N90-10119

THE ACTIVE FLEXIBLE WING AEROSERVOELASTIC WIND-TUNNEL TEST PROGRAM

By

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ABSTRACT

The evolution of advanced, high performance aircraft is requiring that the engineering disciplines of aerodynamics, controls, and structures be integrated into a unified aeroservoelastic technology. To provide for technology maturation, sophisticated analysis and design methodologies must be developed and verified through data correlation with experimental results. The most economical means of obtaining test data that includes the effects of these three disciplines without actually conducting full-scale flight tests is through the use of flexible wind-tunnel models scaled for aeroelastic phenomena. For a specific application of aeroservoelastic technology, Rockwell International Corporation developed a concept known as the Active Flexible Wing (AFW). The concept incorporates multiple active leading- and trailing-edge control surfaces with a very flexible wing such that wing shape is varied in an optimum manner resulting in improved performance and reduced weight. As a result of a cooperative program between the AFWAL's Flight Dynamics Laboratory, Rockwell, and NASA LaRC a scaled aeroelastic wind-tunnel model of an advanced fighter was designed, fabricated, and tested in the NASA LaRC Transonic Dynamics Tunnel (TDT) to validate the AFW concept. Besides conducting the wind-tunnel tests NASA provided a design of an Active Roll Control (ARC) System that was implemented and evaluated during the tests. The ARC system used a concept referred to as Control Law Parameterization which involves maintaining constant performance, robustness, and stability while using different combinations of multiple control surface displacements. Since the ARC system used measured control surface stability derivatives during the design, the predicted performance and stability results correlated very well with test measurements.

The wind-tunnel model described above serves as the basis of a follow-on program to validate LaRC's and Rockwell's aeroservoelastic analysis methodology and multifunction digital control law design capability. This program provides an excellent opportunity for NASA and Rockwell to obtain an experimental database for the subsonic, transonic, and low supersonic speed regimes on an advanced aircraft configuration and to obtain experience with digital control systems and simulation methods. Significant activities to be conducted by NASA LaRC during the next 2 to 3 years to support the program include: (1) the design of multifunction digital control laws for flutter suppression and rolling maneuver load alleviation acting singularly and simultaneously; (2) the design and fabrication of a digital controller and the implementation and coding of advanced control laws; (3) a "hot bench" simulation of a flexible model with unsteady aerodynamics to verify the functionality of the digital controller; and (4) ground vibration, control system functional, and wind-tunnel tests on a model with violent flutter characteristics. Besides providing a multimillion dollar aeroelastic model for the program, Rockwell will design

and fabricate a wing "tip missile" capable of either inducing flutter within the TDT performance envelope or preventing flutter through a decoupler mechanism, assist in the development of the advanced digital control laws, and participate during the testing and evaluation phases.

Some results from the two previous wind-tunnel entries which describe the ARC system and the Control Law Parameterization concept will be presented during the workshop to establish the background for the more advanced studies now being pursued. In addition, a status report on the follow-on cooperative program will be discussed covering all facets of the effort.

THE ACTIVE FLEXIBLE WING AEROSERVOELASTIC WIND TUNNEL TEST PROGRAM A STATUS REPORT

By

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Workshop on Computational Aspects in the
Control of Flexible Systems
Williamsburg, Virginia
July 12-14, 1988

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CFS/01

THE ACTIVE FLEXIBLE WING AEROSERVOELASTIC WIND TUNNEL TEST PROGRAM

The Active Flexible Wing (AFW) AeroServoElastic (ASE) Wind Tunnel Test Program is a recently-initiated cooperative effort between the NASA LaRC and the Rockwell International Corporation. The objective of this effort is to develop the analysis, design and test methodologies required to apply Active Controls Technology (ACT) for controlling and exploiting the aeroelastic characteristics of a flexible aircraft to improve performance. The approach selected to accomplish the program objectives includes the demonstration of various ACT concepts on a flexible full-span wind tunnel model, and the testing of the model to obtain an experimental data base for validating the analysis and design methodologies associated with ACT. This effort is being directed by the Aeroservoelasticity Branch of the Structural Dynamics Division at LaRC.

OUTLINE

I. Program Objectives

II. Background

III. Current Program/Description of Tasks

- Controller Development
- Design of Tip Missile Concept
- Development of EOM
- Synthesis of RMLA and FSS Control Laws
- "Hot Bench" Simulation
- Wind Tunnel Model Testing

V. Concluding Remarks

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OUTLINE

This chart shows an outline of the topics to be discussed. Since the effort has only recently begun, today's presentation is a status report on where we are today. I will begin by reviewing the objectives of the program to scope the tasks involved. I will then describe some of the NASA analysis and test results obtained during a previous AFW wind tunnel test program between the Air Force Flight Dynamics Laboratory, the Rockwell International Corporation and the LaRC. This portion of the presentation will demonstrate the requirement to go beyond what had been accomplished, pushing the state-of-the-art into more challenging and rewarding areas for ACT application. Next, a few charts describing each of the major tasks associated with this program will be discussed along with the progress and milestones recently accomplished. Finally, some concluding remarks and projections will end the presentation.

DEMONSTRATION AND VALIDATION OF ACTIVE AEROELASTIC CONTROL TECHNOLOGY

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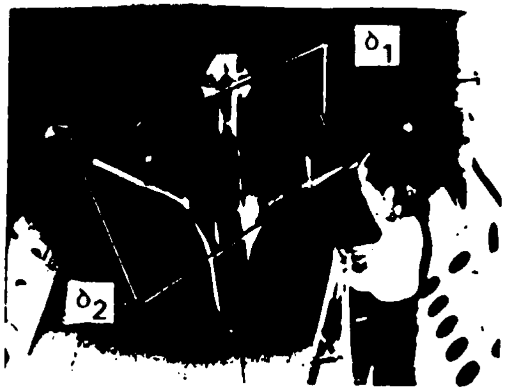
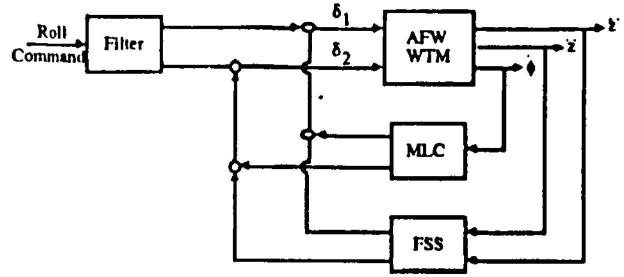


ACTIVE FLEXIBLE WING MODEL



MULTIFUNCTION DIGITAL CONTROL SYSTEM

Objectives:

- Demonstrate Multifunction Control Laws and Validate Analysis Methodologies
- Obtain Experimental Data Base on Advanced Aircraft Configuration
- Obtain Experience with Digital Control Systems and Simulation Methods

NASA Role:

- Design and Fabricate Digital Controller
- Design Advanced Multifunctional Digital Laws and Code Controller
- Perform Real Time Simulation for a Flexible Vehicle Model
- Conduct Ground Vibration, System Functional, and Wind Tunnel Tests

Rockwell Role:

- Provide Flutter Critical AFW Model ($M's) for Technology Demonstration
- Assist in Development of Advanced Control Laws
- Provide Consultation and Participate During Test and Evaluation Phases

DEMONSTRATION AND VALIDATION OF ACTIVE AEROELASTIC CONTROL TECHNOLOGY

The objective of this effort is to demonstrate the potential of using multifunction active control laws for controlling or exploiting aeroelastic response to improve aircraft performance. In addition, it gives NASA an opportunity to obtain an experimental data base on a flexible high performance advanced fighter configuration for validating analysis and design codes, to develop simulation techniques that include structural flexibility and unsteady aerodynamics, and to gain experience with digital control law implementation procedures. The NASA LaRC team consists of about twelve researchers from three different directorates (Structures, Flight Systems and Electronics). The team as a whole has the multidisciplinary experience required to perform the tasks identified for the AFW Aeroservoelasticity Program. The team will be required to design and fabricate the digital controller, design multifunctional control laws and code the controller, perform simulation studies to verify controller operation and conduct all model ground and wind tunnel tests. Rockwell through a Memorandum of Agreement and a separate support contract will provide the wind tunnel model for use during the program, assist in the development of the active control laws and participate during the wind tunnel tests. This cooperative effort provides an excellent opportunity to directly transfer technology to the aerospace industry.

