MIT
Space
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STRAIN ACTUATED AEROELASTIC CONTROL

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NASA Langley Research Center
National Science Foundation

PROJECT GOAL

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

  — Induced Strain Actuation, rather than conventional articulated methods, allows for:

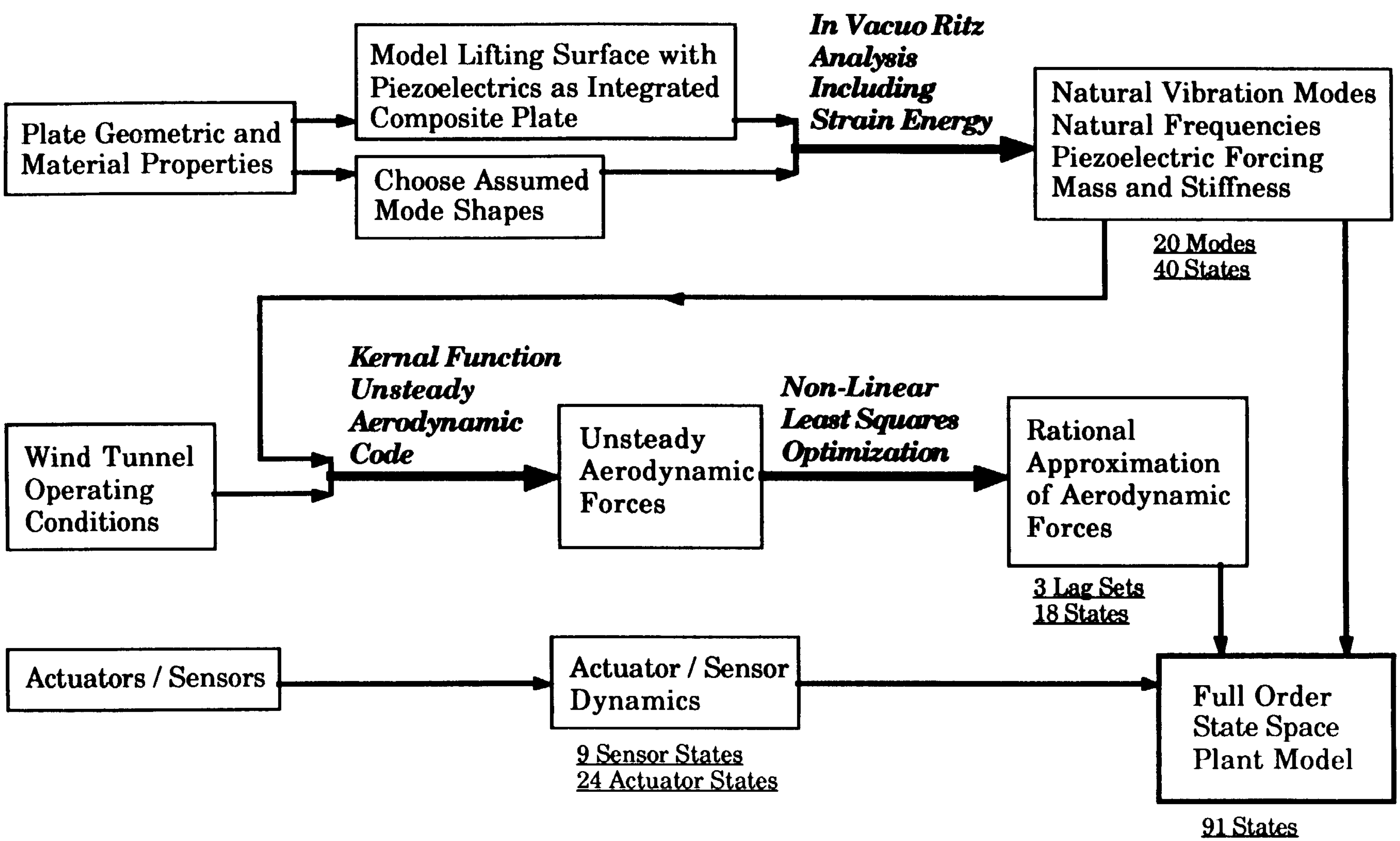
  Control of the Lifting Surface Shape for Altering the Aerodynamic Forces

