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ROLL PLUS MANEUVER LOAD ALLEVIATION CONTROL SYSTEM DESIGNS FOR THE ACTIVE FLEXIBLE WING WIND TUNNEL MODEL

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Abstract

Three designs are discussed for controlling loads while rolling for the Active Flexible Wing (AFW). The goal is to provide good roll control while simultaneously limiting the torsion and bending loads experienced by the wing. Successful development will allow for lighter wing structures to be used, with the control system insuring loads remain within allowable limits. Each controller has been designed for testing in the NASA Langley Transonic Dynamics tunnel on the Rockwell AFW wind tunnel model

The first design uses LQG/LTR techniques to develop a MIMO controller structure between the control surfaces and roll rate and four separate torsion loads. The control system consisted of two parts: The loop controller for stability and a pre-filter which generates load commands as a function of roll command input to the loop controller for performance. Conversion of the physical requirements to LQG/LTR design parameters is shown.

The second design uses a nonlinear gearing function imbedding implicit load control information as an element of a modified SISO controller. While only roll rate has an explicit feedback mechanism, torsion, bending, and hinge load are controlled through the a priory knowledge of the model's control surface to roll and load transfer functions. System stability and robustness are shown by analysis and simulation.

The third design integrates the above RMLA controllers with a high frequency structural mode controller. Using the same surfaces as the RMLA control, its object is to reduce high frequency responses caused by the RMLA and to act as a flutter suppression system. The goal is to operate the integrated controller beyond the model's natural flutter boundary. Design issues of integrating the RMLA and structural mode controllers are discussed.

Introduction

The Advanced Flexible Wing (AFW) is an aeroservoelastically scaled model of a Rockwell fighter design. By allowing the wings to be flexible, they may be lighter and the flexibility exploited for such things as twist and camber control. Additional flexibility, however, reduces the flutter envelope of the wing and active control schemes may be required to stabilize the wing modal dynamics. Control systems discussed in this paper cover maneuver, load, and flutter control systems. An integrated maneuver, load, and flutter controller is a goal of this test program.

Two roll plus maneuver load control designs are discussed. The first design is based on LQG/LTR modern control methods to control roll rate and torsion loads at four different wing locations. The controller is a five input, five output system with 11 internal states. The controller acts a command tracker, generating surface commands to drive the AFW to the state requested by the command generator. The command generator works as a prefilter to provide input signals to the controller corresponding to the desired roll rate and loads profile. With these two things, the prefilter and the controller, a roll maneuver may be performed with a 40% reduction in torsion loads on the wing.

The second design uses a nonlinear surface command function to produce surface position commands as a function of current roll rate and commanded roll rate. It is designed to keep specified wing loads below some specified value while permitting the greatest possible roll axis performance. (A conventional control system design would attempt to control the wing loads continuosly, even when they were well below structural limits. This method degrades roll performance as some control power is used by the load controller.) This controller, in contrast, only controls the loads when they reach some threshold, say 80% of structural limits, to permit the control power to be used for aircraft maneuvers until it is necessary to perform load control. The trade off for this design method is the controller becomes a nonlinear controller instead of a linear one with the accompanying increase in design and analysis complexity.

The final design is a flutter suppression control system. This system stabilizes both symmetric and antisymmetric flutter modes of the AFW. Due to the fact that accelerometers have an output which is a function of the frequency, load sensors are used to provide the feedback signal. The control system design is done using classical techniques. An integrated flutter and roll/loads design is also being developed.

Slide 1 Description of Control Systems

For a top level design goal, Reducing wing loads while maintaining roll performance is the objective of the roll controllers. There are two designs to meet this objective: 1) Linear Feedback (RMLA) using roll rate and load feedback in the controller. This design uses LQG/LTR modern control techniques as the synthesis method. 2) Feedforward Nonlinear Optimal using only roll rate feedback for control and having surface command functions providing load control.

Slide 2 Design Objectives

For both Roll Maneuver designs, similar design goals were used. The stability and time response goals correspond to the MIL-STD parameters for fighter aircraft. The load control criteria were chosen to represent a first step to prove the validity of the concept. Higher levels of load control are achievable at a cost of reduced maneuverability. The robustness criteria is derived from known measurement uncertainty; plant variations from the analytical models may well be higher.

Slide 3 Block Diagram of RMLA

This diagram describes the basic structure used in the RMLA controller. Roll and load commands go through a pre-filter to provide tracking signals to the RMLA controller. The controller is a 5 input (roll rate and wing torsion at four locations) 5 output (trailing edge inboard surfaces together, trailing edge outboard left, trailing edge outboard right, leading edge outboard left and leading edge outboard right) MIMO design with 11 internal dynamic states (the states do not necessarily correspond to physical quantities).

Slide 4 Prefilter Design

An integral part of the RMLA controller is the prefilter. The pre-filter's function is to output 5 tracking commands derived from a roll rate input command. The pre-filter output is based on the open loop dynamics of the AFW. For this design, the roll rate signal was fed directly and the torsion commands were gain scheduled to the roll rate command.

Slide 5 Linear Performance

A step response to a 1 rad/sec roll rate command shows the good roll rate tracking and load control of the LQG/LTR RMLA. A command for torsion only shows the decoupling performance of the controller.

Slide 6 Nonlinear Performance

The response of the AFW+ LQG/LTR RMLA in a complete nonlinear simulation shows the roll tracking of the LQG/LTR RMLA. A simulation of a 40% load reduction with no change in roll performance from the nominal case.

Slide 7 LQG/LTR RMLA Summary

The LQG/LTR RMLA controller has achieved the basic design goals. The LQG/LTR RMLA shows good tracking, channel decoupling, and stability properties.