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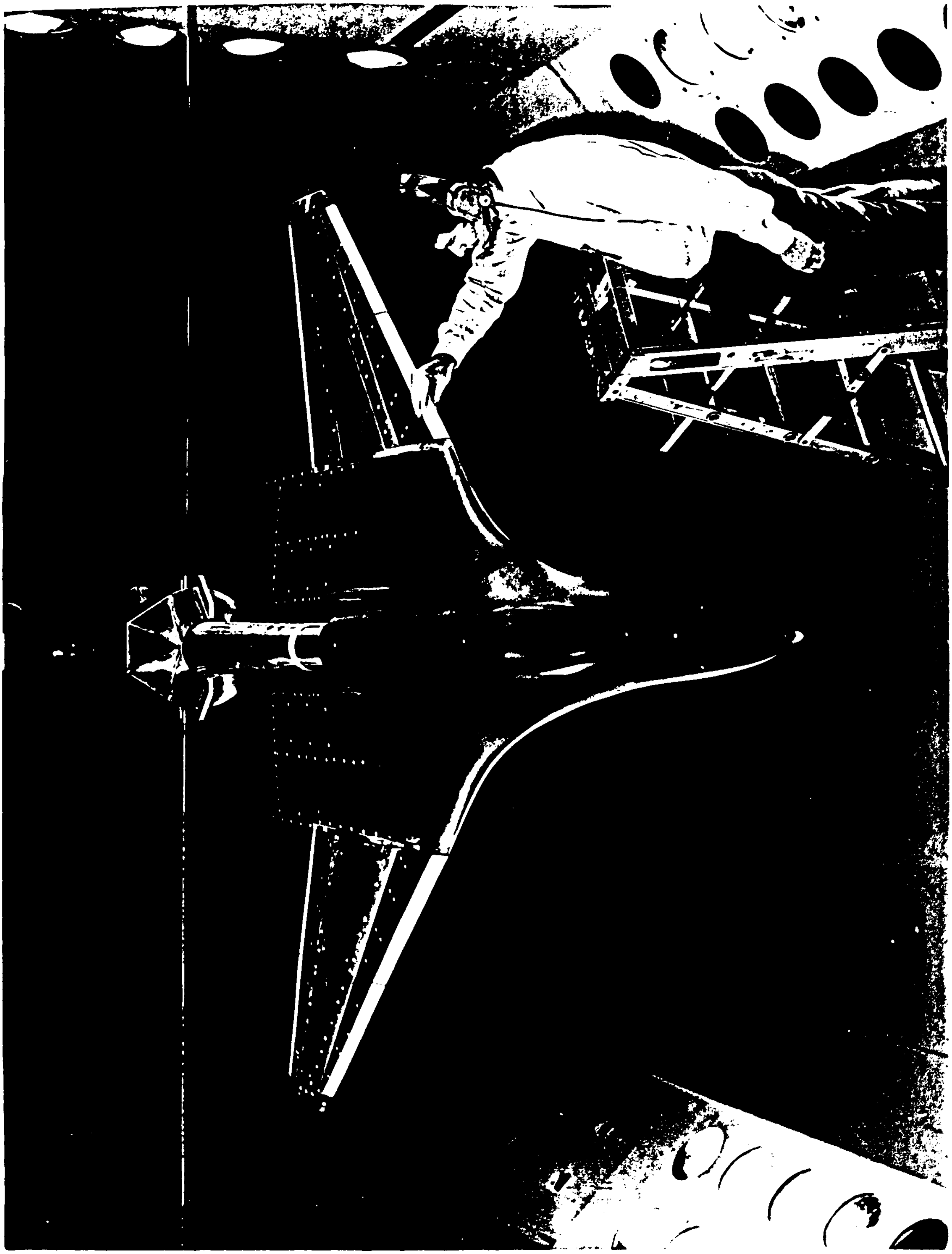

9/2

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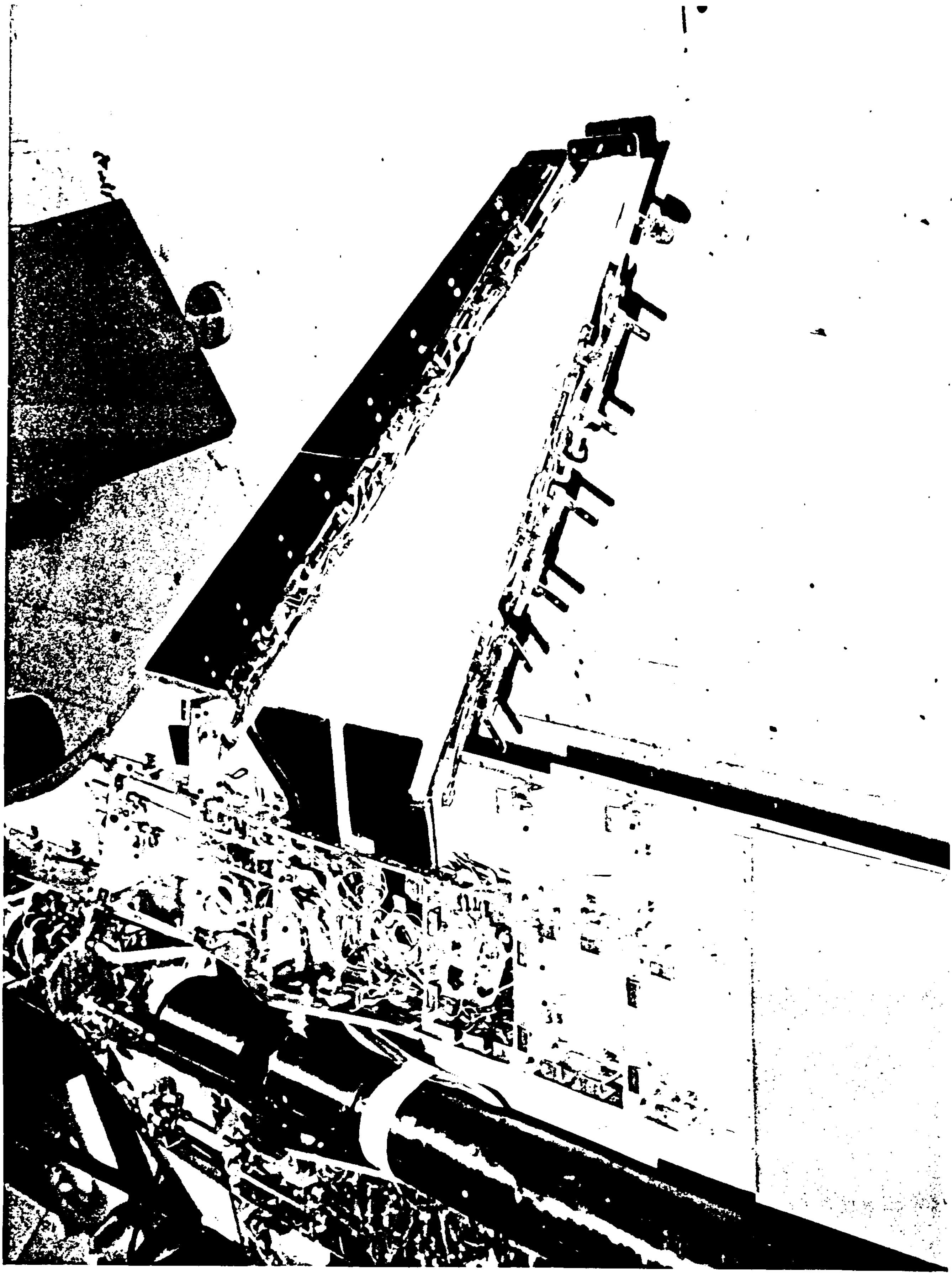
ACTIVE FLEXIBLE WING WIND TUNNEL MODEL MOUNTED IN THE 16-FOOT TRANSONIC DYNAMICS TUNNEL

In mid 1985 the Air Force Flight Dynamics Laboratory in cooperation with the NASA LaRC awarded a research contract to Rockwell International to test advanced control concepts on an aeroelastically scaled full-span wind tunnel model representative of an advanced fighter configuration. The model, shown in the photo mounted in the LaRC 16-Foot Transonic Dynamics Tunnel, was designed and fabricated by Rockwell using company funds. To give some perspective to the photo, the wing span from tip-to-tip is about 9 feet. The model consists of a rigid fuselage with scaled inertia characteristics and flexible wings. The wing box contains an aluminum honeycomb core and aeroelastically tailored plies of graphite epoxy. Each wing has two leading edge and two trailing edge control surfaces powered by rotary vane electrohydraulic actuators. The control surfaces have a chord and span of 25 percent of the local chord and 28 percent of the wing semispan, respectively. They can receive constant signals remotely or time varying signals from a computer for active control investigations. Deflection limits are imposed on the various control surfaces to avoid exceeding hinge moment and wing load limitations. The model has the capability to roll about the sting axis or can be held fixed at any roll angle using a roll brake assembly mounted in the sting. In addition, the model can be tested at various pitch angles remotely controlled by an actuator located in the sting. All actuators are powered by an onboard hydraulic system.



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914

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INTERNAL DETAIL OF THE AFW MODEL

This chart shows the wind tunnel model with some of the fuselage and wing panels removed to expose the complex internal detail required for ASE investigations. The outboard trailing edge control surface is driven by one actuator while the other three are driven by two each. Therefore, the control surfaces are powered by 14 actuators all supplied by onboard hydraulics. Eleven accelerometers (five on each wing and one on the fuselage) can be used as sensors for active control systems or for monitoring model response during testing. In addition, the model has sixteen strain gages, nine rotary variable differential transformers (RVDT) to indicate control surface and pitch actuator position, a roll rate gyroscope and 141 static pressure taps on the upper and lower surfaces of the left hand wing along five spanwise stations. A six-degree of freedom force and moment balance is also present.

