N81-30464

NASA Technical Memorandum 83179

NASA-TM-83179 19810021927

SOME EXPERIENCES WITH ACTIVE CONTROL
OF AEROELASTIC RESPONSE

JERRY R. NEWSOM AND IRVING ABEL

JULY 1981

NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

SOME EXPERIENCES WITH ACTIVE CONTROL OF AEROELASTIC RESPONSE

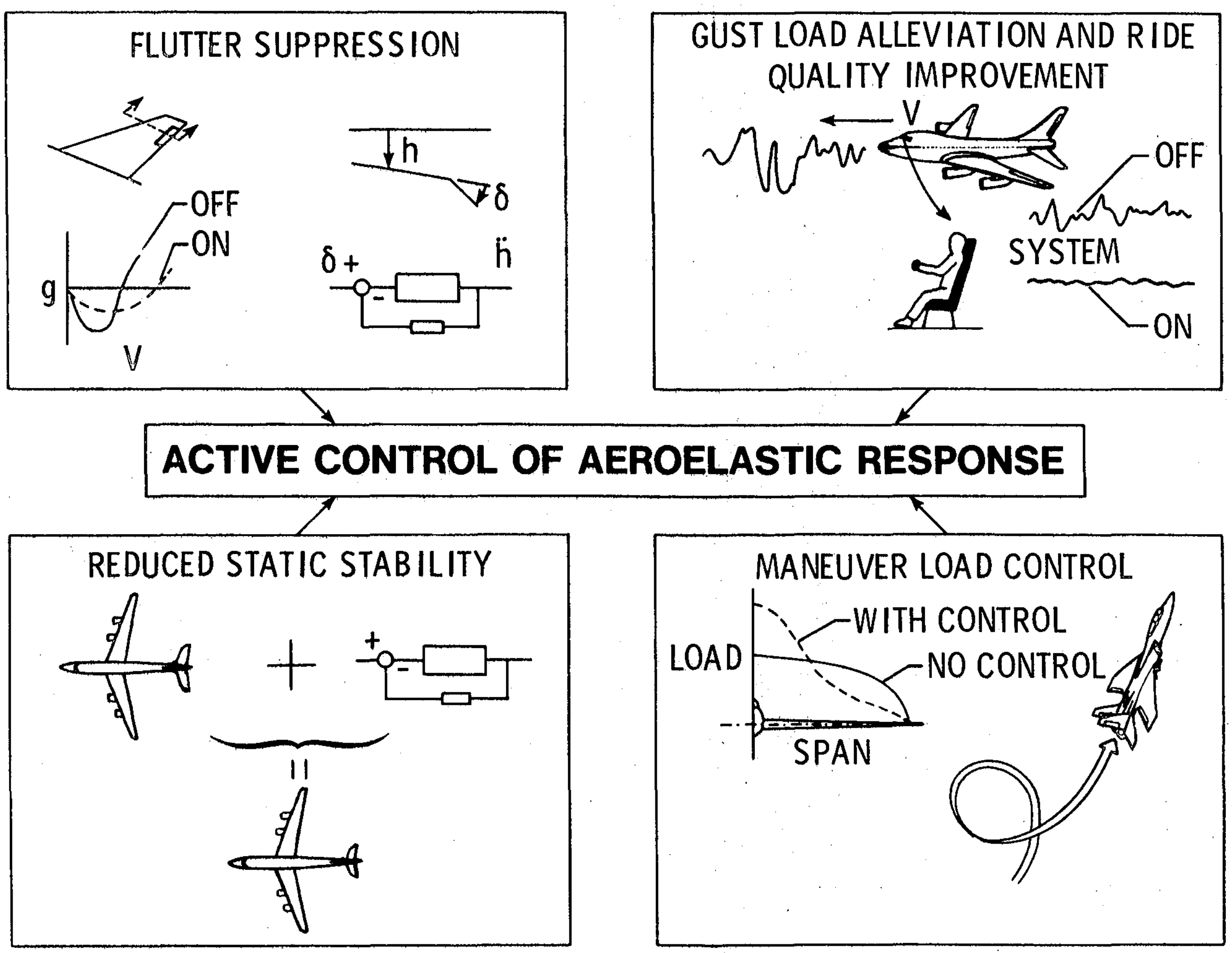
By Jerry R. Newsom and Irving Abel
NASA Langley Research Center
Hampton, Virginia

ABSTRACT

Traditionally, aircraft control systems have been designed primarily to achieve a desired flightpath in response to pilot or guidance system commands. However, considerable effort is now being focused on the additional use of control systems to control aeroelastic response. This presentation describes some of the experiences encountered at the NASA Langley Research Center while performing research in active control technology. The experiences are categorized in terms of analysis and experiments.