  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

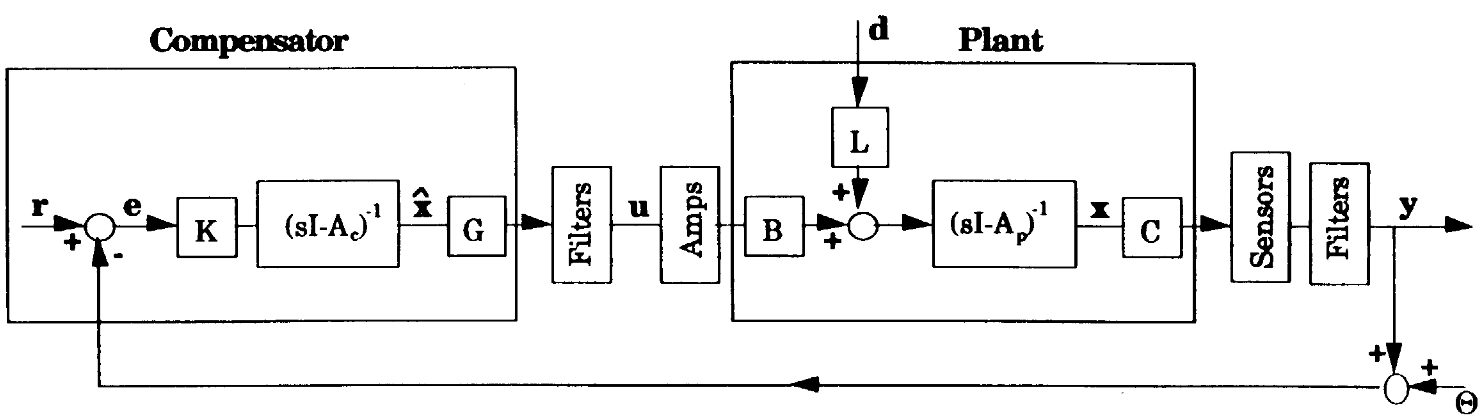


CONTROL LAW DESIGN METHODOLOGY

- **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

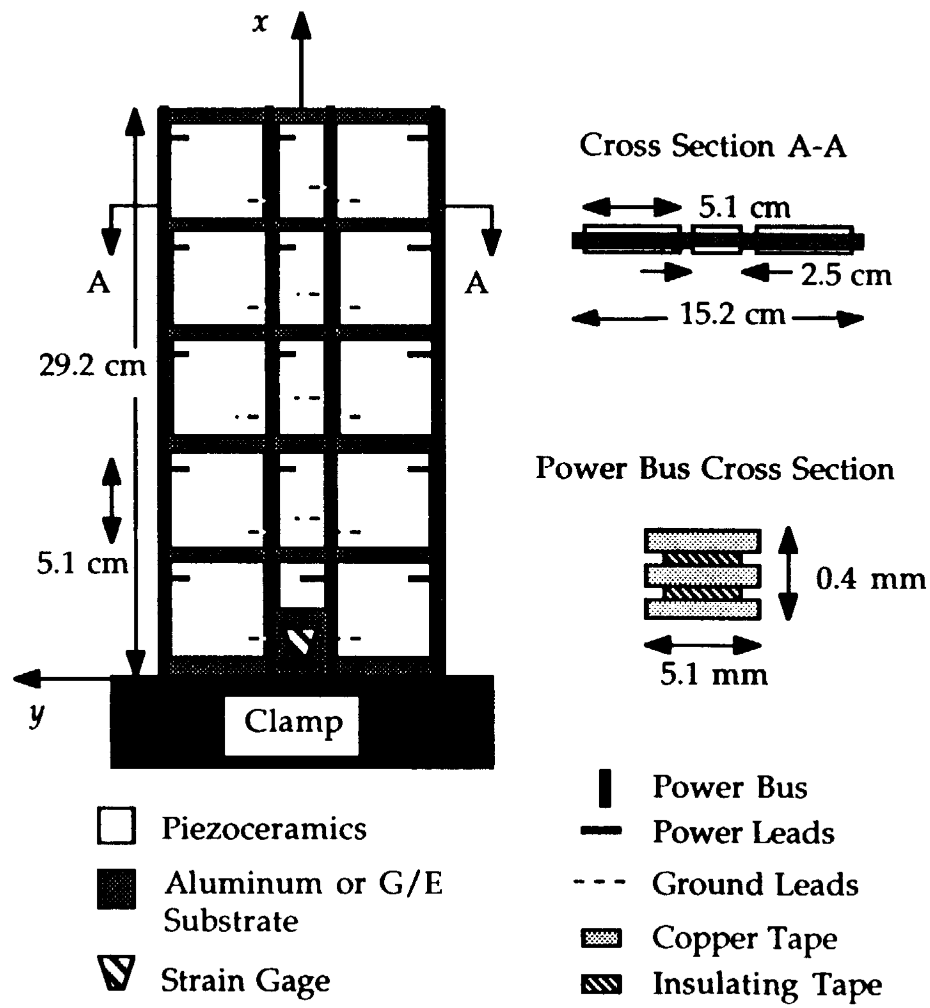
SYSTEM BLOCK DIAGRAM

- **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**



ADAPTIVE WING TEST ARTICLE