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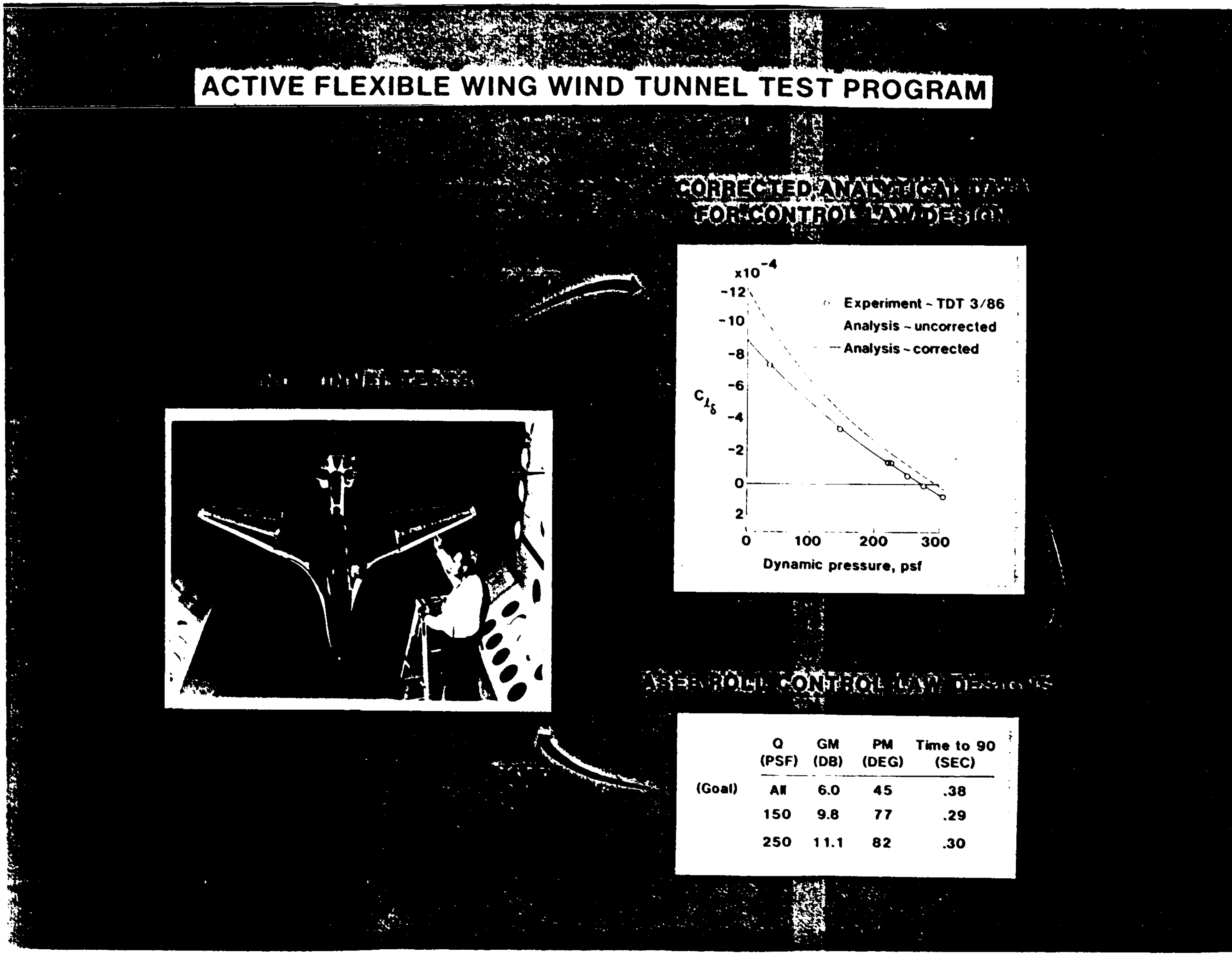
ACTIVE FLEXIBLE WING WIND TUNNEL TEST PROGRAM
CORRECTED ANALYTICAL DATA
FOR CONTROL LAW DESIGN
x10^-4
-12
-10
-8
-6
-4
-2
0
2
C_lδ
Experiment - TDT 3/86
Analysis - uncorrected
Analysis - corrected
0
100
200
300
Dynamic pressure, psf
ROLL CONTROL LAW DESIGNS
Q (PSF) | GM (DB) | PM (DEG) | Time to 90 (SEC)
(Goal) All 6.0 45 .38
150 9.8 77 .29
250 11.1 82 .30

ACTIVE FLEXIBLE WING WIND TUNNEL TEST PROGRAM

The AFW concept integrates active controls technology with a flexible structure by using leading and trailing edge control surfaces to deform the wing in an optimum manner to enhance aerodynamic performance and control. Two wind tunnel tests were previously conducted to validate the AFW concept. The purpose of the first test (March and April, 1986) was to measure static aeroelastic and flexiblized stability derivative data as model angle-of-attack and control surface deflections were varied. Some typical comparisons between an experimentally determined stability derivative and the predicted (uncorrected analysis) value as a function of dynamic pressure is shown in the upper right hand corner of the figure. The corrected analysis results were determined by using two separate "correction factors" in the analysis. The first factor was used to match the expected rigid value of the stability derivative (extrapolation of the experimental data to the zero dynamic pressure value). The second factor, which varied with dynamic pressure (flexibility effect), was used to match the experimental values of the stability derivative with dynamic pressure and to match the reversal conditions for each appropriate control surface. These factors were then employed during the design of the active roll control law which was evaluated during the 2nd test period. The predicted performance for the roll control law design is shown in the lower right portion of the figure. For both flight conditions analyzed, the predicted performance exceeded the goals established. In addition to these tests, the model was flutter tested for safety considerations across the planned flight envelop even though the model was designed to be flutter free.

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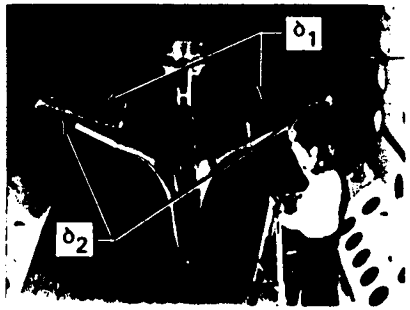
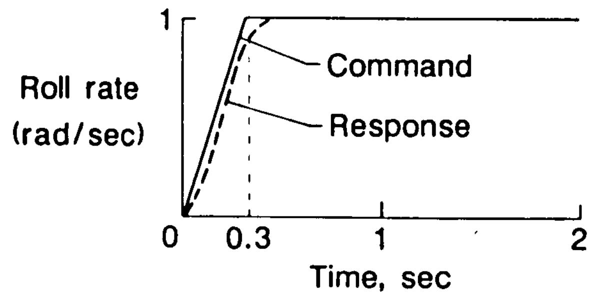
AEROSERVOELASTIC ANALYSIS VALIDATED BY WIND TUNNEL TESTS

