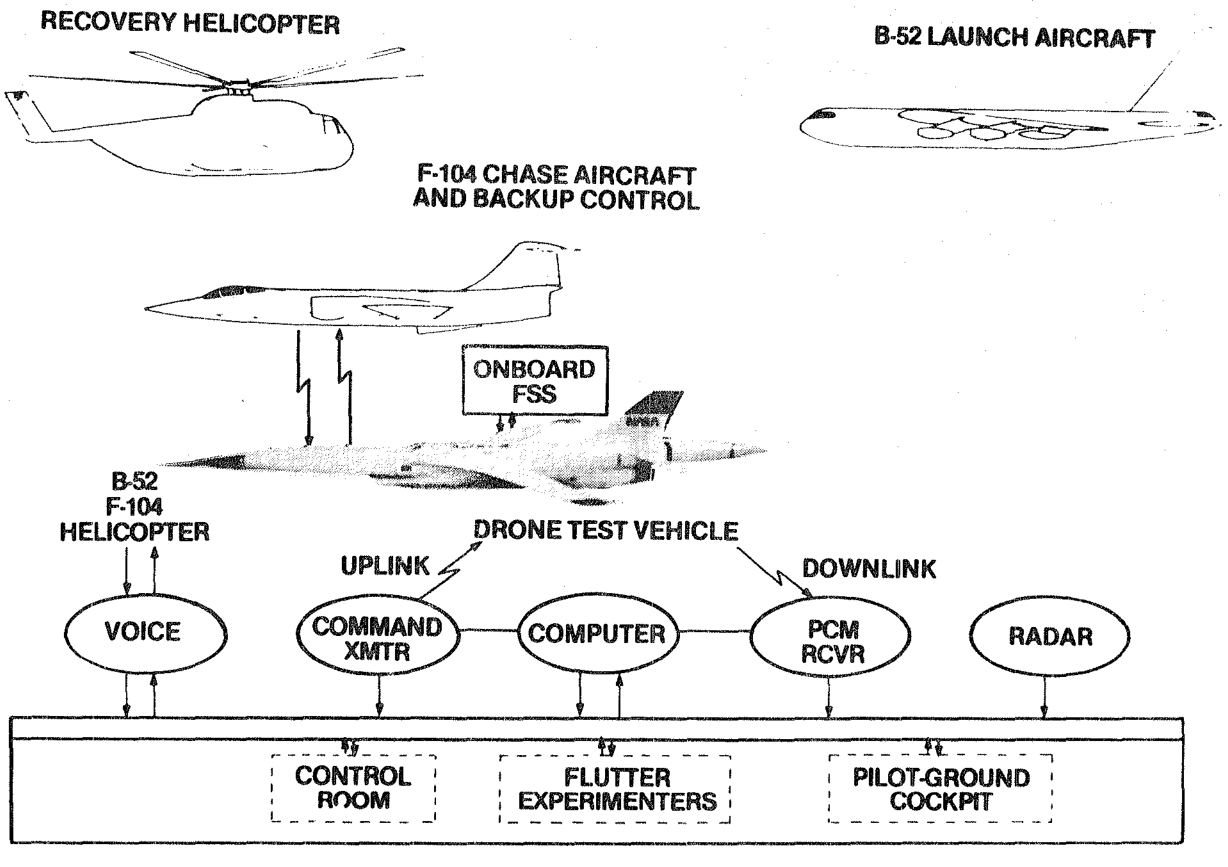
- FLUTTER WITHIN FLIGHT ENVELOPE
- ACTIVE FLUTTER SUPPRESSION SYSTEM
- SUPERCRITICAL AIRFOIL

ARW-2

- FUEL CONSERVATIVE WING DESIGN
  - HIGH ASPECT RATIO (AR = 10.3)
  - LOW SWEEP (= 25°)
  - ADVANCED SUPERCRITICAL AIRFOIL
- INTEGRATED DESIGN PROCEDURES
- MULTIPLE ACTIVE CONTROLS CRITICAL TO FLIGHT OPERATION