Slide 8 LQG/LTR RMLA Future Directions

The RMLA controller can be refined in its design by expanding the design to handle non-square cases. This would allow for inputs to be any combination of control commands and outputs to be the desired surfaces. The pre-filter may also be improved by designing it as a dynamic model follower or command generator.

Slide 9 Feedforward Block Diagram

The RMLA Feedforward Nonlinear Optimal Controller block diagram shows how the roll rate command is input to the control surface functions. The surface functions contain the load information which provides the load control. The only inputs to this control system are the commanded roll rate and the actual roll rate. From this information, the surface functions output surface commands which will produce the desired acceleration about the current roll rate.

Slide 10 Design Method for Feedforward

The design method for the feedforward controller can be stated as 'Control loads only when they are near limits'. This is accomplished by developing surface control functions by optimization methods. Using loads as constraints, surface deflections are found which will provide the desired roll rate and roll acceleration without violating the constraints. The surface functions will have a linear range where no load constraints have been encountered and a nonlinear range where constraints are active.

Slide 11 Example of Surface Function

This plot are two views of the control surface functions. Notice the linear region around zero and the nonlinearities as constraints are encountered. In the 2-d plot, the trailing edge outboard surface becomes the primary load control surface with the trailing edge inboard increasing in gain to maintain roll performance. This follows our intuitive expectations as the trailing edge outboard surfaces have high load authority but low roll power and the trailing edge inboard surfaces have the highest roll power. Given we are trying to keep total surface deflections to a minimum, this pattern makes sense.

Slide 12 Summary of Feedforward Optimal Design

The feedforward optimal controller is capable of maintaining roll performance while controlling wing loads. An important consideration is the controller is a linear design in term of roll rate and roll acceleration. A simulation of this controller is currently underway for test this winter.

Slide 13 Flutter Control Block Diagram

Flutter control is used on the AFW to expand the flight envelope while keeping the low weight, flexible wings. The flutter control block diagram show how the flutter suppression system is an integral part of the aircraft dynamics.

Slide 14 Flutter Suppression Control Law

The Rockwell method for flutter design is similar to that employed by NASA except load sensors were used for feedback instead of accelerometers. This is because load sensors are also used for the roll control laws and to eliminate the frequency gain of accelerometers.

Slide 15 Combined Maneuver, Flutter, and Load Control

A proposed design for integrated maneuver, flutter, and load control would exploit the frequency separation between the maneuver dynamics and the flutter dynamics. The controllers will be designed separately and combined to produce the total controller.

Slide 16 Combined Maneuver, Flutter, and Load Control Block Diagram

The block diagram indicates how each surface command signals would be combined into the total controller design. Any combination of flutter controller and maneuver/loads controller could be used in this scheme.

Slide 17 Future of AFW Controls

A goal of this design/testing program is to demonstrate a snap-roll maneuver beyond the flutter boundary with load reduction. This would open up new areas of performance for aircraft in such things as weight reduction and improved agility. Additional work is also being done with new nonlinear controllers to improve the aircraft performance while coping with conflicting control requirements.

ROLL PLUS LOAD ALLEVIATION CONTROL SYSTEMS

Objective: To maintain maximum roll capability while reducing wing loads.

- Torsion
- Bending
- Hinge Moments

Approach: 1) Linear Feedback Design (Roll Maneuver Load Alleviation, RMLA)

- Roll and Load Feedback
- Command Following
- LQG/LTR Synthesis

2) Feedforward Nonlinear Optimal Design

- Use constrained optimization to develop surface command functions producing the desired roll performance without exceeding wing loads.
- Roll feedback only

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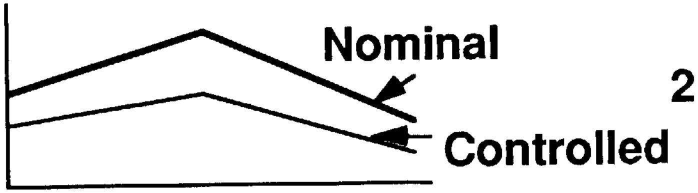
DESIGN OBJECTIVES

Stability: 6dB of gain margin and 45 degrees of phase margin. These apply to every loop for multivariable designs.

Time Response: Achieve time-to-90 degrees in 0.4 seconds (scaled MIL-SPEC) with minimal overshoot and good command tracking

Load Control: For design 1, reduce torsion moments by >20% throughout the roll maneuver. For design 2, limit Torsion, Bending, and Hinge moments to <80% of the test trip limits.