Mach = 0.90 Dynamic pressure = 250 psf

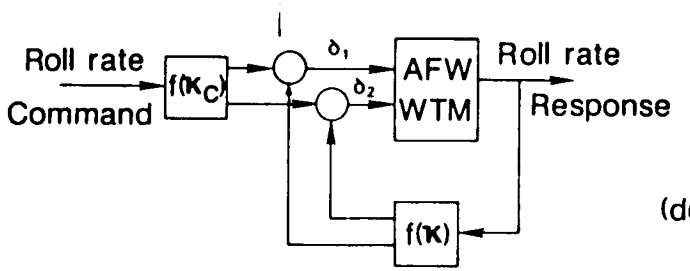
Active flexible wing model



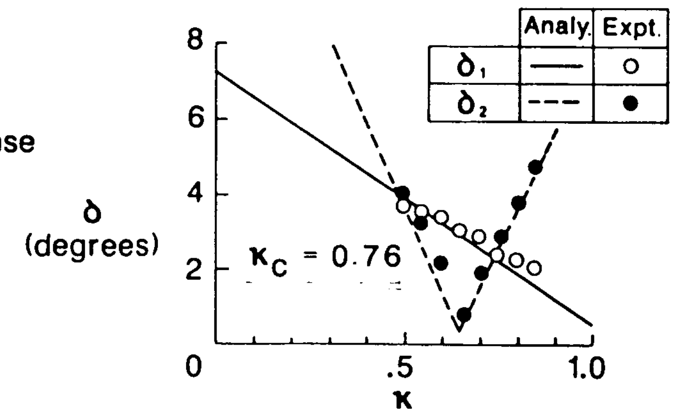
Roll rate performance



Block diagram of active roll control system



Control law parameterization



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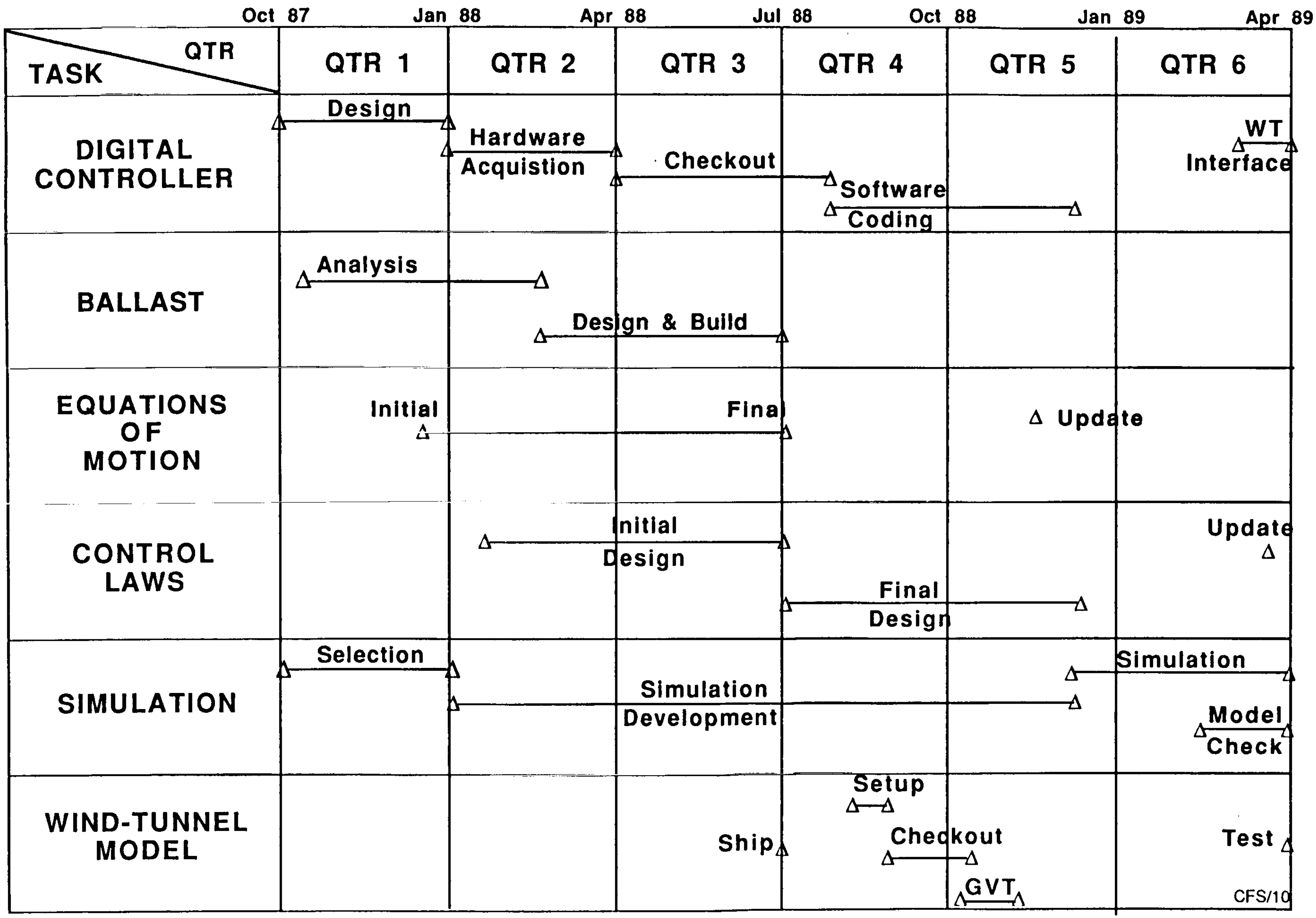
AEROSERVOELASTIC ANALYSES VALIDATED BY WIND TUNNEL TESTS

The 2nd wind tunnel test period was conducted during February and March, 1987 to evaluate Active Roll Control (ARC), Maneuver Load Control and Structural Mode Control Systems developed by Rockwell under Air Force sponsorship. In addition, an ARC system designed by NASA using the aerodynamic corrections factors discussed previously and a "parameterization" procedure was evaluated in the tunnel. This "parameterization" procedure allowed the designer the flexibility of maintaining a fixed closed loop stability and a fixed closed loop roll performance while using different commanded control surface deflections for the active surfaces involved. The consequence of this concept is that the deflections of one pair of control surfaces can be traded-off against the deflections another pair with no loss or gain in aircraft stability or system performance. This idea becomes very important when control surfaces are required to undertake multiple active control functions simultaneously. The chart shows some of the NASA ARC system test results obtained. The lower right hand figure presents a sampling of data to demonstrate the principle of the concept and illustrates the excellent correlation obtained between the test and the calculated data. The figure shows that by changing one control law parameter, stability and performance are maintained while different amounts of leading edge and trailing edge control surface deflections are used.

920

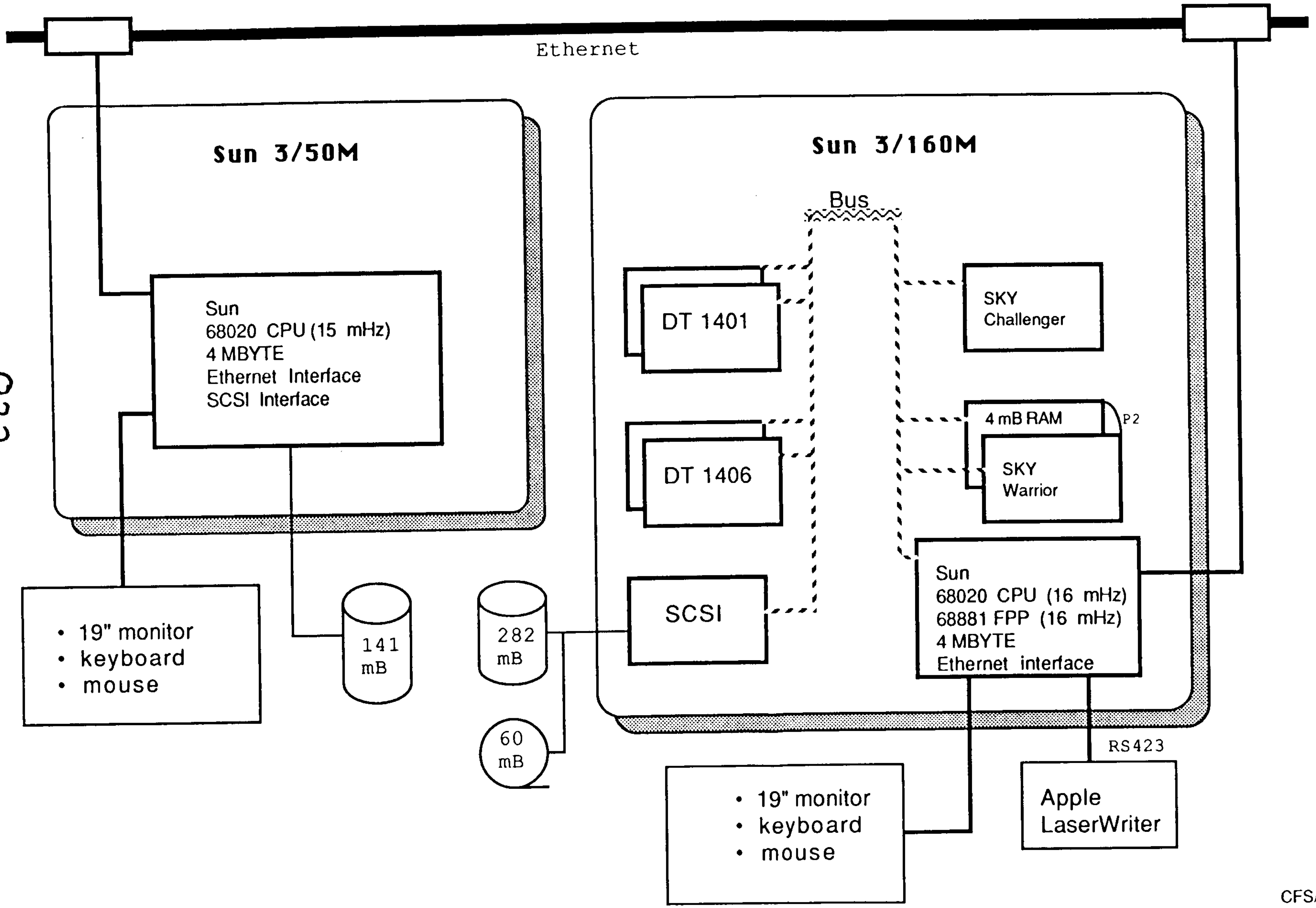
AFW SCHEDULE FOR FIRST WIND-TUNNEL TEST



AFW SCHEDULE FOR FIRST WIND-TUNNEL TEST

Two wind tunnel test entries are planned for the current program; the 1st entry is scheduled for April, 1989 and the 2nd test, one year later. During the 1st entry active flutter suppression and rolling maneuver load alleviation systems will be demonstrated separately. A schedule showing the major activities prior to the 1st wind tunnel entry is presented on the chart. These multidiscipline activities include: 1) the model digital controller design, acquisition/fabrication, checkout and software coding; 2) the design and fabrication of a wing tip missile device to cause flutter within the flight envelope of the model and to act as a flutter-stopper for safety purposes; 3) the development of the aeroelastic equations of motion for six different model structural conditions; 4) the synthesis of the RMLA and the FSS active control laws; 5) the "hot bench" simulation of the digital controller and associated software; and 6) the appropriate ground testing of the model to define its structural and dynamic zero-airspeed characteristics. Each of these activities will be discussed separately in the following figures. Although the details involving the 2nd wind tunnel entry will not be discussed here, the goal is to demonstrate active flutter suppression while the model is undergoing rolling maneuvers and alleviating wing loads.