- **Cantilever Plate Configuration: Actuators Cover 71% of Plate**



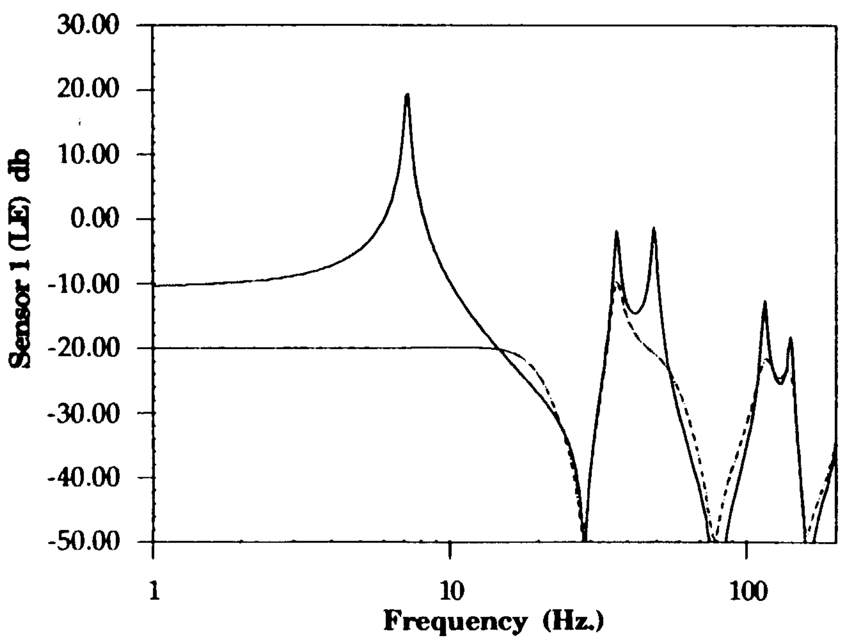
BENCH - TOP EXPERIMENTS

- **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**

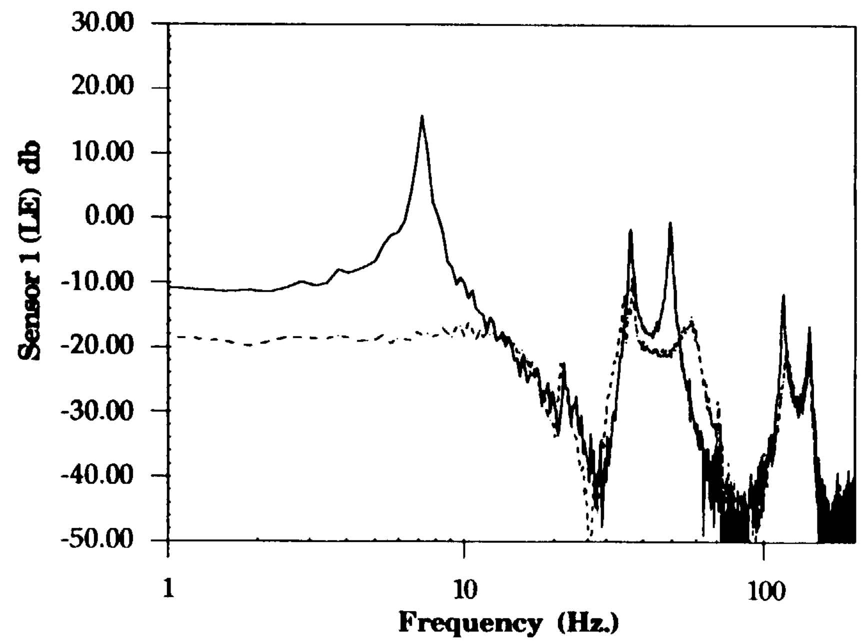
BENCH-TOP DISTURBANCE REJECTION: OPEN AND CLOSED LOOP RESPONSE