1



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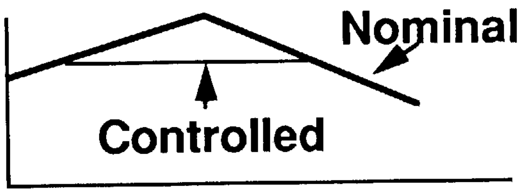
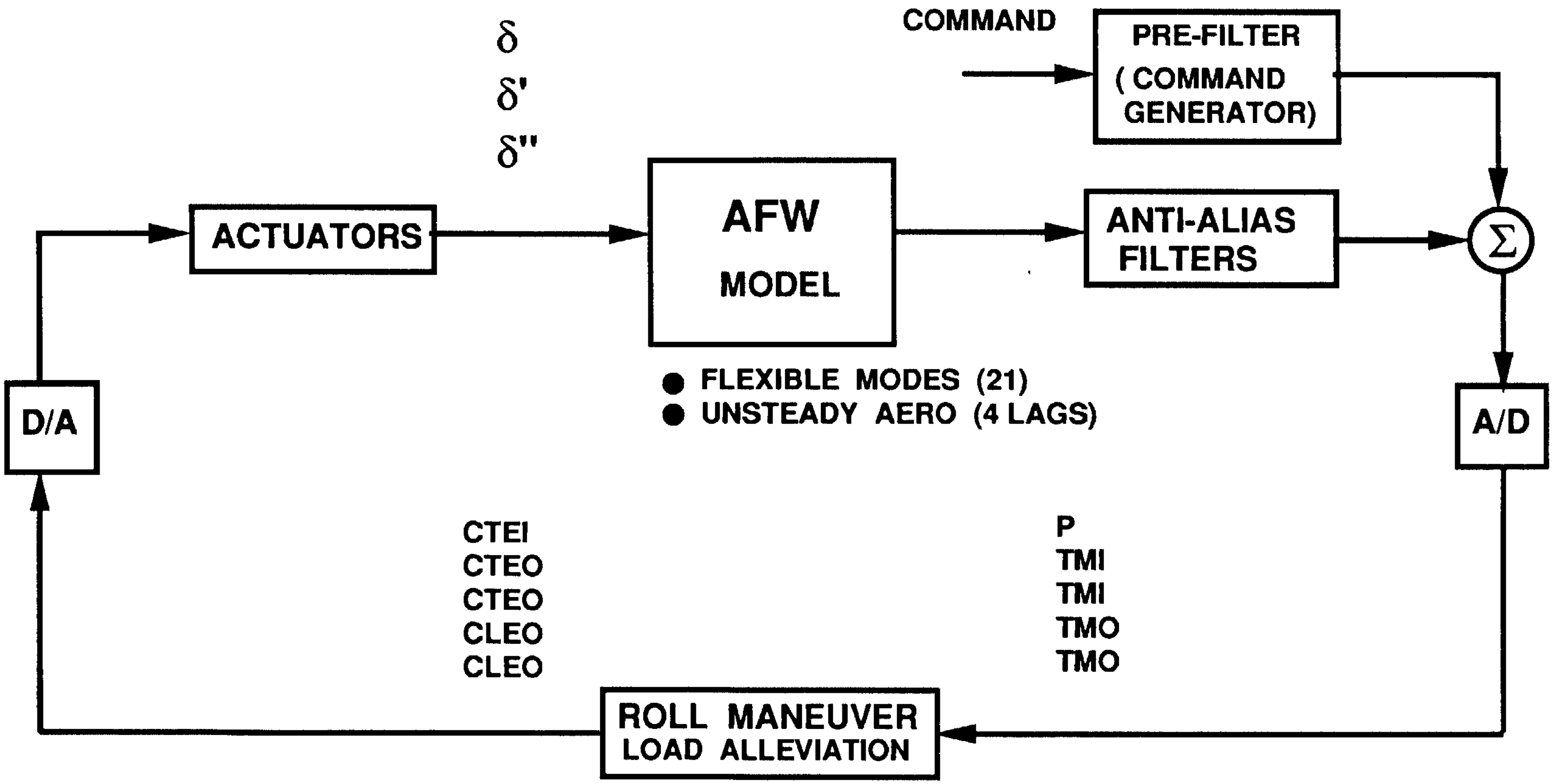


Robustness: Controllers must handle the known uncertainty of the model parameters.

RMLA CONTROL BLOCK DIAGRAM



- FLEXIBLE MODES (21)
- UNSTEADY AERO (4 LAGS)

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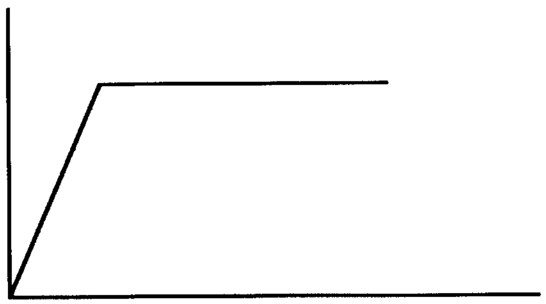
PRE-FILTER DESIGN AND IMPLEMENTATION

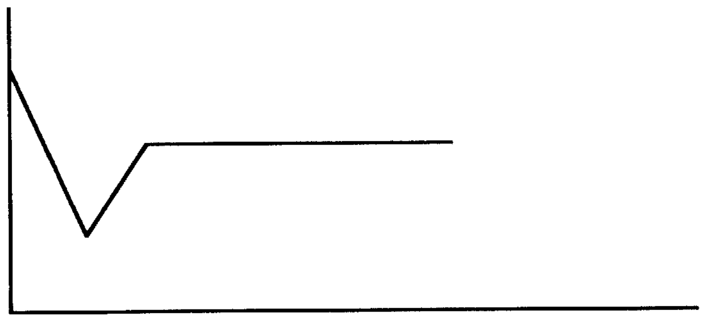
The pre-filter takes a roll rate command and generates the 5 commands required by the RMLA controller.

Roll Rate is used directly.

The torsion commands are generated using the knowledge of the open loop (for load control) response. Load commands are given as some percentage of the open loop response.