AFW CONTROL LAW DEVELOPMENT SYSTEM



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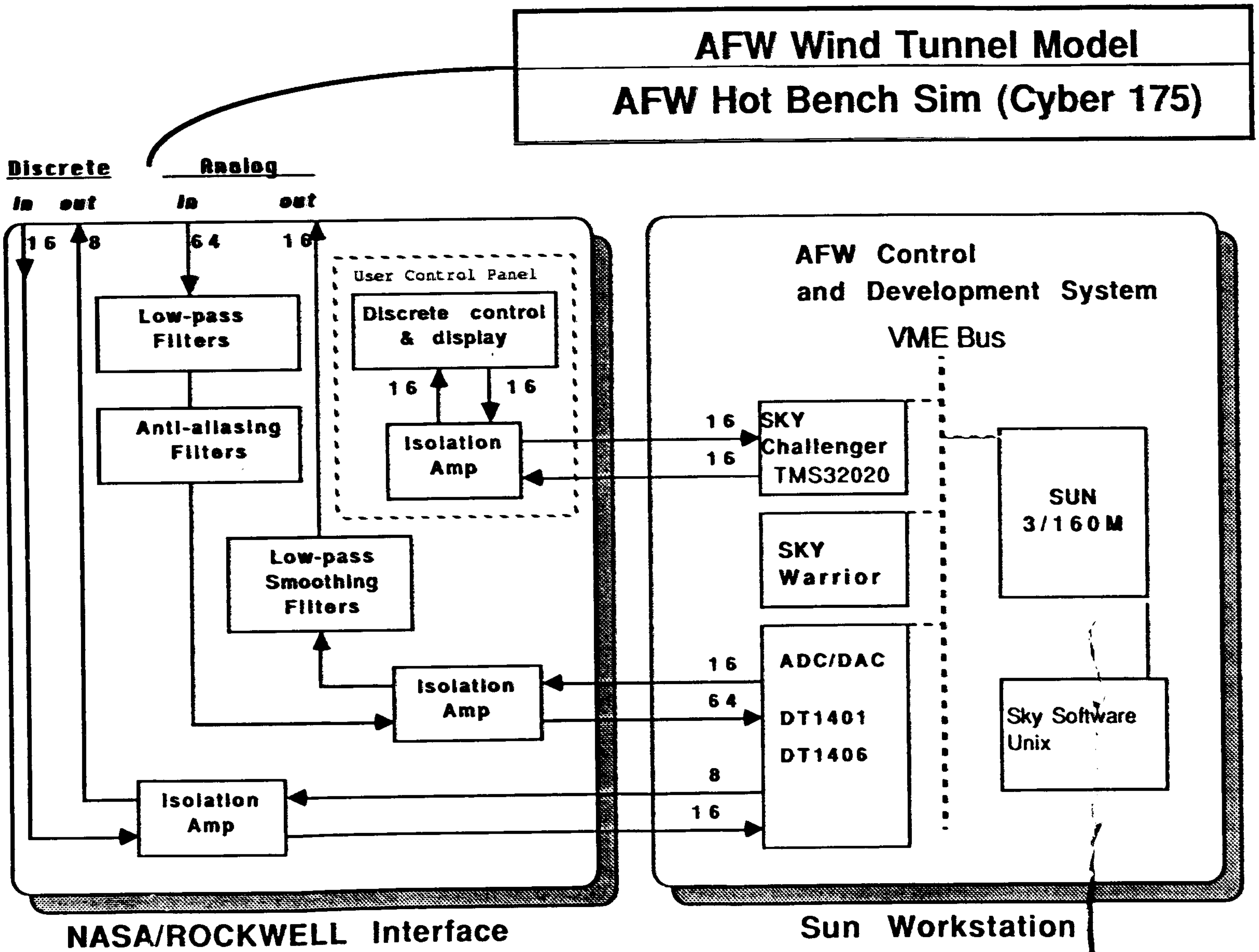
AFW CONTROL LAW DEVELOPMENT SYSTEM

The control law development system for the AFW wind tunnel model includes a Sun 3/160M and a Sun 3/50M workstation, a 141 megabyte hard disk with a 60 megabyte tape backup and a Apple LaserWriter for printer output. The workstations, driven by the Unix operating system, are connected through a Ethernet line. This network provides an excellent environment for several people to develop software and implement control laws independently. The Sun 3/50M is only used during the control law development, implementation and coding phases of the program. To execute the control laws the Sun 3/160M workstation requires a SKY Challenger processor board and a SKY Warrior processor board to be attached to the VME bus. The SKY Challenger is a VME digital signal processor board that is required to perform the scheduling and interfacing of the control law to the AFW model during simulation and testing phases. The SKY Warrior is a VME array processor board which can be used by either the Sun or the Challenger for performing high speed floating point arithmetic. In addition, two DT 1401 (VME Data Translation Cards) each of which has 32 analog-to-digital converters (ADC) and 2 digital-to-analog converters (DAC), and two DT 1406 each of which has 8 DAC are required to interface the incoming and outgoing model signals. These four boards provide 64 ADC and 20 DAC for use by the control program. A 282 megabyte SCSI is also attached to the bus for the storage of data.

AFW MODEL DIGITAL CONTROLLER



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AFW MODEL DIGITAL CONTROLLER

This chart contains a schematic drawing of the "interface box" and the AFW Control and Development System the comprise the model digital controller. The interface box processes the signals coming from or going to either the wind tunnel model or the "hot bench" simulation through low-pass filters, anti-aliasing filters and electrical isolation networks. The purpose of the low-pass filters is to reduce the high frequency noise and to limit voltage spikes that might appear on any of the 64 analog input lines. Currently, a 4th order Butterworth filter with a cutoff frequency of 100 Hz is planned to be used during the wind tunnel tests for the anti-aliasing filters. To be compatible with the "hot bench" simulation computers, the cutoff frequency of the anti-aliasing filters will require time scaling. The 16 analog signals returning to the model or to the simulation computer will also be filtered to prevent sharp edge transitions from being sent to the actuators. The Development System consists of several components linked to the Sun Workstation. The SKY Challenger is required to command the SKY Warrior, control the management of the data acquisition system (reads the ADC and writes to the DAC), monitor and update the User Control Panel, check limits and act as the system timekeeper. As described on the previous chart the SKY Warrior performs the required high speed floating point arithmetic.

AFW FLUTTER BOUNDARY MODIFIED BY THE ADDITION OF A WING TIP MISSILE

Goal: Demonstrate Significant Increase in Flutter Dynamic Pressure Using Digital Active Flutter Suppression System

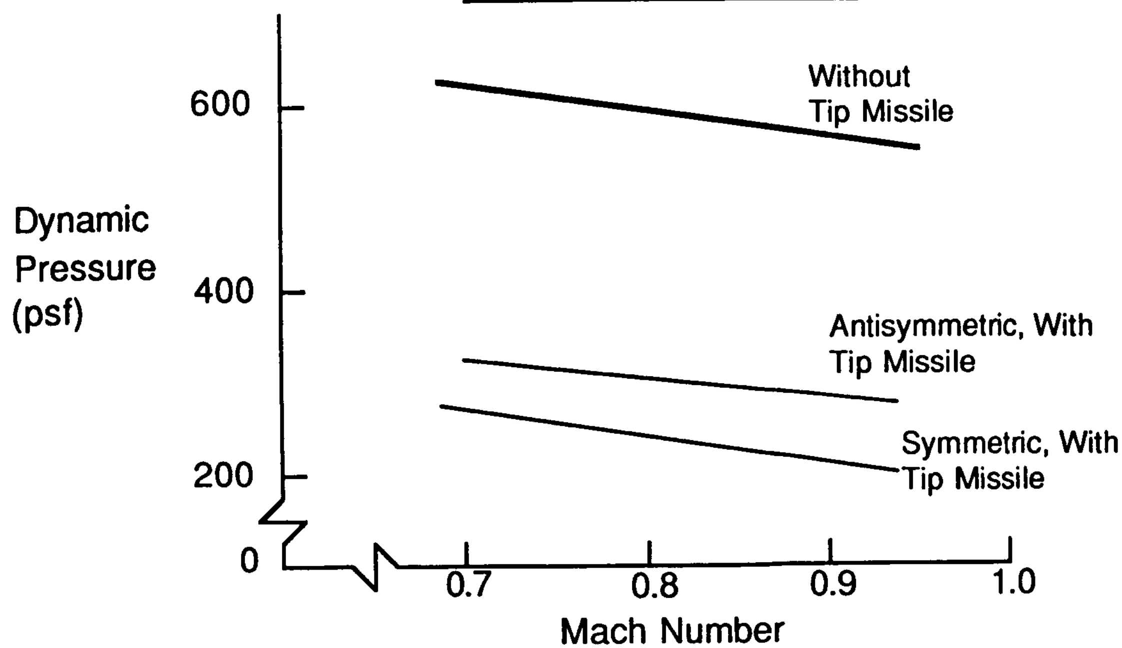
Problem: Basic AFW Flutter Boundary is Beyond the TDT Tunnel Limits