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

Analytic Model



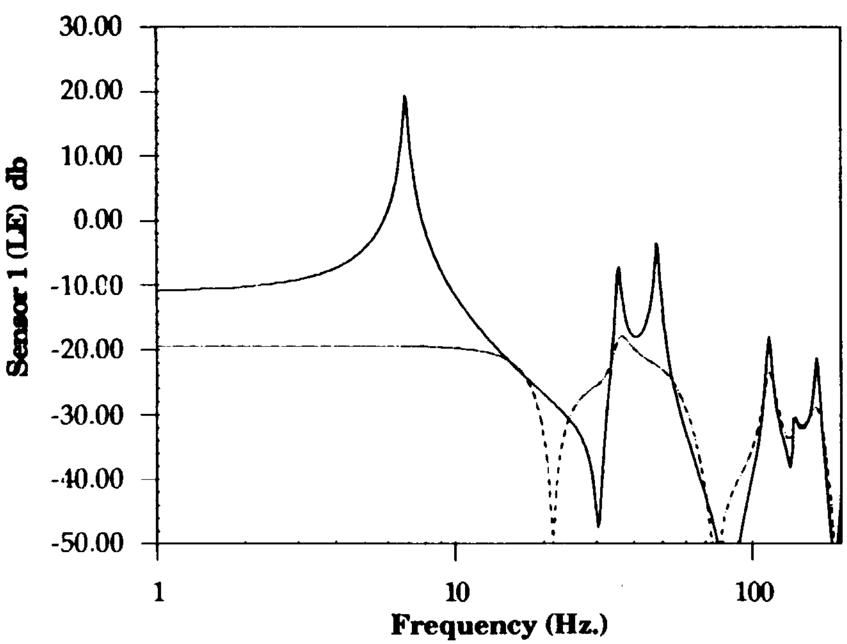
Bench-Top Experiments



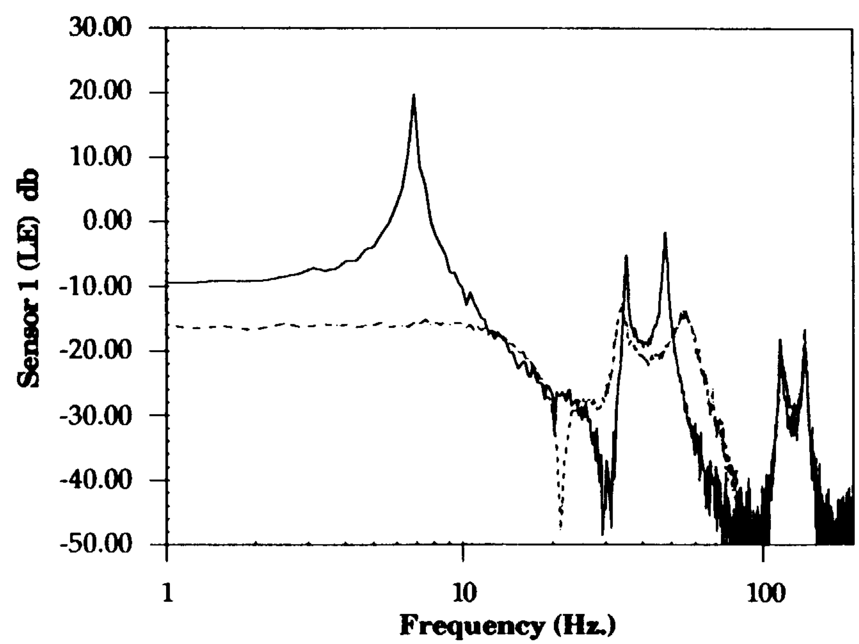
BENCH-TOP DISTURBANCE REJECTION: OPEN AND CLOSED LOOP RESPONSE

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

Analytic Model

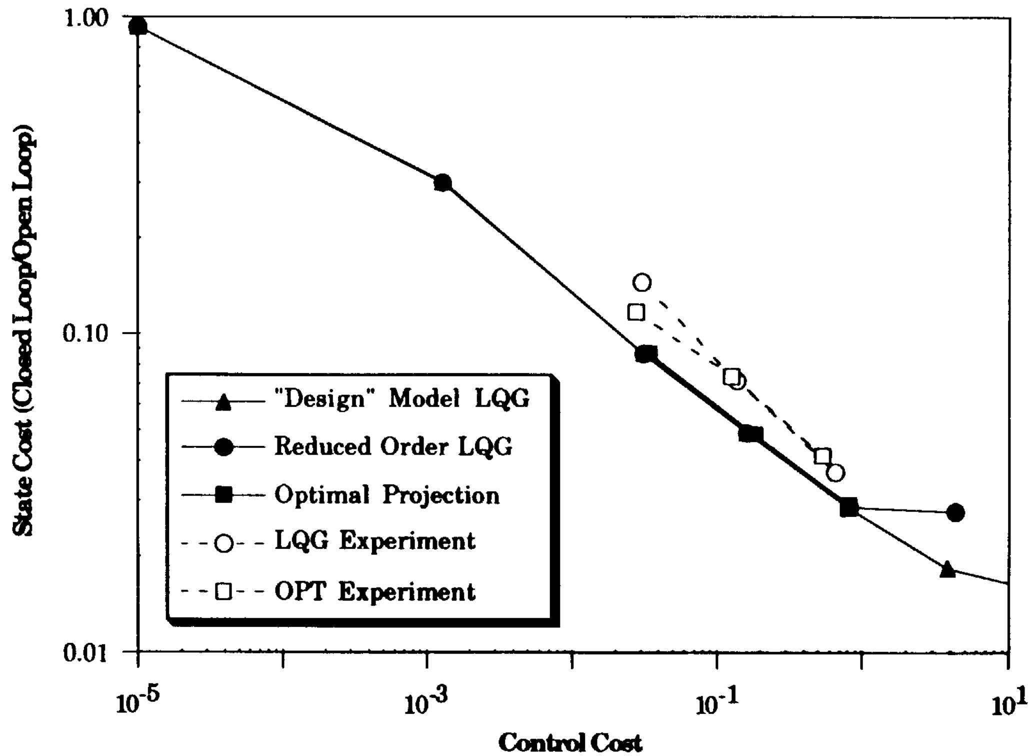