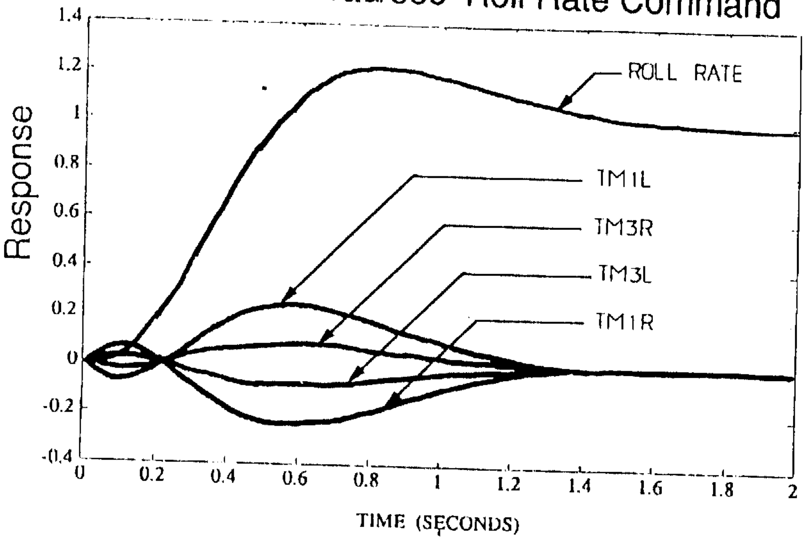


Roll Rate Command

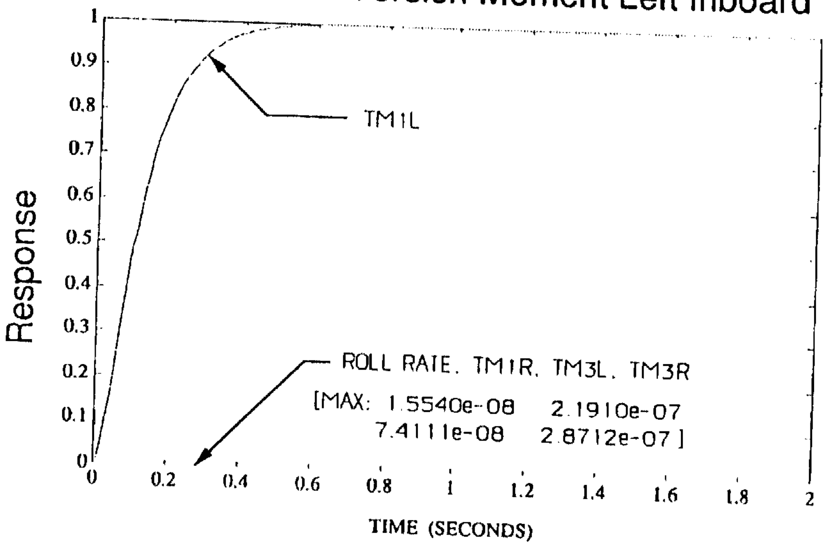


Typical Torsion Command

LINEAR PERFORMANCE ANALYSIS INDICATES CONTROL OF ROLL RATE AND LOADS



Response to 1 rad/sec Roll Rate Command



Response to 1 ft*lb Torsion Moment Left Inboard

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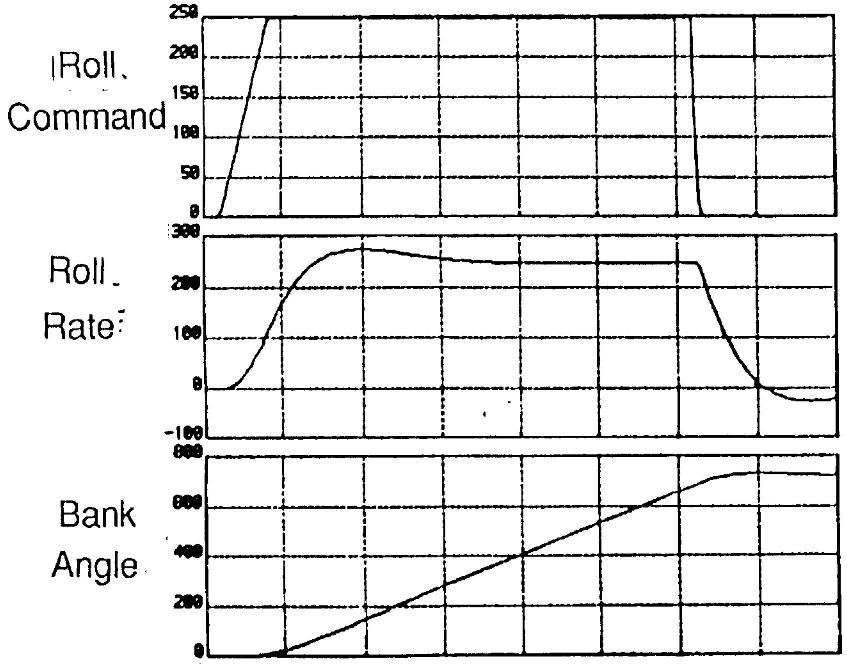
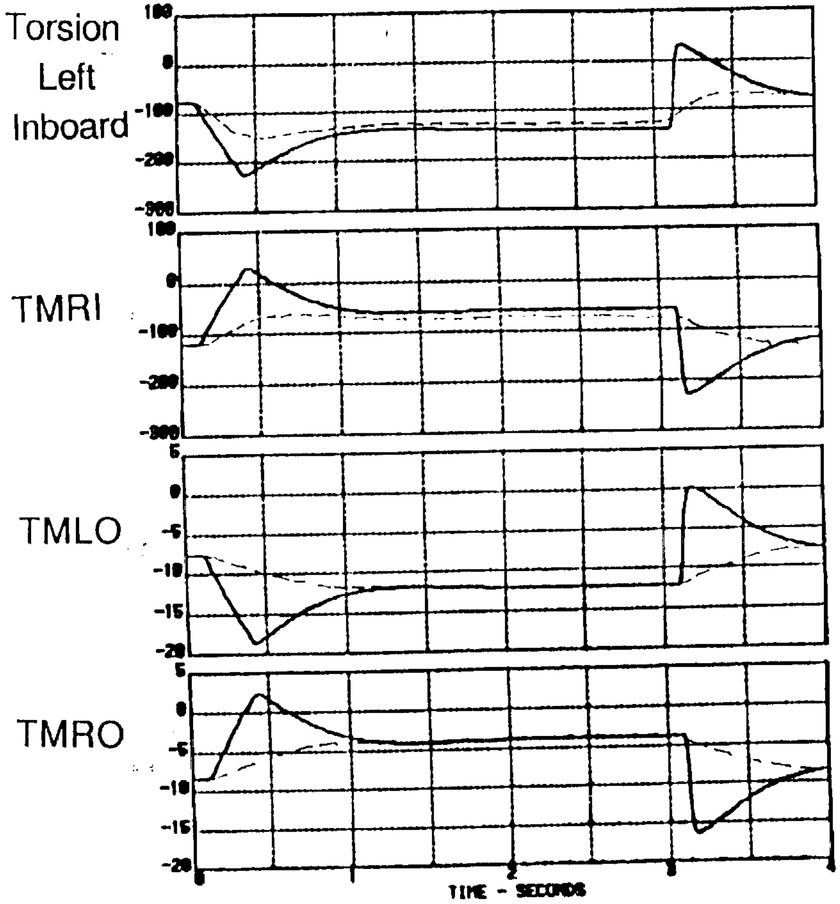
FULL ATW SIMULATION OF ROLL MANEUVER WITH LOAD REDUCTION