Solution: Add Wing Tip Missile to Lower Flutter Boundary

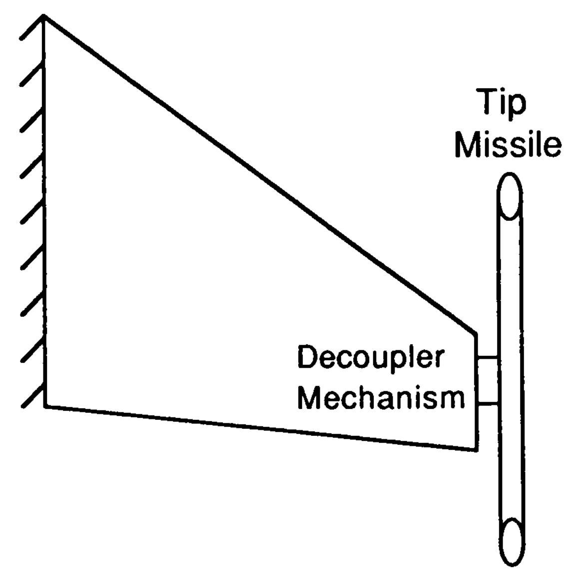
Benefit: Tip Missile Designed to be a Flutter Stopper for Safety

926

FLUTTER BOUNDARIES



AFW Wing



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AFW FLUTTER BOUNDARY MODIFIED BY THE ADDITION OF A WING TIP MISSILE

Since active flutter suppression is one of the concepts being investigated during the present program, it is necessary to modify the model so that it will have a flutter instability within the operational capabilities of the TDT. In addition, this flutter instability must occur at sufficiently low dynamic pressures such that flutter suppression may be demonstrated experimentally. Several options were considered for lowering the flutter speed of the wind tunnel model; the option most attractive was to add a wing tip missile. The tip missile significantly increases the wing pitch inertia while only slightly changing the wing total mass. This in effect decreases the zero-airspeed 1st wing torsion and 1st bending mode frequencies, and brings the two frequencies closer together. Because of the aerodynamic/structural/inertia interaction, the two modes will coalesce and cause flutter at a significantly lower dynamic pressure than without the tip missile present. The lower left figure on the chart shows typical flutter boundary calculations for the model with and without the tip missile present. Because of the close proximity of a symmetric and an antisymmetric flutter boundary, the active flutter suppression system must be capable of preventing both flutter modes simultaneously if the concept is to be effective. An added benefit of using a tip missile for causing flutter is its ability, with a little ingenuity, of returning the model to a flutter-free and, thus safe condition. This is accomplished by decoupling the missile dynamics from the wing by the use of a soft pitch spring at the wing/missile interface. The decoupling mechanism could be two pins, one stiff and one soft, as shown in the figure to the right. With the two pins installed the model would be flutter critical; with the stiff pin retracted, the wing is decoupled from the missile and becomes flutter free.

EQUATIONS OF MOTION

$$[M]\{\ddot{q}(t)\} + [D]\{\dot{q}(t)\} + [K]\{q(t)\} + \frac{1}{2}\rho v^2[Q(t)]\{q(t)\} + \frac{1}{2}\rho v^2\{Q_G(t)\}\frac{w_g(t)}{v} = \{0\}$$

928

FREQUENCY DOMAIN:

- Fourier Transform EOM
- $Q(i\omega)$ and $Q_G(i\omega)$ are transcendental tabular functions

LAPLACE DOMAIN:

- Laplace Transform EOM
- $Q(s)$ and $Q_G(s)$ approximated by: $A_o + A_1\frac{b}{v}s + A_2\left(\frac{b}{v}s\right)^2 + \sum_{m=3}^{6}\frac{sA_m}{\left(s + \frac{v}{b}\beta_{m-2}\right)}$

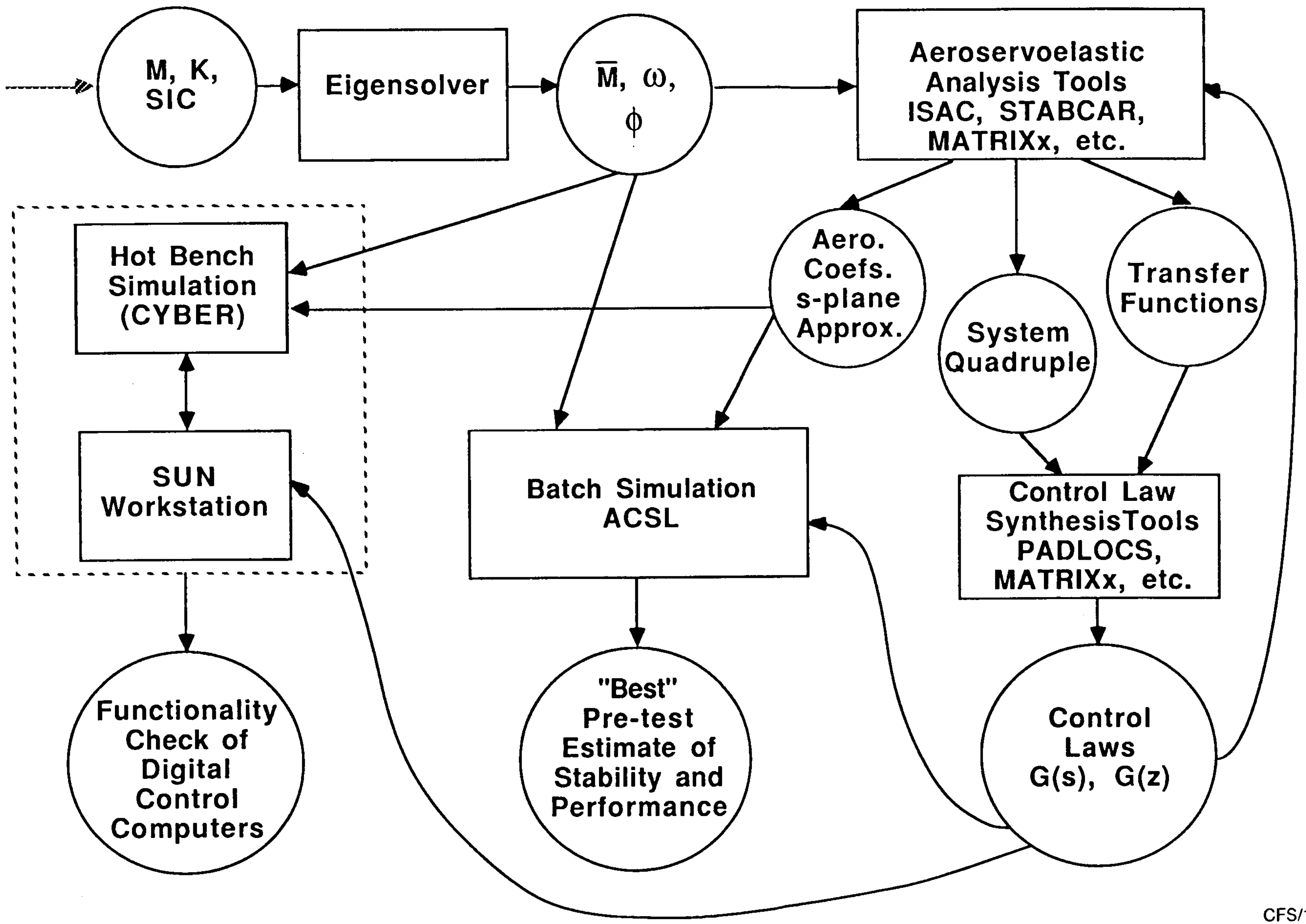
STATE SPACE EOM:

- Inverse Transform Laplace Domain EOM
- Obtain the first order representation: $\dot{x} = Ax + B_c u_c + B_G u_G$

EQUATIONS OF MOTION

One approach to formulating the equations of motion of an elastic aircraft is based on a chosen set of vehicle vibration modes and the Lagrange energy equation. Considering only small perturbations from a level equilibrium flight condition, the aircraft can be represented by a set of linear equations expressed in terms of the generalized coordinates, q(t). An example of such an equation is provided at the top of the slide. This equation represents a summation of forces and includes the inertial, the dissipation and the internal restoring forces, and the aerodynamic forces caused by the aircraft's rigid body, control surface and flexible motions and caused by gusts. To determine the aeroelastic characteristics of the vehicle, these equations are classically transformed into the frequency domain so that state-of-the-art unsteady aerodynamic theories based on simple harmonic motion can be used. These unsteady aerodynamic generalized force coefficients are transcendental tabular functions of several parameters, including frequency. Analyses in the frequency domain are straight forward using common methods. To perform aeroelastic analyses and design studies that include the effects of active feedback control systems, the equations of motion are transformed into the Laplace domain. The transformation of these equations into the Laplace domain is complicated by the transcendental functions of the generalized forces. The use of rational functions to approximate the generalized forces provides one solution to this problem. Several procedures are available for determining the rational function approximations. The equation shown on the slide is one of the more common forms. Here, a least square fit of the aerodynamic data is performed to determine the coefficients of the polynomial for each element of the frequency dependent generalized force matrices. Once the transformed generalized forces are obtained, the equations of motion are then placed into state-space form for design investigations.