ACTIVE CONTROL OF AEROELASTIC RESPONSE

This chart illustrates the functions that are usually associated with active control of aeroelastic response. Because of its impact on safety of flight, flutter suppression is probably the concept furthest from practical implementation and has received significant attention. The concept is to increase the flutter speed of the vehicle through the use of active controls. The benefit to be derived from flutter suppression is usually reduced structural weight. Gust load alleviation and ride quality improvement apply to flight through atmospheric turbulence. Gust load alleviation allows reduced structural weight by reducing wing loads. Ride quality control improves the passenger ride comfort. Reduced static stability is an active control function that does not directly involve aeroelastic response. The benefits are reduced drag and a smaller horizontal tail. Maneuver load control also is used to reduce wing loads and the benefit is reduced structural weight.



ELEMENTS OF PRESENTATION

The presentation is divided into three major elements. The first is analytical experiences. Both analysis and design will be discussed. The second is experimental experiences. Both wind-tunnel and flight tests will be discussed. The last is future activities.

- ANALYTICAL EXPERIENCES
- EXPERIMENTAL EXPERIENCES
  - WIND-TUNNEL TESTS
  - FLIGHT TESTS (DAST)
- FUTURE ACTIVITIES

ANALYTICAL EXPERIENCES

Analysis

The analysis of an actively controlled flexible aircraft requires that the interfaces among unsteady aerodynamics, structures, and control theory be properly considered. Because of the multidisciplinary nature of the problem, the format of the equations of motion and the analytical methods used to solve them are many times inconsistent. To properly handle these problems is a complex task that requires the use of efficient multidiscipline computer programs. The need for these types of computer programs was evident in the early 70's and resulted in a recommendation by a NASA advisory committee. In response to this recommendation, several computer programs for analyzing actively controlled flexible aircraft were developed. One of the first of these programs was FCAP (Flight Controls Analysis Program; ref. 1) developed under contract by Aerospace Systems, Inc. The ISAC (Interaction of Structures, Aerodynamics, and Controls; ref. 2) program was developed at Langley and is used regularly in NASA-related research. DYLOFLEX is an integrated system of stand-alone computer programs which performs dynamic loads analyses of flexible airplanes with active controls (ref. 3). It was developed under contract by the Boeing Company and is available from COSMIC (Computer Software Management and Information Center).

RECOMMENDATION: DEVELOPMENT OF EFFICIENT MULTIDISCIPLINE COMPUTER PROGRAMS FOR ANALYSIS AND DESIGN OF STRUCTURES AND CONTROL SYSTEMS

RESPONSE: COMPUTER SOFTWARE

- FCAP
- ISAC
- DYLOFLEX

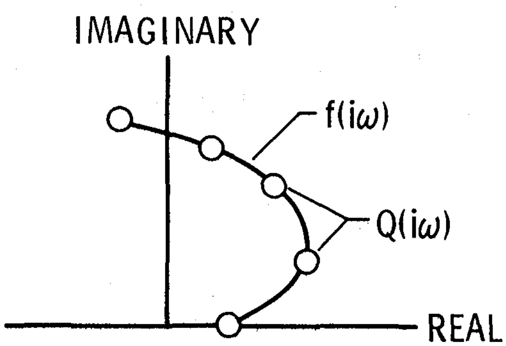
UNSTEADY AERODYNAMICS APPROXIMATION

All of the programs listed on the previous chart incorporate unsteady aerodynamics. From a stability calculation point of view, the incorporation of unsteady aerodynamics presents a problem that each program handles differently. This chart illustrates a solution to this problem that has received considerable attention.

Unsteady aerodynamics are computed for simple harmonic motion at specified values of frequency. Furthermore, the real and imaginary parts of the aerodynamic forces are available only in tabular form ($Q(i\omega)$). The approach taken here and implemented in the ISAC program is to allow the variation of the aerodynamic forces with frequency to be approximated by a rational function of $i\omega$ ($f(i\omega)$; (ref. 4). There are several techniques available for obtaining a rational function. The most widely known are the so-called least squares (ref. 5) method and the Pade (ref. 6) method. With either of these methods, the Laplace variable s is substituted for $i\omega$ and time derivatives are then associated with the powers of s. This results in a set of constant coefficient differential equations that can be used in an eigenvalue analysis to determine stability. In addition, the equations of motion are in a form that can be used for control law design.