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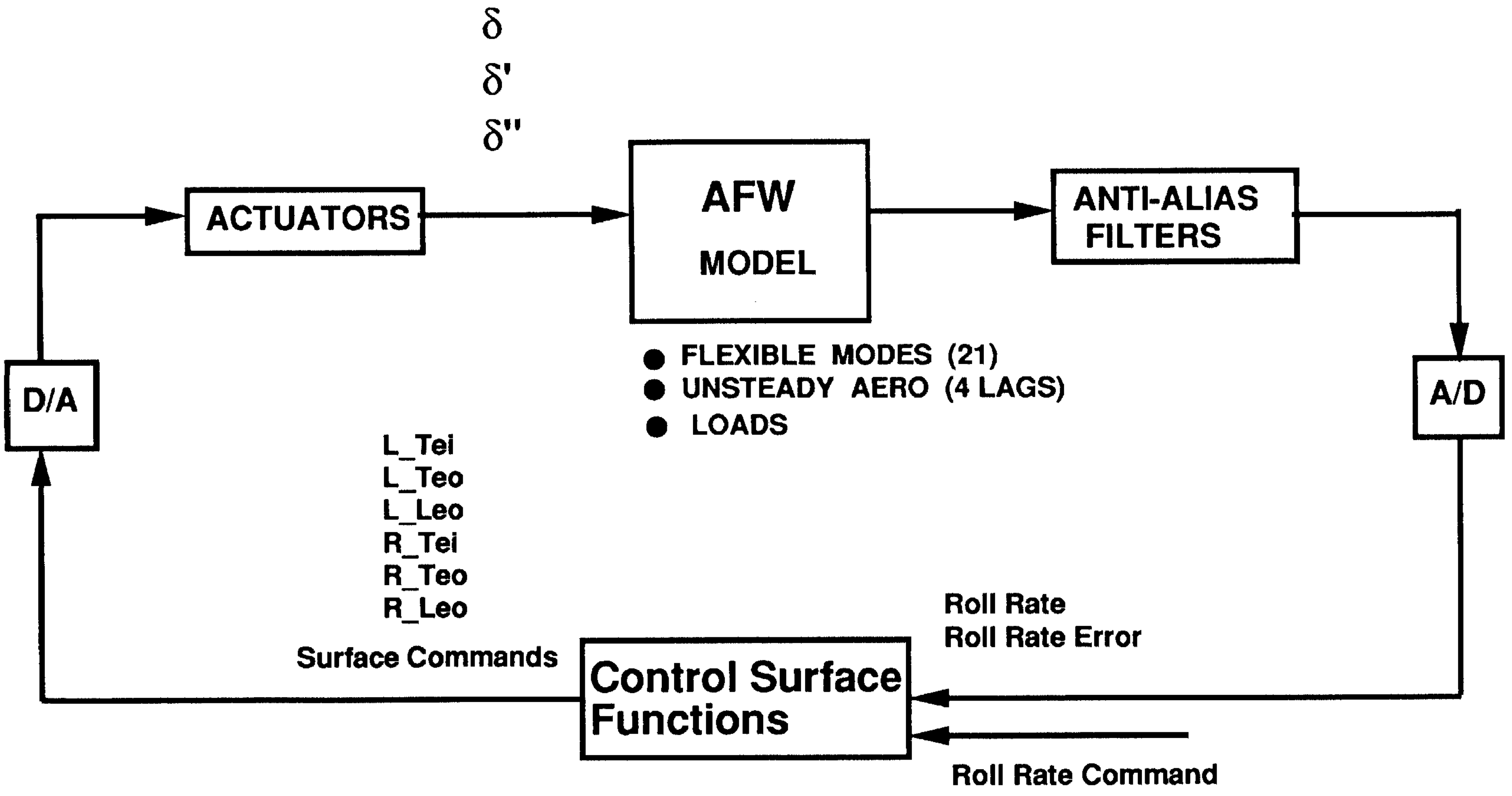
RMLA SUMMARY OBSERVATIONS

- DECOUPLING
  - ACHIEVE ROLL RATE WITHOUT TORSION MOMENT
  - ACHIEVE TORSION MOMENT WITHOUT ROLL RATE
- GOOD TRACKING
  - ALL OUTPUTS EQUAL ALL COMMANDS
  - ZERO ERROR
  - SMALL CROSS-COUPLING TRANSIENT
- GAIN MARGIN AND PHASE MARGIN

RMLA FUTURE DIRECTIONS

1. **Non-square input-output**
   - (e.g. more load control feedback locations than control surfaces)
2. **Expand pre-filter designs**
   - Implicit model following
   - Command Generator Tracker
3. **Extend the method**
   - all-axis Maneuver Load Control for aircraft to reduce / limit loads on all aircraft surfaces.