ANALYSIS FLOW



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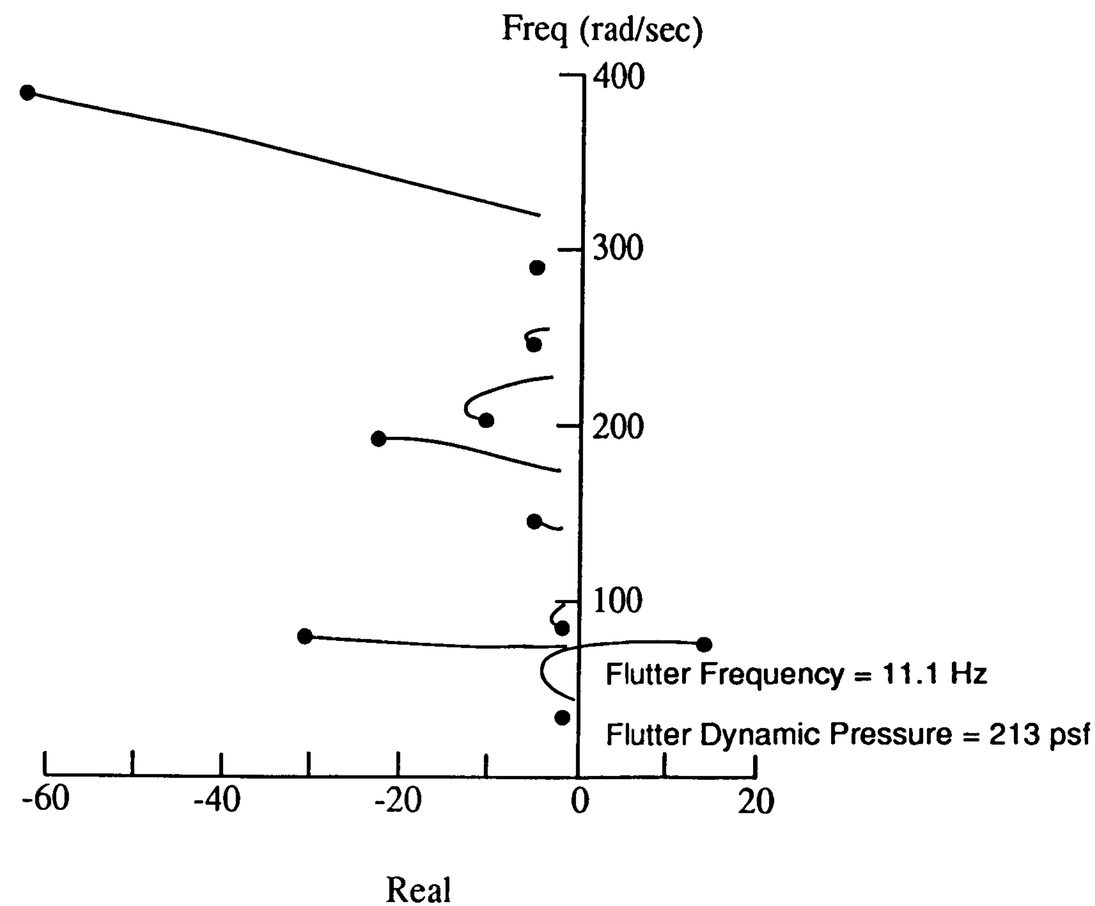
ANALYSIS FLOW

This chart illustrates the major analyses performed and the flow of data and information between analyses. Circles represent both input to and output from the various analyses; rectangular boxes represent analyses. The starting point, at the upper left, is a circle containing lumped-mass matrices and either stiffness or structural-influence-coefficient matrices. These matrices have come from a structural analysis code (not shown) and go into an eigenvalue/eigenvector analysis yielding in-vacuum frequencies, mode shapes and generalized masses. These quantities then go to three other boxes, the first of which is labelled Aeroservoelastic Analysis. Within this box the open-loop (and, when control laws are available, the closed-loop) aeroelastic equations of motion are generated, various analyses are performed, and intermediate results are passed "downstream" to a Control Law Synthesis box and two Simulation boxes. When generated, control laws are passed back up to the Aeroservoelastic Analysis box for computation of closed-loop frequency responses, closed-loop time responses, closed-loop flutter, etc. Control laws and other data are also passed to the two Simulation boxes which ultimately provide a functionality check of the digital control computers and a "best" pre-test estimate of the stability and performance of the closed-loop wind tunnel model.

C-5

SYMMETRIC FLUTTER ROOT LOCUS

Stiff Tip Missile Spring, M = 0.9



SYMMETRIC FLUTTER ROOT LOCUS

Various analysis procedures can be used to obtain the aeroelastic characteristics of the model. This chart shows typical stability results using a root locus approach. To adequately define the flutter stability for the AFW wind tunnel model it was necessary to develop equations of motion for six different model representations. These included the model undergoing symmetric motion with the tip missile attached to the wing with either the stiff spring or the soft spring as discussed previously, and the model undergoing antisymmetric motion with the tip missile attached to the wing with either the stiff spring or the soft spring with the roll brake on and off. The data shown on the plot represents the AFW model undergoing symmetric motion with the tip missile attached to the wing with a stiff spring. Mach 0.9 doublet lattice unsteady aerodynamics were used for these calculations. Velocity was held constant and the air density was varied so that a matched point solution was obtained. For this analysis, the first ten vehicle elastic modes were used to define the generalized coordinates. The predicted flutter mode involves the coalescence of the 2nd and 3rd elastic modes at a dynamic pressure of 213 psf at a frequency of 11.1 Hz as can be seen when the 2nd elastic mode root moves into the right half plane. The objective of the FSS is to move the unstable root back into the left hand plane of the plot.