UNSTEADY AERO $\Longrightarrow$

ω	$Q(i\omega)$ REAL	$Q(i\omega)$ IMAGINARY
0	—	—
5	—	—
10	—	—
20	—	



$$f(i\omega) = Q(i\omega)$$

$$\Downarrow$$

$$\mathring{x} = Ax + Bu$$

$$\Downarrow$$

DESIGN TECHNIQUES

- LEAST SQUARES
- PADE

ANALYTICAL EXPERIENCES

Design

The NASA advisory committee previously referred to also recommended the development of computer programs for the design of control systems. Therefore, in addition to analysis, control law design has also been an integral part of our research. Since control law design is generally more difficult than analysis, it has lagged behind from the viewpoint of production computer programs. The primary emphasis of our work has been the development of design methodology. Three methods for designing 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 (refs. 7 and 8). We are now beginning to apply these basic methods to other active control functions (ref. 9). Optimal control theory seems to be the best suited for the task of designing multifunctional active control systems. Therefore, a considerable amount of attention is being given to design methods that employ optimal control theory.

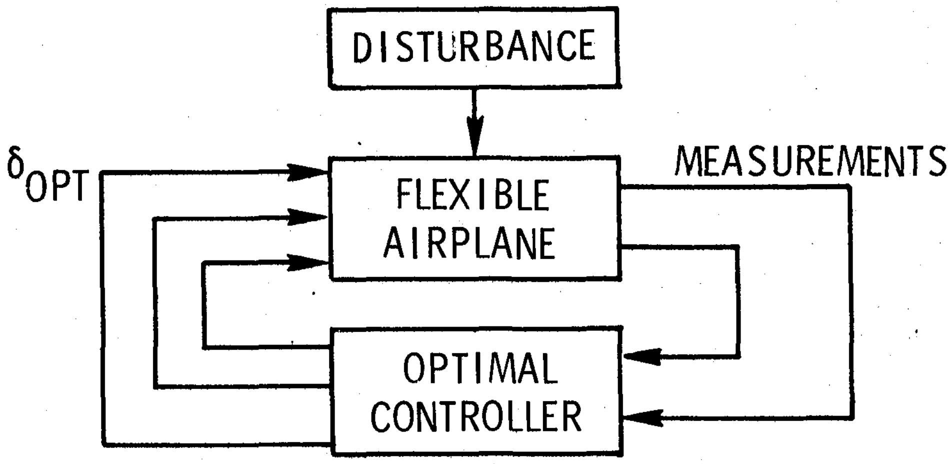
RECOMMENDATION: DEVELOPMENT OF EFFICIENT MULTIDISCIPLINE COMPUTER PROGRAMS FOR ANALYSIS AND <u>DESIGN</u> OF STRUCTURES AND CONTROL SYSTEMS

RESPONSE: METHODOLOGY

- CLASSICAL
- AERODYNAMIC ENERGY
- → OPTIMAL CONTROL THEORY

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.