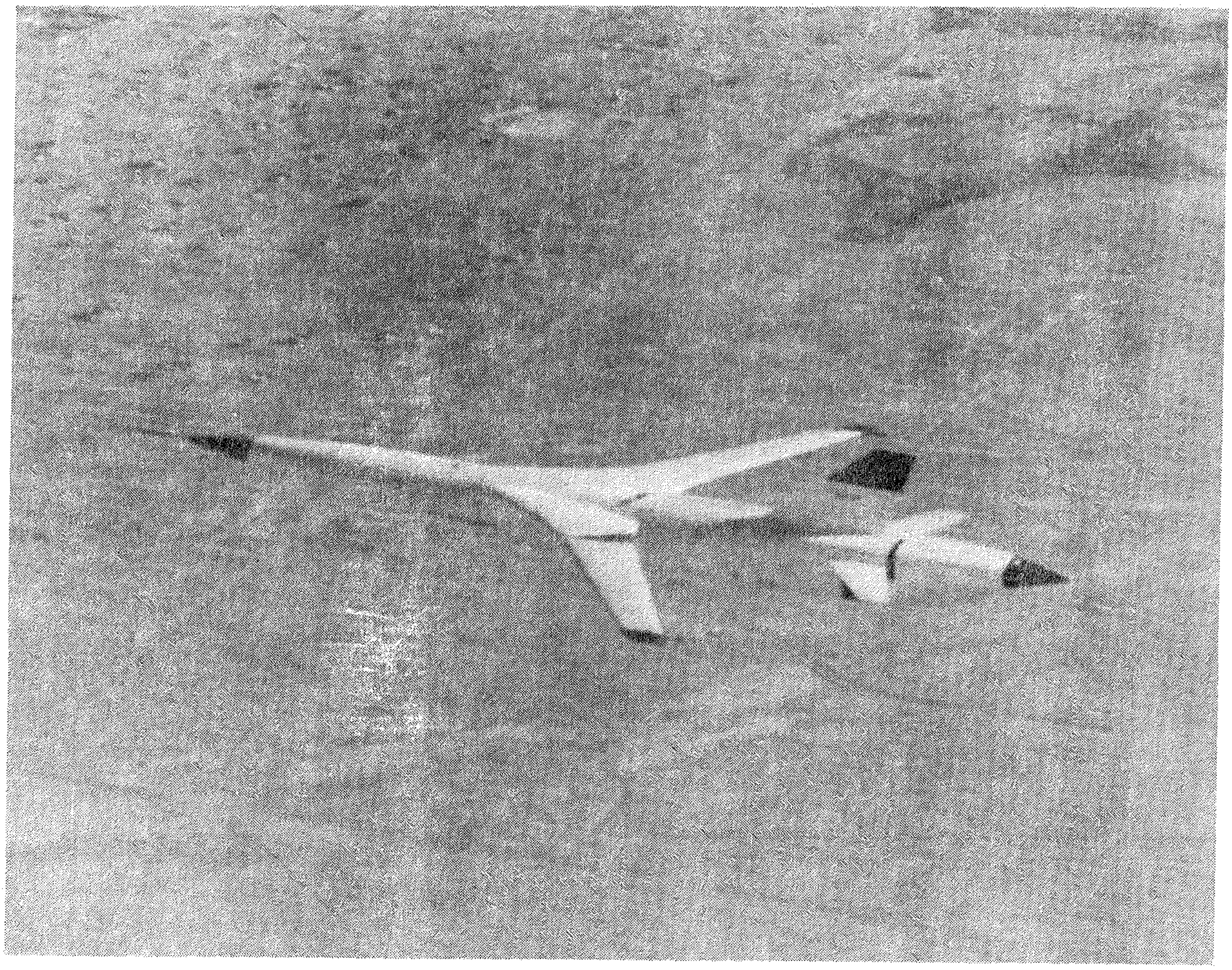
DAST OPERATIONAL CONCEPT

DAST uses an Air Force version of the Firebee II target drone as the basic test bed. The standard Firebee wing is removed and replaced with the research wing of interest. The operational sequence, as depicted on this chart, involves an air launch from beneath the wing of a B-52 carrier aircraft; a free flight test phase of between 20 and 40 minutes (depending on Mach number and altitude); followed by a midair retrieval by helicopter via a parachute recovery system. During the free flight phase, a test pilot controls the vehicle from a ground cockpit. An F-104 aircraft is used as chase and the copilot of this aircraft serves as a backup flight controller for the drone in case of a malfunction with the uplink system. Data from the experiments are provided in real-time to the ground by means of a pulse-code-modulated telemetry system. Experimenters provide real-time assessments of the status of the research wing and its associated active control systems. This assessment is based on the response of the wing to control surface sweeps and pulses. Flight tests are being performed at the Dryden Flight Research Center located at Edwards Air Force Base, California.