FEEDFORWARD NONLINEAR OPTIMAL CONTROL BLOCK DIAGRAM



δ
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ACTUATORS

AFW
MODEL

- FLEXIBLE MODES (21)
- UNSTEADY AERO (4 LAGS)
- LOADS

ANTI-ALIAS FILTERS

A/D

D/A

L_Tei
L_Teo
L_Leo
R_Tei
R_Teo
R_Leo

Surface Commands

Control Surface Functions

Roll Rate
Roll Rate Error

Roll Rate Command

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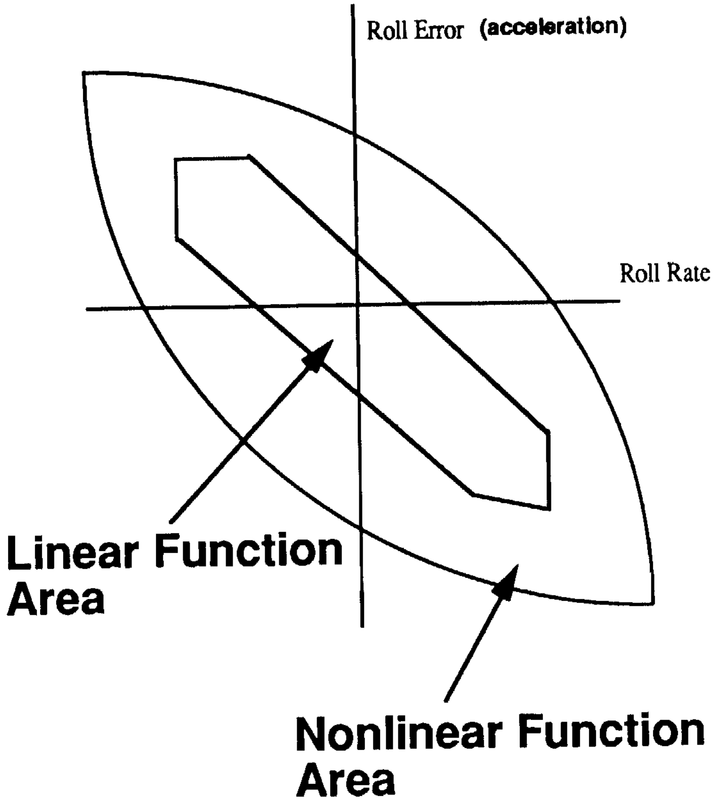
DESIGN METHOD FOR FEEDFORWARD NONLINEAR OPTIMAL FUNCTIONS



Loads < Design Limits

Roll Rate and Roll Acceleration are inputs.

$\mathrm{Min}(f) = \Sigma\ \delta_i$

The limit of the achievable envelope occurs when multiple conflicting load limit constraints are encountered.

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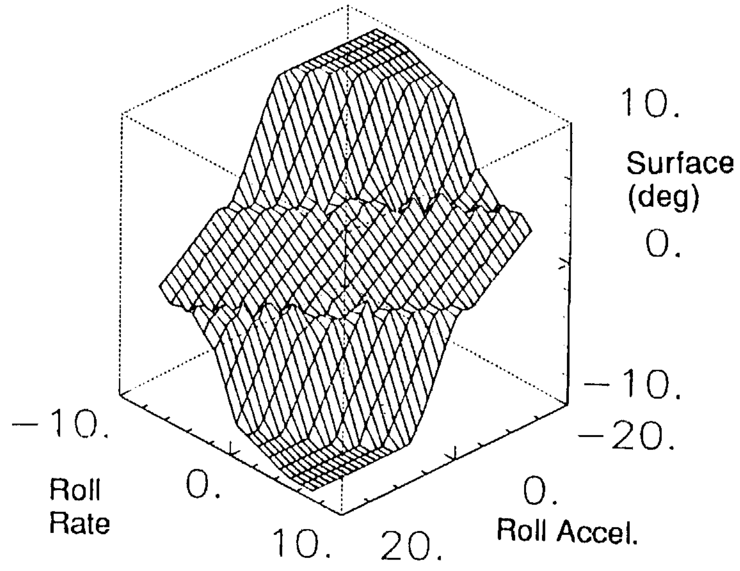
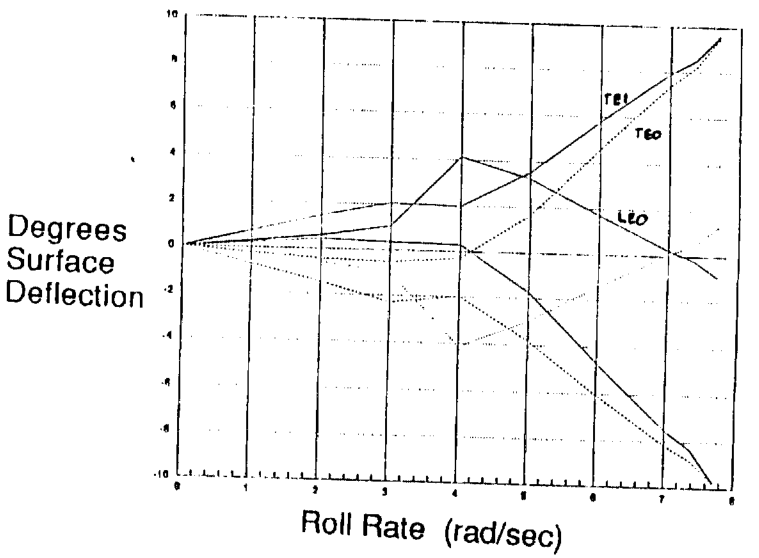
EXAMPLE OF SURFACE CONTROL FUNCTION