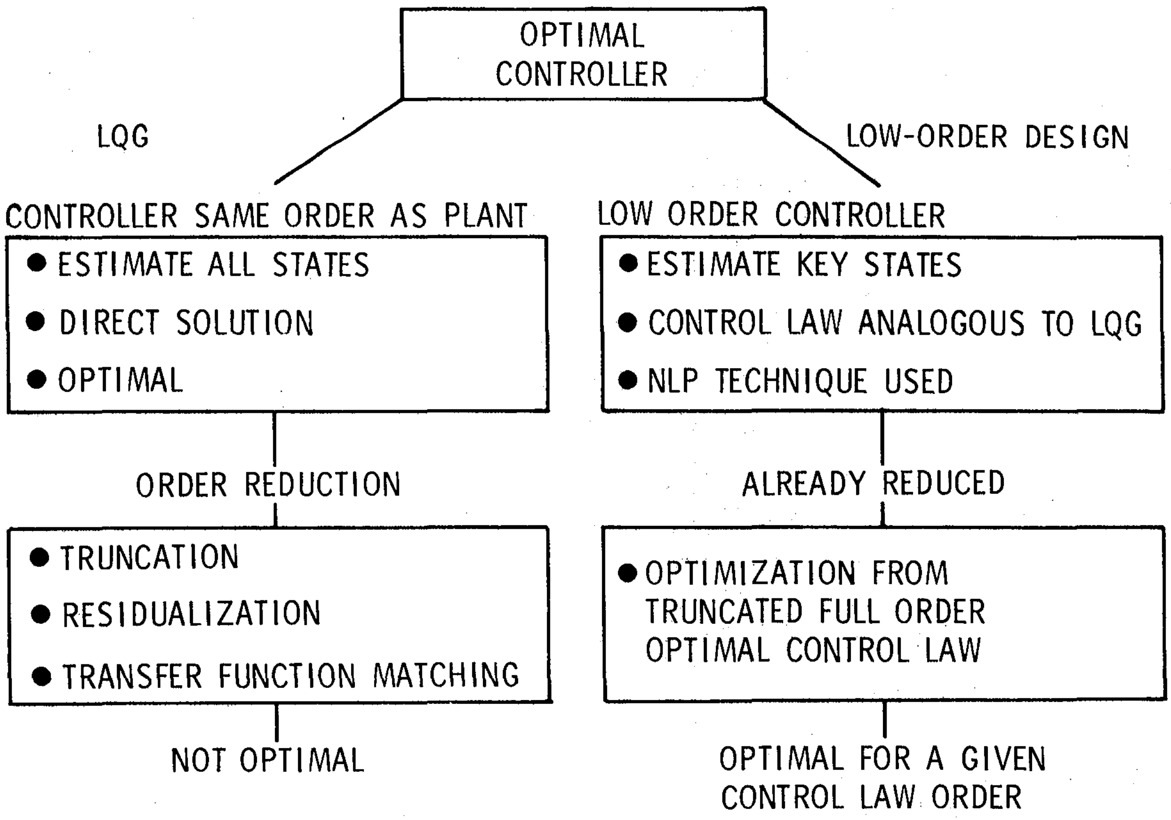


- OPTIMIZATION CRITERIA
  - CONTROL DEFLECTION
  - BENDING MOMENT
- MULTIPLE SENSORS/CONTROLS SIMULTANEOUSLY
- MULTIPLE CONTROL TASKS
- ADAPTABLE TO DIGITAL DESIGN/ANALYSIS

OPTIMAL CONTROLLER DESIGN

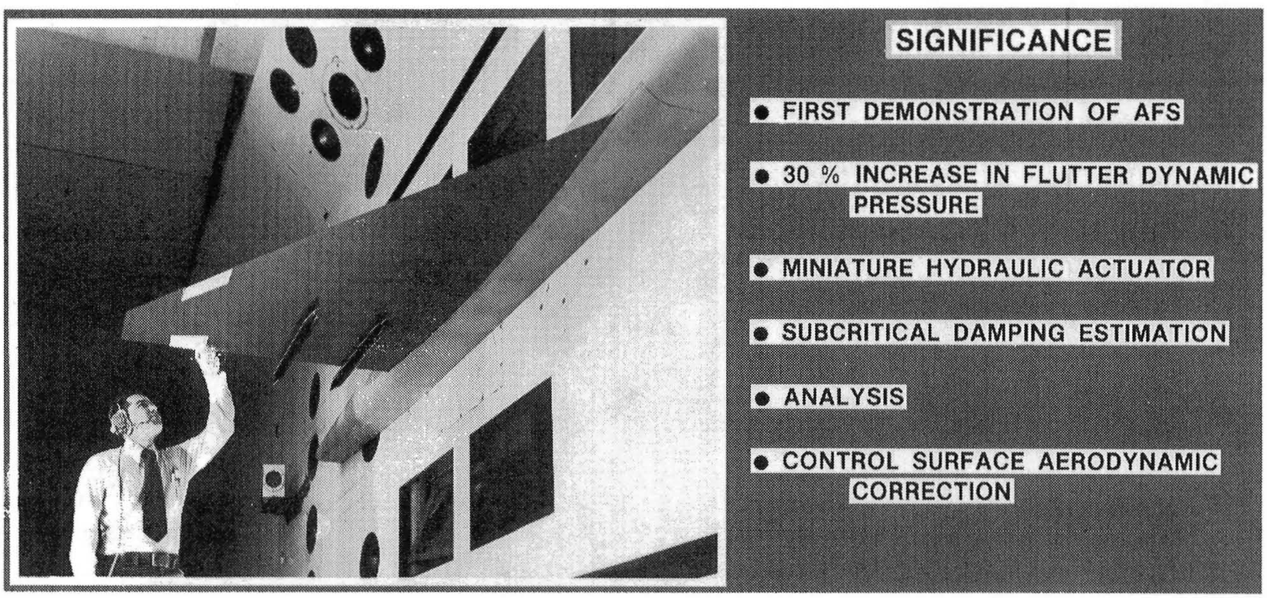
The Linear-Quadratic-Gaussian (LQG) method has become the most widely accepted means of synthesizing optimal controllers (ref. 10). However a shortcoming of this method, in particular for high-order systems (characteristic of flexible airplanes), is the requirement that the control law be of the same 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. 8, 11, and 12). 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. 13). 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 programing 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.