Bench-Top Experiments



BENCH-TOP DISTURBANCE REJECTION: STATE COST VERSUS CONTROL COST

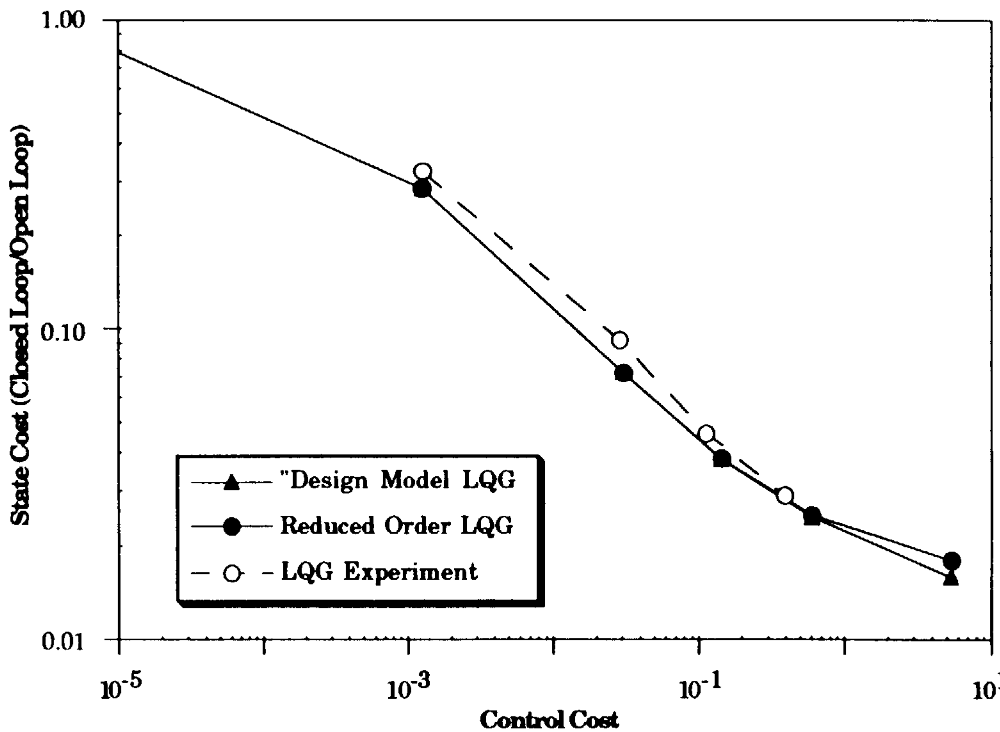
- **Aluminum Bench Mark Specimen**
- **Reduced Order LQG & OPT Designs:** **Sensor Noise = 3.0%**



- **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

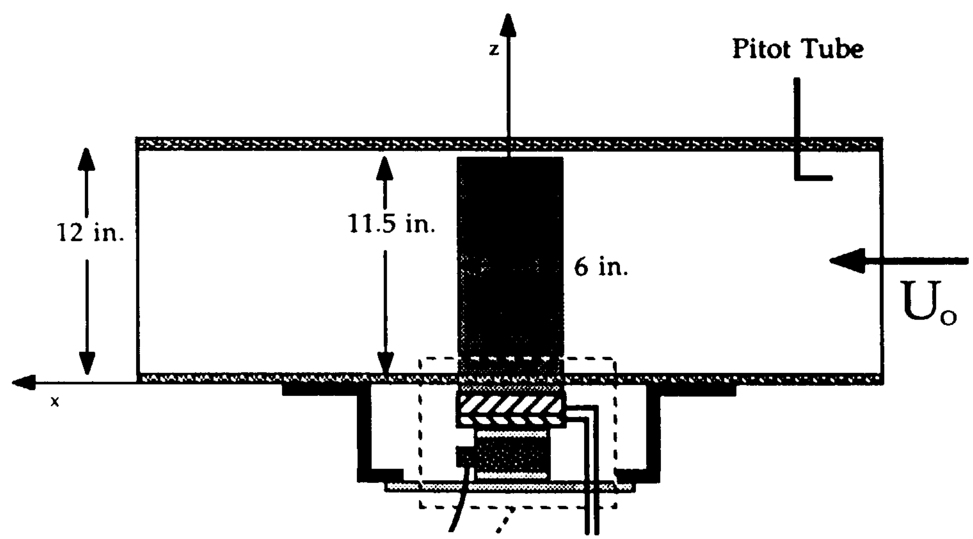
- **Aeroelastic Control Issues**

Performance Objectives	Control Law Objectives
Flutter Suppression	Stability
Vibration Suppression	Plant Regulation
Gust Alleviation	Disturbance Rejection
Maneuverability	Low Frequency Command Following

- **Result: A Well Regulated Plant with High Loop Gain in the Low Frequency Regime is Desired**

