STRAIN ACTUATED AEROELASTIC CONTROL

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Project Sponsors:

General Dynamics Corporation
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PROJECT GOAL

- Develop and Demonstrate Strain Actuated Lifting Surface Technology for Aeroelastic Control

- Induced Strain Actuation, rather than conventional articulated methods, allows for:
  
  Control of the Lifting Surface Shape for Altering the Aerodynamic Forces
  
  Direct Control of the Strain in the Structure and Dynamic Mode Shapes
SPECIFIC OBJECTIVES

- Develop a Capability for Analyzing Plate-Like Aeroelastic Lifting Surfaces
- Develop MIMO Control Laws for the Strain Actuated Adaptive Wing
- Demonstrate that Strain Actuation is an Effective means of Achieving Aeroelastic Control
STRUCTURAL AND AERODYNAMIC MODELLING

Model Lifting Surface with Piezoelectrics as Integrated Composite Plate

Choose Assumed Mode Shapes

In Vacuo Ritz Analysis Including Strain Energy

Natural Vibration Modes
Natural Frequencies
Piezoelectric Forcing
Mass and Stiffness

20 Modes
40 States

Wind Tunnel Operating Conditions

Kernal Function
Unsteady Aerodynamic Code

Unsteady Aerodynamic Forces

Non-Linear Least Squares Optimization

Rational Approximation of Aerodynamic Forces

3 Lag Sets
18 States

Actuators / Sensors

Actuator / Sensor Dynamics

9 Sensor States
24 Actuator States

Full Order State Space Plant Model

91 States
CONTROL LAW DESIGN METHODOLOGY

• Reduce "Full" Order Model to "Design" Model
  — Obtain Minimum Realization
  — Find Hankel Singular Values
  — Retain Modes with Largest Hankel SV's and DC Components of Others

• Design Linear Quadratic Gaussian Compensator
  — Cost Minimization
  — Loop Shaping

• Reduce "Design" Model to "Controller" Model
  — Same Procedure as Above
  — Optimal Projection
SYSTEM BLOCK DIAGRAM

- Plant Model from Raleigh-Ritz and Unsteady Aerodynamic Analysis
- Sensor, Amplifier and Filter Dynamics Included in "Full" System
- Magnetic Shaker (Bench) or Gust Generator (WT) Disturbance Source
- MIMO Compensators Designed using Reduced Order LQG or Optimal Projection Theory
- Compensators Implemented by a Real Time Digital Control Computer

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ADAPTIVE WING TEST ARTICLE

- Cantilever Plate Configuration: Actuators Cover 71% of Plate
BENCH - TOP EXPERIMENTS

- Correlate Analytic Model and Check Hardware Functionality

- Verify Control Law Design Procedure and Gain Necessary Controller Design Experience

- Demonstrate High-Authority Large-Bandwidth Disturbance Rejection Capabilities
BENCH-TOP DISTURBANCE REJECTION: 
OPEN AND CLOSED LOOP RESPONSE

- Aluminum Bench Mark Specimen
- Reduced Order LQG Design: $\rho = 1e^{-2}$  Sensor Noise = 3.0%

![Analytic Model](image1)

![Bench-Top Experiments](image2)
BENCH-TOP DISTURBANCE REJECTION: OPEN AND CLOSED LOOP RESPONSE

- Graphite/Epoxy Bend/Twist Coupled Specimen
- Reduced Order LQG Design: $\rho = 1\times 10^{-2}$  Sensor Noise = 3.0%

Analytic Model

Bench-Top Experiments

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BENCH-TOP DISTURBANCE REJECTION: STATE COST VERSUS CONTROL COST

- Aluminum Bench Mark Specimen
- Reduced Order LQG & OPT Designs: Sensor Noise = 3.0%

- State Cost Reduced by 96% (14 db RMS)
BENCH-TOP DISTURBANCE REJECTION: STATE COST VERSUS CONTROL COST

- Graphite/Epoxy Bend/Twist Coupled Specimen
- Reduced Order LQG Design: Sensor Noise = 3.0%

State Cost Reduced by 96% (14 db RMS)
WIND TUNNEL EXPERIMENTS

- Aeroelastic Control Issues

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- Result: A Well Regulated Plant with High Loop Gain in the Low Frequency Regime is Desired
WIND TUNNEL SET-UP

- 1 Foot Low Turbulence Tunnel
  - Test Section: 8" x 12"
  - Maximum Speed: 100 MPH

- Gust Generator 1 Semi-Chord Ahead of Leading Edge

- Laser Displacement Sensors Built Into Side of Test Section
WIND TUNNEL GUST ALLEVIATION:
OPEN AND CLOSED LOOP RESPONSE AT 60 MPH

- Aluminum Bench Mark Specimen
- Reduced Order LQG Design: $\rho = 1e^{-1}$, Sensor Noise = 1.0%
WIND TUNNEL GUST ALLEVIATION: OPEN AND CLOSED LOOP RESPONSE AT 60 MPH

- Graphite/Epoxy Bend/Twist Coupled Specimen
- Reduced Order LQG Design: $\rho = 1e^0$  Sensor Noise = 0.5%

Analytic Model

Bench-Top Experiments
WIND TUNNEL GUST ALLEVIATION:
STATE COST VERSUS CONTROL COST AT 60 MPH

- Aluminum Bench Mark Specimen
- Reduced Order LQG Design: Sensor Noise = 0.5%

- State Cost Reduced by 84% (8 db RMS)
WIND TUNNEL GUST ALLEVIATION:
STATE COST VERSUS CONTROL COST AT 60 MPH

- Graphite/Epoxy Bend/Twist Coupled Specimen
- Reduced Order LQG Design: Sensor Noise = 1.0%

- State Cost Reduced by 84% (8 db RMS)
WIND TUNNEL COMMAND FOLLOWING:
OPEN AND CLOSED LOOP ERROR AT 60 MPH

Graphite/Epoxy Bend/Twist Coupled Specimen: Low Bandwidth

Analytic Model

Bench-Top Experiments
WIND TUNNEL COMMAND FOLLOWING:
OPEN AND CLOSED LOOP ERROR AT 60 MPH

Graphite/Epoxy Bend/Twist Coupled Specimen: High Bandwidth

Analytic Model

Bench-Top Experiments
WIND TUNNEL FLUTTER SUPPRESSION: OPEN LOOP FLUTTER SPEED

- Aluminum Plate Original Flutter Speed About 125 MPH

- Flutter Speed Lowered to 88 MPH by:
  - Adding 1.6x Original Weight
  - 0.8 Semi-Chords Behind the TE

![Graph showing wind speed vs. frequency]
WIND TUNNEL FLUTTER SUPPRESSION: CLOSED LOOP STATE COST CURVES

- Finite State Cost (stable system) for Any Control Weight
- High Frequency Modes Are Destabilized as Gain Becomes Large