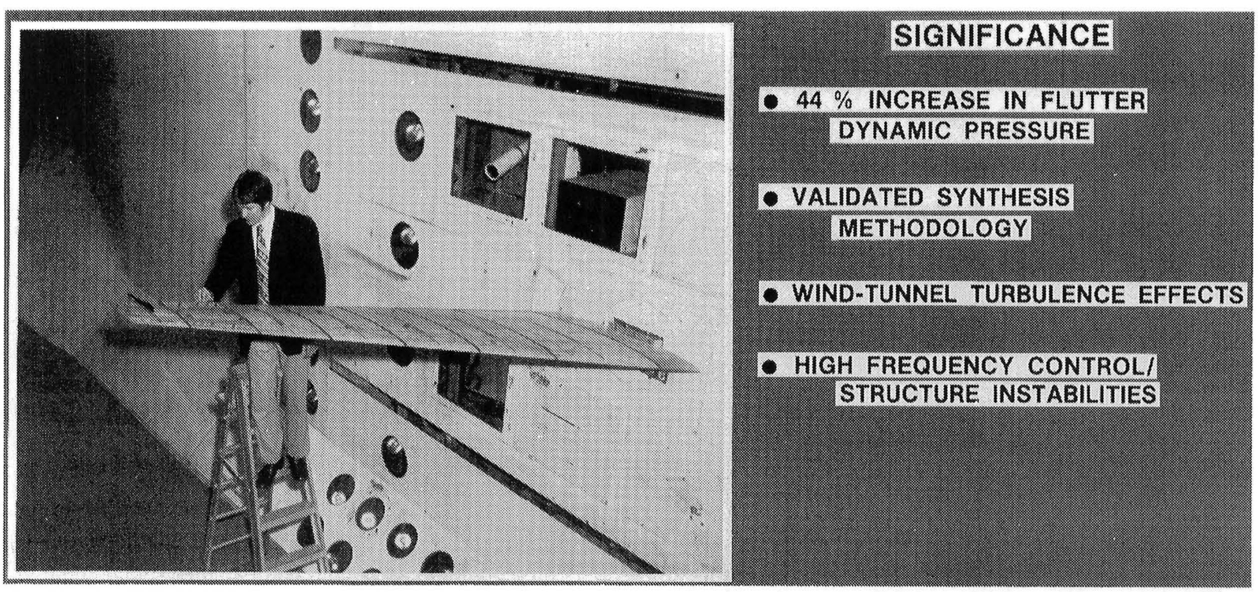
DELTA WING MODEL

Experimental studies have made a major contribution to the active control technology program developed at the NASA. The Delta-wing model (whose photograph is on this chart) was the first experimental demonstration of flutter suppression in this country (ref. 14). At a Mach number of 0.9, increases in the flutter dynamic pressure ranging from 12.5 percent to 30 percent were demonstrated with active controls. One of the major contributions of this wind-tunnel program was the development of miniature hydraulic actuators. These actuators paved the way for future wind-tunnel tests of aeroelastically scaled models. To evaluate the performance of an active flutter suppression system, subcritical response techniques must be employed. Three different methods were used to determine subcritical response of the Delta-wing model and the results are described in reference 14. Analytical methods were used to predict both open-loop and closed-loop stability, and the results agreed reasonably well with the experiment. However, for the closed-loop case, it was necessary to use a control surface aerodynamic correction factor that was derived using measured hinge moment data.



DAST MODEL

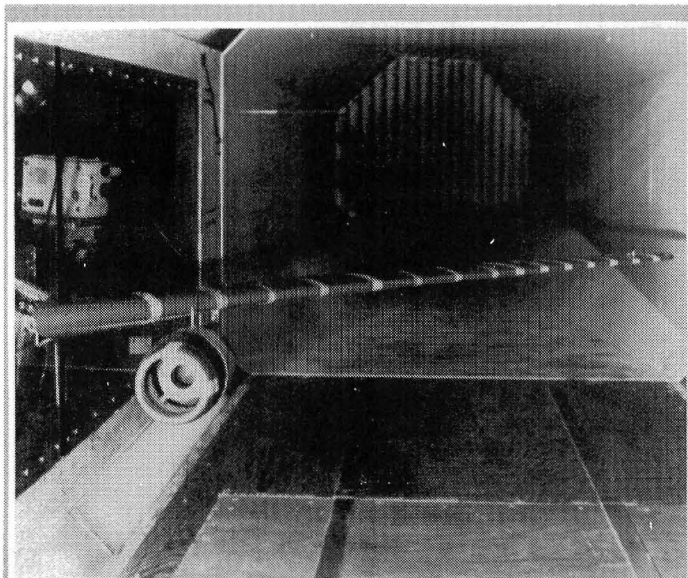
The aeroelastic model used for this study was originally built to support the DAST flight program (ref. 15). The objective of the wind-tunnel study was to provide a 44 percent increase in flutter dynamic pressure. Two control laws were designed (ref. 16). One control law was based on the aerodynamic energy method and the other was based on the results of optimal control theory. At Mach 0.95, a 44 percent increase in flutter dynamic pressure was achieved with both control laws, thereby validating the two synthesis methodologies. Experimental results indicated that the performance of the systems was not as good as that predicted by analysis. The results also indicated that wind-tunnel turbulence is an important factor in both control law synthesis and experimental demonstration.