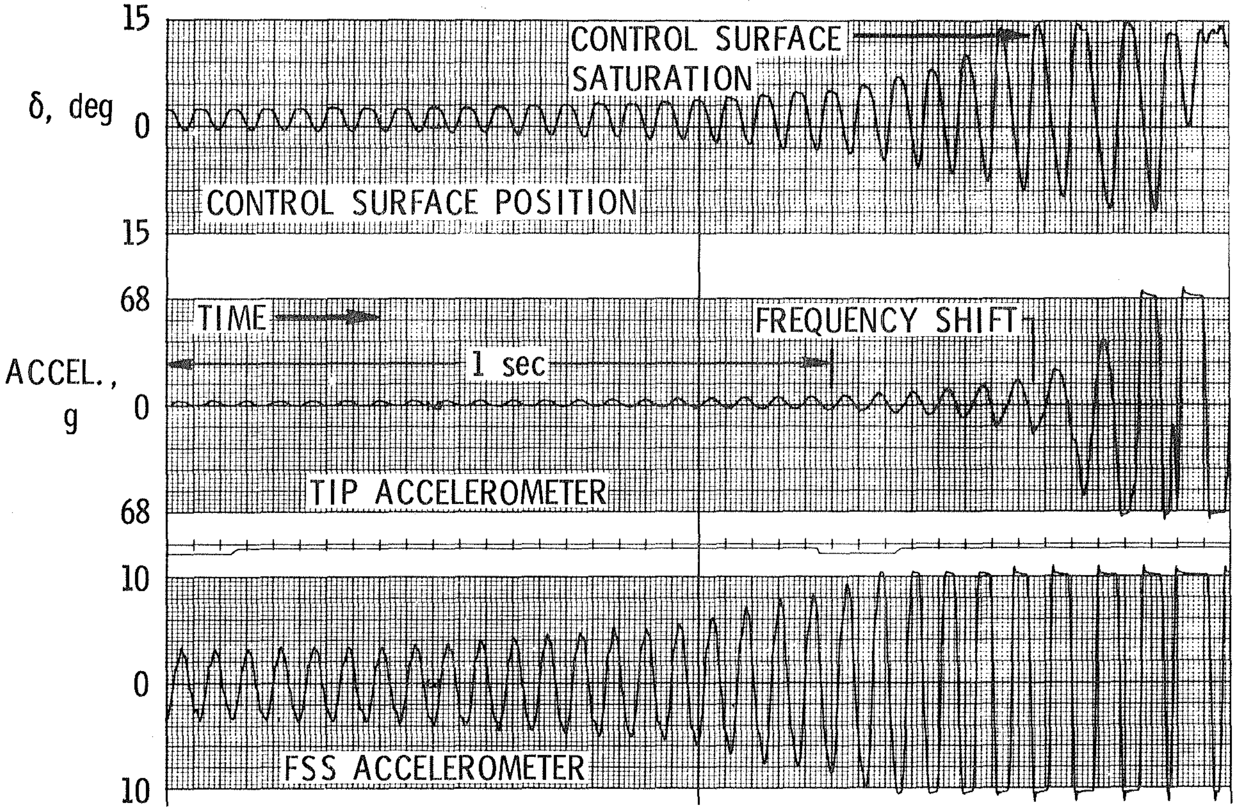
ARW-1 FLIGHT TESTS

Three flights have been made with the first research wing. (See references 20-22.) The first flight in October 1979 principally involved overall flight systems evaluations and results led to further work with the flight control system. The second flight was made in March 1980 and was highly successful. The third flight was conducted in June 1980. Following acquisition of data at four points of increasing Mach number at 4.6 km altitude, flutter was inadvertently encountered in advancing to the fifth data point. The right wing separated from the aircraft, and due to excessive damage to the parachute on emergency deployment, impact velocity was excessive and the airframe was damaged beyond repair. The ARW-1 wings and airframe are presently being rebuilt and flight testing should begin in the fourth quarter of 1981.



FLUTTER ONSET TIME HISTORY

Flutter was encountered on DAST ARW-1 as speed was being increased from one test point to another at a Mach number slightly above 0.8. The procedure was to excite the wing with a symmetric sine sweep and an antisymmetric sine sweep, progress to the next higher test point while exciting the wing every 3-4 seconds with symmetric and antisymmetric pulses and observing the response of the wing accelerometer output on a strip chart. The time history of wing tip acceleration during flutter onset can be observed from the flutter suppression system (FSS) accelerometer output scaled to ±10 g peak and subsequently by another accelerometer located at the wing tip which was scaled to ±68 g peak. It was observed that a frequency shift (from about 19 Hz to about 14.5 Hz) occurred at a time corresponding to when control surface amplitude saturation was reached. Since this event would effectively reduce gain, the frequency shift probably corresponds to a shift to essentially the open-loop condition. Subsequent to this time, the amplitude quadrupled in two cycles. An aft-located mass, designed to be released in emergencies, was released, but apparently due to the rapid buildup was not effective in stopping flutter. The flutter incursion was later attributed to an error in the gain implemented in the FSS.



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16. Abstract

The application of active controls 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 the NASA in the early 1970's to advance this concept. This presentation describes some of the activities of the Langley Research Center (LaRC) in advancing active controls technology. Activities are categorized into the development of appropriate analysis tools, control law synthesis methodology, and experimental investigations aimed at verifying both analysis and synthesis methodology.

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