Left Trailing Edge Inboard Deflection vs Roll Rate and Acceleration

Surface Deflections @ zero Roll Acceleration



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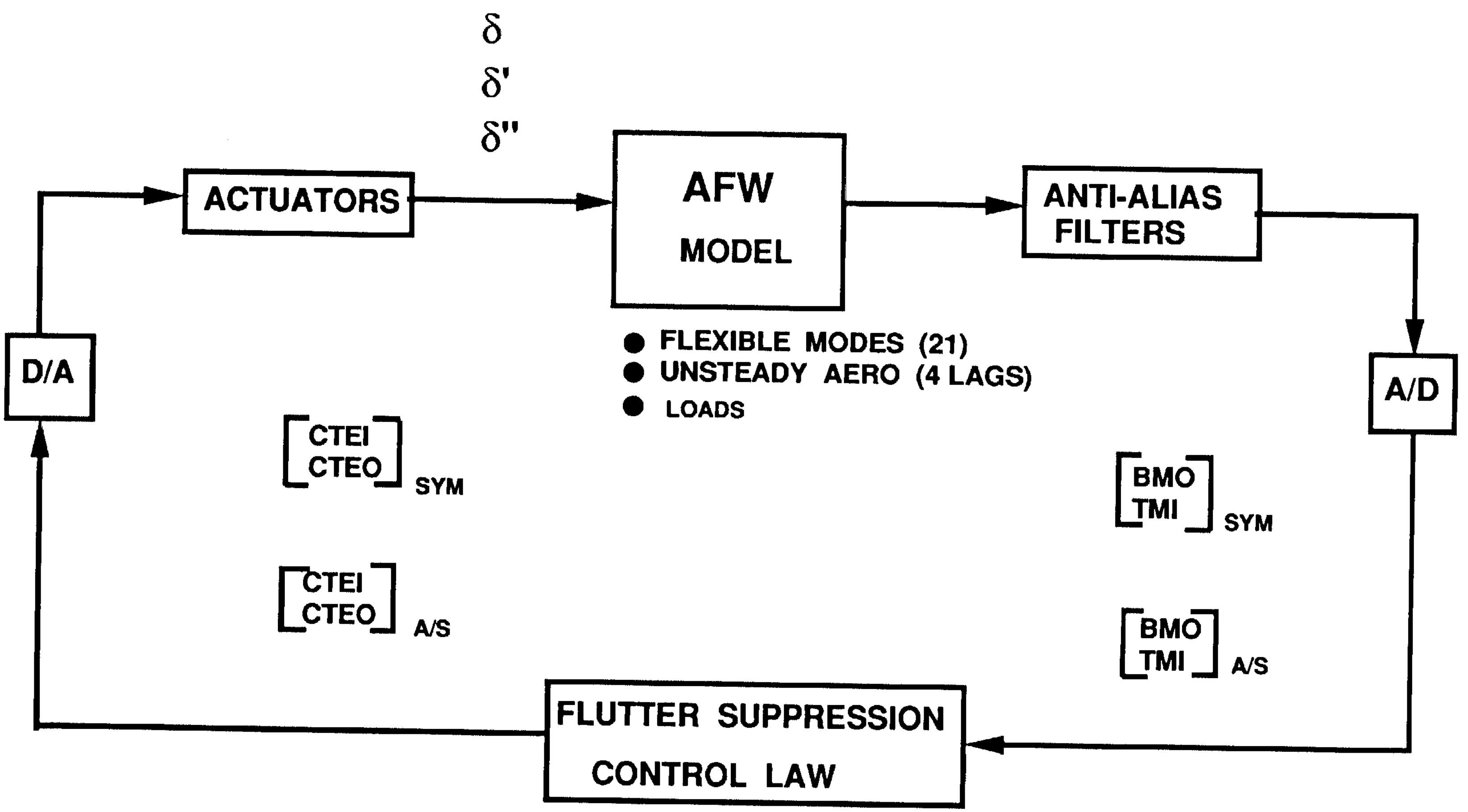
SUMMARY OF FEEDFORWARD OPTIMAL DESIGN

The Feedforward Nonlinear Optimal Controller can maintain roll performance while achieving loads <80% of non load control algorithms.

The design is linear in terms of roll rate and roll acceleration control; control power is a linear function of rate and acceleration.

Has applications to agility control as the system delivers maximum control force available.

FLUTTER CONTROL BLOCK DIAGRAM



- FLEXIBLE MODES (21)
- UNSTEADY AERO (4 LAGS)
- LOADS

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FLUTTER SUPPRESSION CONTROL LAW

Classical design method to stabilize flutter dynamics

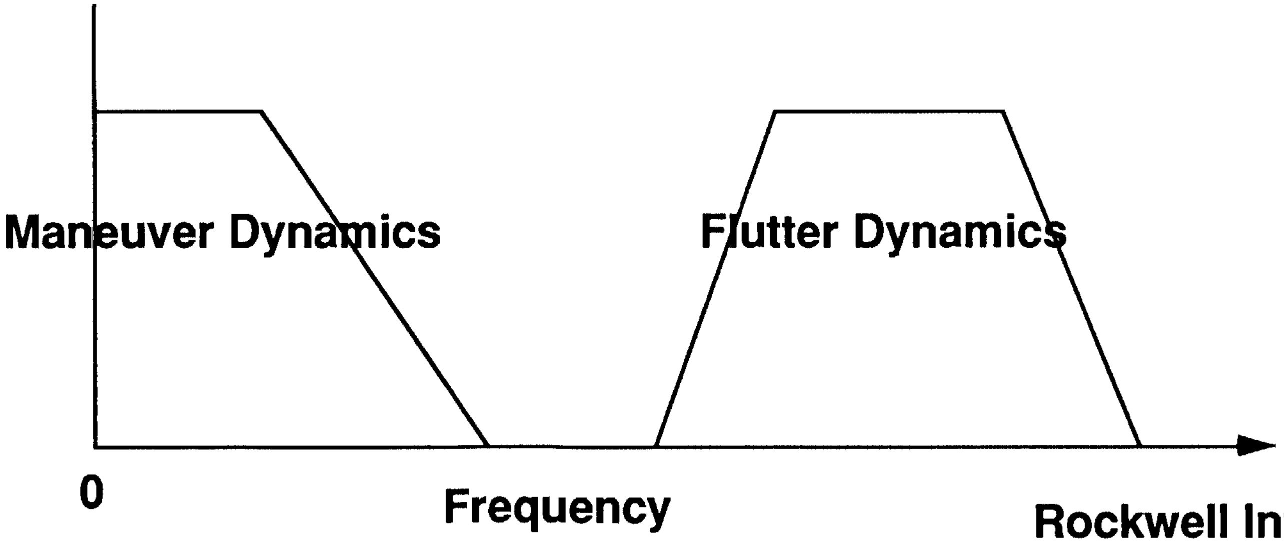
Uses load sensors for feedback control. Load sensors are used to avoid the nonlinear frequency effects of accelerometers.