DC-10 MODEL

A cooperative study with the Douglas Aircraft Company was initiated to apply control law design methods developed by NASA to a realistic transport configuration 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. 17). The aeroelastic model (shown in the photograph on this chart) is representative of a wing which has a 4.27 m span increase over the standard DC-10 wing.

Two control laws were designed at NASA Langley using different design methods (ref. 18). Both control laws demonstrated a 59 percent increase in flutter dynamic pressure. The performance of the control laws as a function of gain and phase was also evaluated. Calculations performed prior to wind-tunnel testing predicted all experimental trends. During the wind-tunnel tests, both structural damping and phase characteristics of the actuator were identified as very important factors related to the effectiveness of the control laws. In addition, a correction factor was used to account for control surface effectiveness and did improve the correlation between measured and predicted characteristics.



SIGNIFICANCE

- 59 % INCREASE IN FLUTTER DYNAMIC PRESSURE
- PERFORMANCE AS A FUNCTION OF GAIN AND PHASE
- ANALYSIS PREDICTED ALL EXPERIMENTAL TRENDS
- STRUCTURAL DAMPING EFFECTS
- ACTUATOR DYNAMICS
- CONTROL SURFACE AERODYNAMIC CORRECTION

DAST

What Is It?

(Drones for Aerodynamic and Structural Testing)

The concept of the DAST program (ref. 15) 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