SYNTHESIS METHODOLOGIES

1. Classical Analog Design → Digital Realization → Constrained Optimization → Final Digital Control Law

2. Analog LQG → Order Reduction → Digital Realization → Constrained Optimization → Final Digital Control Law

3. Direct Digital Design

4. Eigensystem Design Techniques

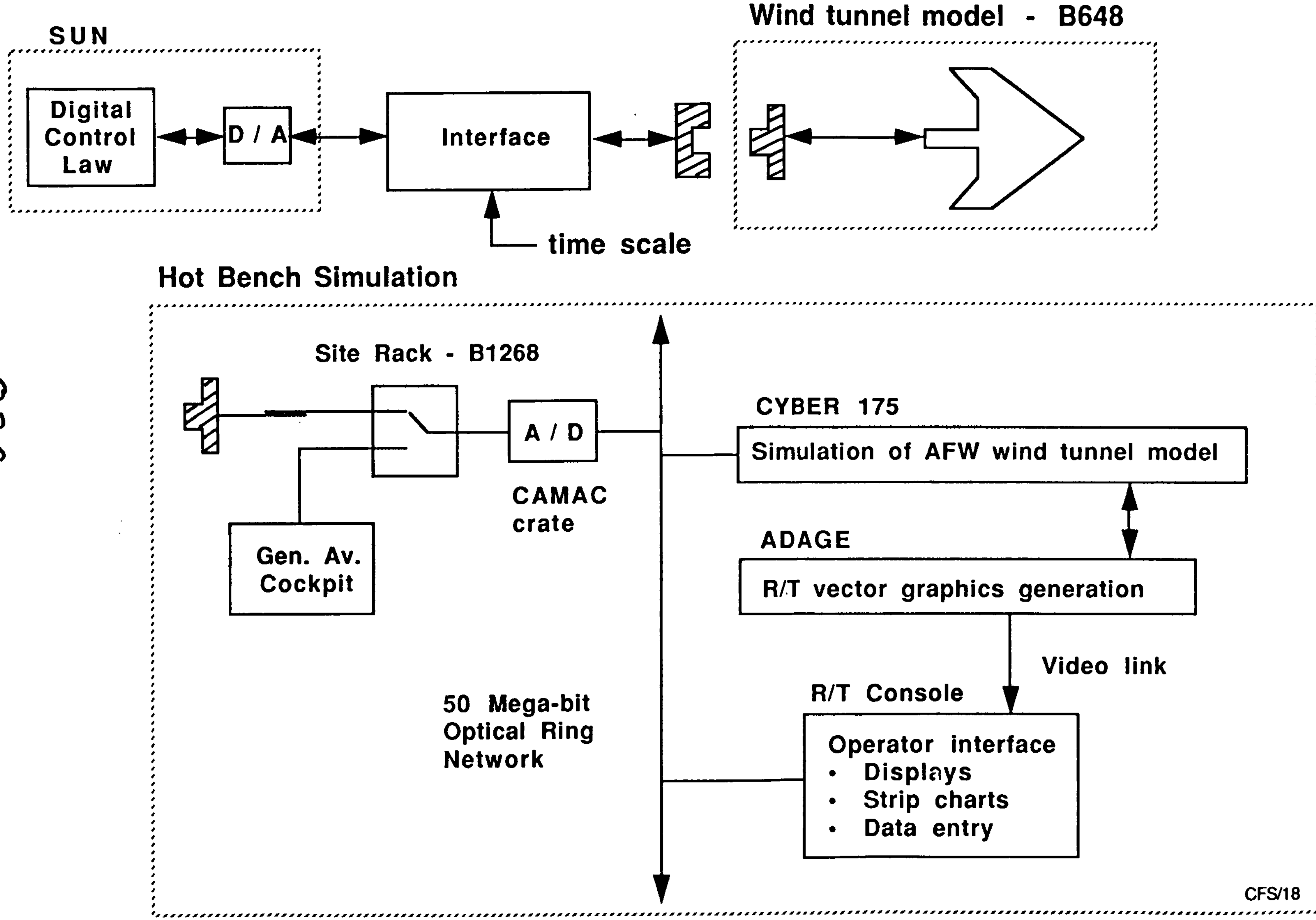
934

CFS/17

SYNTHESIS METHODOLOGIES

Several approaches that include classical analog and modern/optimal control techniques are being evaluated for use in designing the digital active flutter suppression system. The classical techniques being considered are based on root locus, Bode (transfer functions) or Nyquist plots and are useful for single-input, single-output systems. Once an analog control law which provides at least minimum stability for the aircraft at a certain design point is found, it is transformed into the z-domain and then optimized based on constraints such as design loads, actuator deflection and rate limits, and stability margins. The optimization task results in improved stability margins and robustness characteristics. The Linear-Quadratic-Gaussian (LQG) method is a systematic approach for designing multi-input, multi-output control laws. The LQG method is based on minimizing a cost performance index consisting of quantities such as control deflection, design loads, accelerations, etc. The control law developed using this technique, however, is the same order as the aircraft being modeled. For flexible aircraft with unsteady aerodynamic forces, the number of states required to represent the vehicle is usually quite large. This order problem is solved through the truncation or residulation of the Kalman Filter. As described above, the LQG reduced-order control law is transformed into the digital domain and further optimized to improve performance and robustness. A third approach being considered involves the direct digital design of the control law. The methodology for the direct synthesis (determination of the coefficients for the z terms) of the digital FSS uses constrained optimization, and will meet multiple design requirements if necessary while maintaining reasonable stability requirements. The last method being evaluated is an eigensystem design technique. The method involves the placement of the closed loop roots to obtain a control law with satisfactory stability, performance and robustness characteristics.

SYSTEM OVERVIEW OF HOT BENCH SIMULATION



SYSTEM OVERVIEW OF HOT BENCH SIMULATION

The purpose of the "hot bench" simulation is to provide a comprehensive evaluation of the functionality of the Sun digital controller and the user control software, and to provide a low order, linear check of the flexible/dynamic system coupled with the active control laws. It is planned that this activity will be accomplished by attaching the Sun digital controller to a Cyber 175. The Cyber represents the AFW aeroelastic equations of motion modeled to include a sufficient number of elastic modes and the unsteady aerodynamic forces needed to accurately predict the static and dynamic characteristics of the test article across its expected test envelop. The Cyber will send sensor and other model or test condition information to the Sun for processing by the digital controller and will receive control actuator displacements from the Sun. Issues which can be investigated during the "hot bench" simulation besides the user control software, and control law stability and performance evaluations include:

1) the operation of the flutter stopper,
2) actuator transfer function differences between left and right wings which could cause coupling between symmetric and antisymmetric model characteristics,
3) failed actuators and sensors,
4) control surface displacement and rate limits.

A schematic that demonstrates the procedure to provide the interface between the Sun digital controller with the Cyber 175 during the "hot bench" simulation or to the AFW model during the wind tunnel tests is shown on this chart. On a previous chart, the NASA/Rockwell Interface box was discussed. Recall that this box takes discrete and analog signals from the wind tunnel model or from the Cyber during the "hot bench" simulation studies. Because of the clock step and time step differences between the Sun and the Cyber, it will be necessary to conduct the simulation in synchronized slow time.

PRELIMINARY AFW MODEL TEST PLANS

- o Ground Vibration Tests
- o Control System Functional Tests
  - Open Loop Transfer Function Measurements
- o Servoelastic Coupling tests
  - Closed Loop limit Cycle and Ground Resonance
- o Wind Tunnel Tests
  - Measure Control Surface Stability Derivatives
  - Obtain Static Pressure Distributions at Selected Wing Locations
  - Perform Roll Maneuvers with and without Active Load Alleviation
  - Define Flutter Free Test Envelop for Decoupled Tip Missile
  - Define Passive Flutter Boundary
  - Demonstrate Active Flutter Suppression

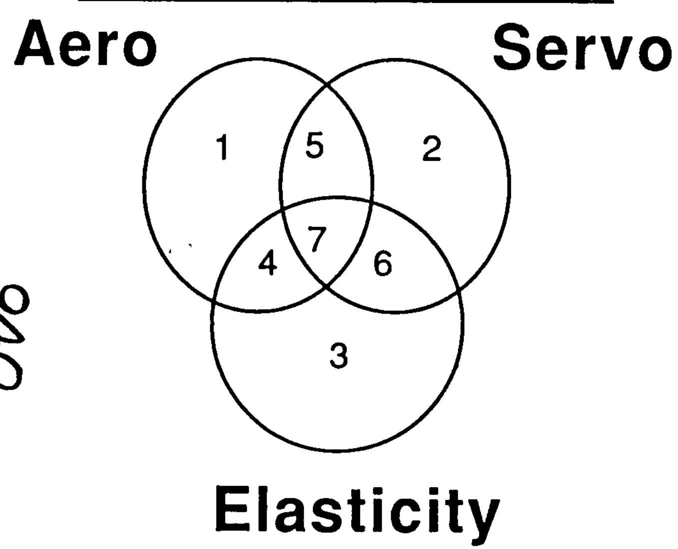
PRELIMINARY AFW MODEL TEST PLANS

The wind tunnel model will arrive at LaRC during the summer of 1988 for extensive ground testing prior to installing the model into the Transonic Dynamics Tunnel. Initially, the model will be ground vibration tested with the tip missile attached to the wing using both the stiff and soft spring representations separately. Symmetric and antisymmetric elastic mode frequencies, mode shapes and structural damping coefficients will be obtained with the model roll brake on and off. In addition, all sensor signals expected to be used by the active control laws will be measured. During these tests all actuators will be hydraulically powered. Open loop end-to-end tests will be accomplished to obtain transfer functions over a broad frequency range for all control surface/sensor combinations using several different amplitude signals to evaluate the nonlinear effects. The transfer function of selected components, such as the actuators and sensors will also be measured separately. Closed loop tests will also be accomplished for each active control law to be evaluated in the wind tunnel. These tests will include limit cycle tests to measure gain and phase margins at zero airspeed, model stability evaluations following an impulse excitation, and ground vibration tests. The intent of these tests is to obtain measured data for validating math models at zero airspeed (without aerodynamics). The various math models will be corrected and the control system designs updated as appropriate prior to the wind tunnel tests. Finally, the chart shows the expected wind tunnel tests and the order of conducting these tests. Routine force, moment and static pressure data will be measured first. Next the performance of the Rolling Maneuver Load Alleviation System will be evaluated. The higher risk tests which include the passive flutter and the active flutter suppression tests for preventing a high frequency violent flutter mode will be accomplished last.

VALIDATION OF TOOLS FOR MULTIDISCIPLINARY TECHNOLOGY

940

MULTIDISCIPLINARY AREAS



1. Aerodynamics
2. Controls
3. Structures
4. Aeroelasticity
5. Closed-Loop Stability and Control
6. Servoelasticity
7. Aeroservoelasticity

PLANNED TESTS/VALIDATION

Static Pressure Distributions

Analog and Digital Transfer Functions

Frequencies and Mode Shapes

Control Effectiveness and Flutter

None Planned

Closed-Loop Ground Tests

"Hot Bench" Simulation/RMLA and FSS

VALIDATION OF TOOLS FOR MULTIDISCIPLINARY TECHNOLOGY

In summary, aeroservoelasticity is a multidisciplinary technology that involves unsteady aerodynamics, active control systems and flexible structures. This chart illustrates the potential interactions of these three technologies with the aid of three intersecting circles to represent individual technical disciplines. ASE represents that area common to all three circles. To adequately develop analysis and design tools for application to ASE, it is important and critical to validate software within each area of interacting technologies. Recall, that one of the objectives of this program is to obtain test data for evaluating the usefulness and accuracy of our codes involved in the design of flexible vehicles. The approach being followed during this program is to obtain experimental data to validate each of the primary technical disciplines prior to proceeding to levels involving two interacting technologies or three (ASE for this case). In conclusion, the NASA/Rockwell AFW program began in October, 1987 and will continue for about three years. This presentation has been a status report that addressed:

1) why the program is being pursued,
2) where we are today, and
3) what to look forward to in the coming months.

For those interested in pursuing the progress of the program, additional status reports will be presented at various conferences and workshops during the program.