Both SISO and MIMO control designs. SISO designs use one sensor input and give one control surface output. MIMO designs use two sensors for input and generate two distinct surface output commands.

DESIGN PHILOSOPHY OF COMBINED MANEUVER, FLUTTER SUPPRESSION AND LOAD CONTROL

Flutter controllers and Maneuver + Loads controllers can be designed separately and combined in a linear manner.

Frequency separation of the flutter and maneuver + loads phenomenon allows for this design method.



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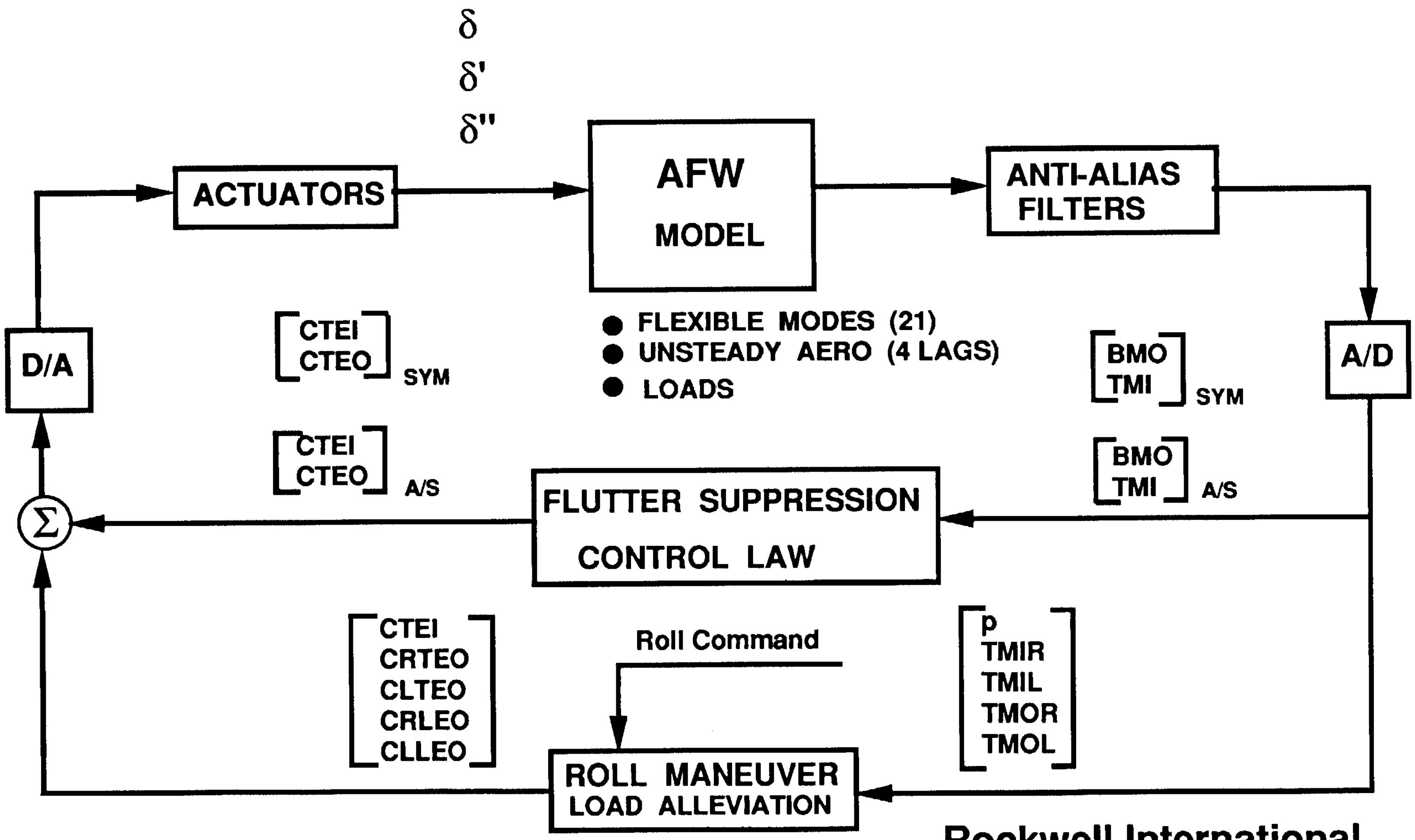
COMBINED RMLA AND FLUTTER CONTROL BLOCK DIAGRAM



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FUTURE OF ATW CONTROL EFFORT

- Final objective is to demonstrate a snap-roll maneuver (time to $90 < 0.4$ sec.) with load reduction beyond the flutter boundary.

- Possibility to integrate all axis maneuver + load + flutter control. Additional control schemes show promise for resolving conflicting design constraints while maintaining an intuitive design method for the flight control system.

- With all aircraft designs seeking ways to reduce weight, active control schemes can allow lighter and more flexible aircraft a larger flight envelope and greater safety margins.

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