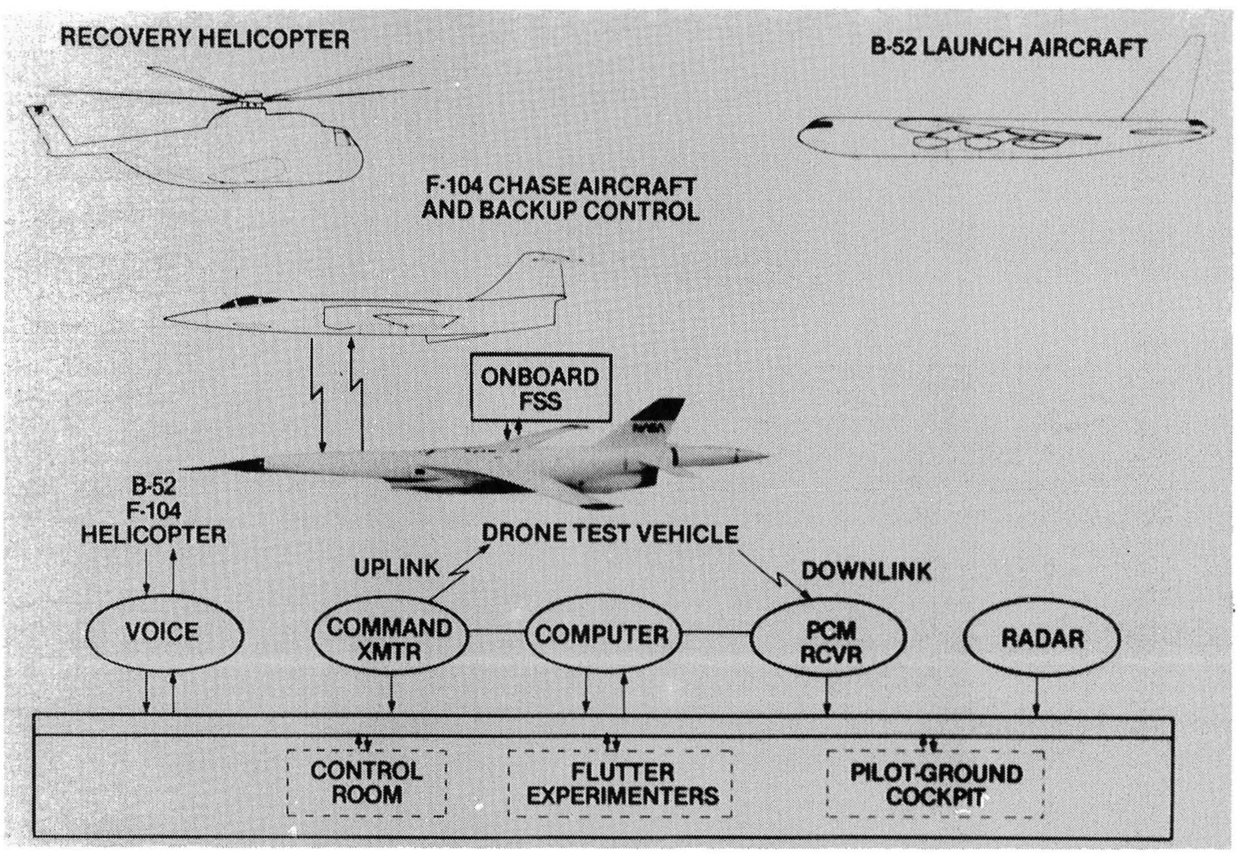
EMPHASIS

- TRANSONIC REGION
- AEROELASTIC EFFECTS

DAST

How Do We Do It?

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 NASA Dryden Flight Research Center located at Edwards Air Force Base, California.



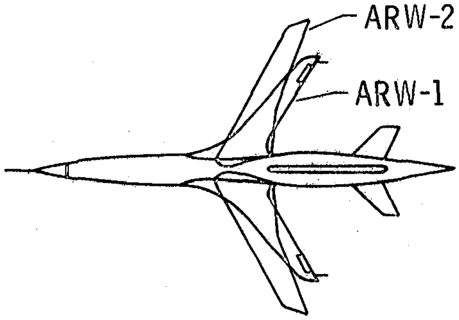
DAST

What Are We Doing It With?

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.

DAST RESEARCH WINGS



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
- MULTIPLE ACTIVE CONTROLS CRITICAL TO FLIGHT OPERATION
  - FSS
  - MLA
  - GLA
  - RSS

FUTURE ACTIVITIES

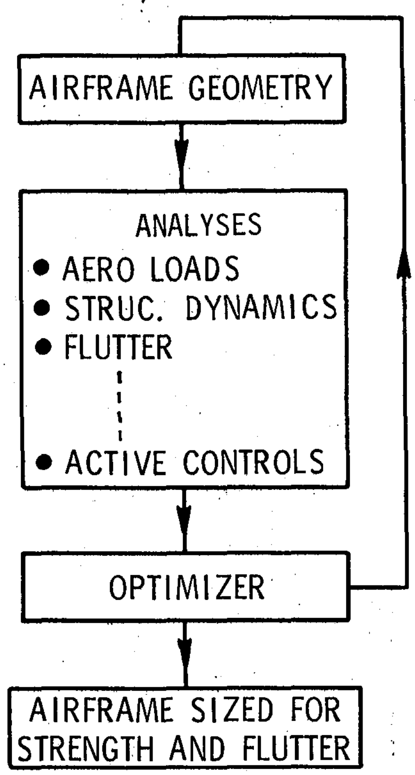
Control Concepts and Synthesis

Several of the future activities being planned for active controls research are listed on this chart. Improved analysis and synthesis methodology which include the incorporation of new unsteady aerodynamic theories, the development of multifunctional active control law synthesis methodology, sensitivity analysis (ref. 19), and sampled-data analysis and design are among the future research tasks. Wind-tunnel tests and flight tests such as the DAST program are aimed at validating active control technology. In the context of overall methodology development, the incorporation of active controls into the aircraft design process is the main emphasis (ref. 20). This will put active controls on the same level as aerodynamics, structures, etc., and would allow the maximum benefit of active control technology to be derived.

INTEGRATED OPTIMIZATION APPROACH

ACTIVE CONTROLS

- IMPROVED ANALYSIS AND SYNTHESIS METHODOLOGY
- VALIDATED TECHNOLOGY
- INTEGRATE INTO OPTIMIZATION PROCESS



REFERENCES

1. Noll, R. B.; and Morino, L.: FCAP--A New Tool for the Evaluation of Active Control Technology. AIAA Paper No. 75-1059, Aug. 1975.

2. Peele, Ellwood L.; and Adams, William M. Jr.: A Digital Program for Calculating the Interaction Between Flexible Structures, Unsteady Aerodynamics, and Active Controls. NASA TM 80040, 1979.

3. Perry, B. III; Kroll, R. I.; Miller, R. D.; and Goetz, R. C.: DYLOFLEX: A Computer Program for Flexible Aircraft Flight Dynamic Loads Analyses With Active Controls. J. Aircraft, Vol. 17, No. 4, April 1980, pp. 275-282.

4. Roger, K. L.: Airplane Math Modeling Methods for Active Control Design. Structural Aspects of Active Controls. AGARD-CP-228, Aug. 1977.

5. Abel, I.: An Analytical Technique for Predicting the Characteristics of a Flexible Wing Equipped With an Active-Flutter-Suppression System and Comparison With Wind-Tunnel Data. NASA TP 1367, Feb. 1979.

6. Dunn, H. J.: An Analytical Technique for Approximating Unsteady Aerodynamics in the Time Domain. NASA TP 1738, Nov. 1980.

7. Nissim, E.; and Abel, I.: Development and Application of an Optimization Procedure for Flutter Suppression Using the Aerodynamic Energy Concept. NASA TP 1137, Feb. 1978.

8. Newsom, J. R.: A Method for Obtaining Practical Flutter Suppression Control Laws Using Results of Optimal Control Theory. NASA TP 1471, Aug. 1979.

9. Newsom, J. R.; and Mukhopadhyay, V.: Application of Constrained Optimization to Active Control of Aeroelastic Response. NASA TM 83150, June 1981.

10. Athans, Michael: The Role and Use of the Stochastic Linear-Quadratic-Gaussian Problem in Control System Design. IEEE Trans. Autom. Control, Vol. AC-16, No. 6, December 1971, pp. 529-552.

11. Gangsaas, Dagfinn; and Ly, Vy-Loi: Application of a Modified Linear Quadratic Gaussian Design to Active Control of a Transport Airplane. AIAA Paper No. 79-1746, August 1979.

12. Mahesh, J. K.; Stone, C. R.; Garrard, W. L.; and Hausman, P. D.: Active Flutter Control for Flexible Vehicles. NASA CR-159160, Nov. 1979.

13. Mukhopadhyay, V.; Newsom, J. R.; and Abel, I.: A Method for Obtaining Reduced Order Control Laws for High Order Systems Using Optimization Techniques. NASA TP 1876, 1981.

14. Sandford, M. C.; Abel, I.; and Gray, D. L.: Development and Demonstration of a Flutter Suppression System Using Active Controls. NASA TR 450, December 1975.

15. Murrow, H. N.; and Eckstrom, C. V.: Drones for Aerodynamic and Structural Testing (DAST)--A Status Report. J. Aircraft, Vol. 16, No. 8, August 1979, pp. 521-526.

16. Newsom, J. R.; Abel, I.; and Dunn, H. J.: Application of Two Design Methods for Active Flutter Suppression and Wind Tunnel Test Results. NASA TP 1653, May 1980.

17. Winther, B. A.; Shirley, W. A.; and Heimbough, R. M.: Wind-Tunnel Investigation of Active Controls Technology Applied to a DC-10 Derivative. AIAA Paper No. 80-0771, May 1980.

18. Abel, I.; and Newsom, J. R.: Wind-Tunnel Evaluation of NASA-Developed Control Laws for Flutter Suppression on a DC-10 Derivative Wing. AIAA Paper No. 81-0639, April 1981.

19. Sobieszczanski-Sobieski, J.; Barthelemy, J.-F.; and Riley, K. M.: Sensitivity of Optimum Solutions to Problem Parameters. NASA TM 83134, May 1981.

20. Sobieszczanski-Sobieski, J.; and Goetz, R. C.: Synthesis of Aircraft Structures Using Integrated Design and Analysis Methods--Status Report. NASA CP-2059, Oct. 1978, pp. 63-76.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM 83179		

4. Title and Subtitle	5. Report Date
SOME EXPERIENCES WITH ACTIVE CONTROL OF AEROELASTIC RESPONSE	July 1981
	6. Performing Organization Code 505-33-63-02
7. Author(s) Jerry R. Newsom and Irving Abel	8. Performing Organization Report No.
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Virginia 23665	10. Work Unit No.
	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Presented at the Advanced Flight Control Symposium, Colorado Springs, Colorado, August 5-7, 1981.

16. Abstract

Traditionally, aircraft flight control systems have been designed primarily to achieve a desired flightpath in response to pilot or guidance system commands. However, considerable effort is now being focused on the use of control systems to control aeroelastic response. This paper describes some of the experiences encountered at the NASA Langley Research Center while performing research in active control technology. The experiences are categorized in terms of analysis and experiments.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Active controls research	Unclassified - Unlimited Subject Category 39

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	18	A02

N-305