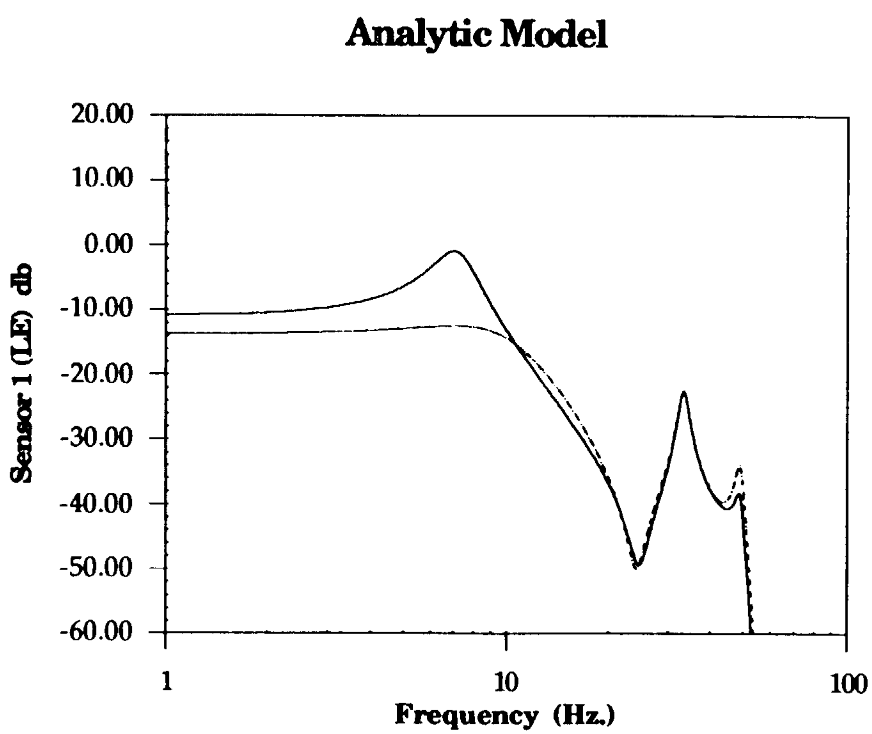
WIND TUNNEL SET-UP

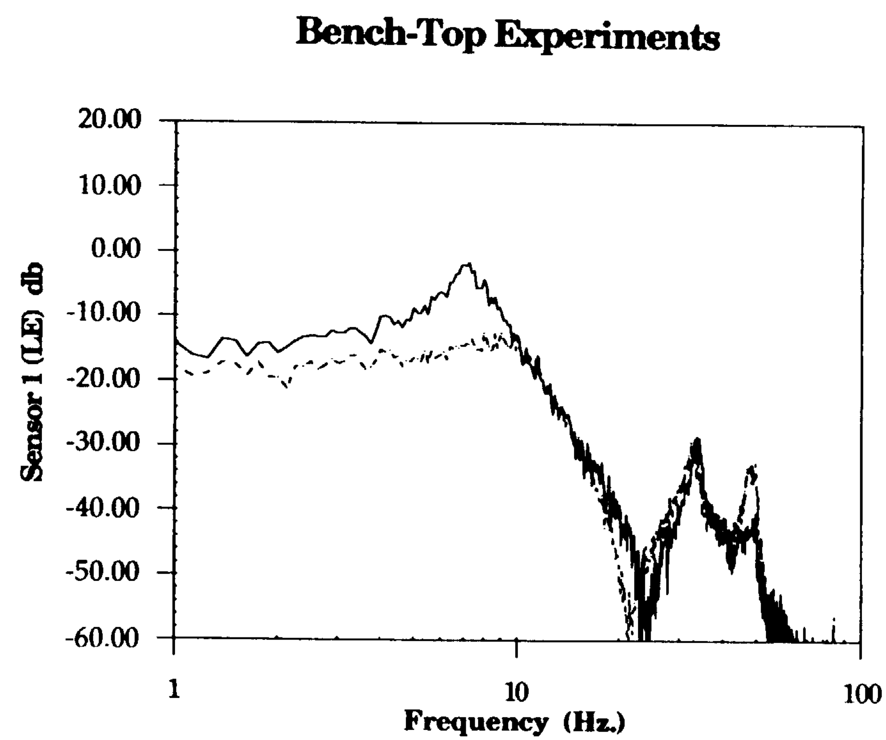
- **1 Foot Low Turbulence Tunnel**
  - Test Section: 8" x 12"
  - Maximum Speed: 100 MPH
- **Gust Generator 1 Semi-Chord Ahead of Leading Edge**
- **Laser Displacement Sensors Built Into Side of Test Section**



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%**

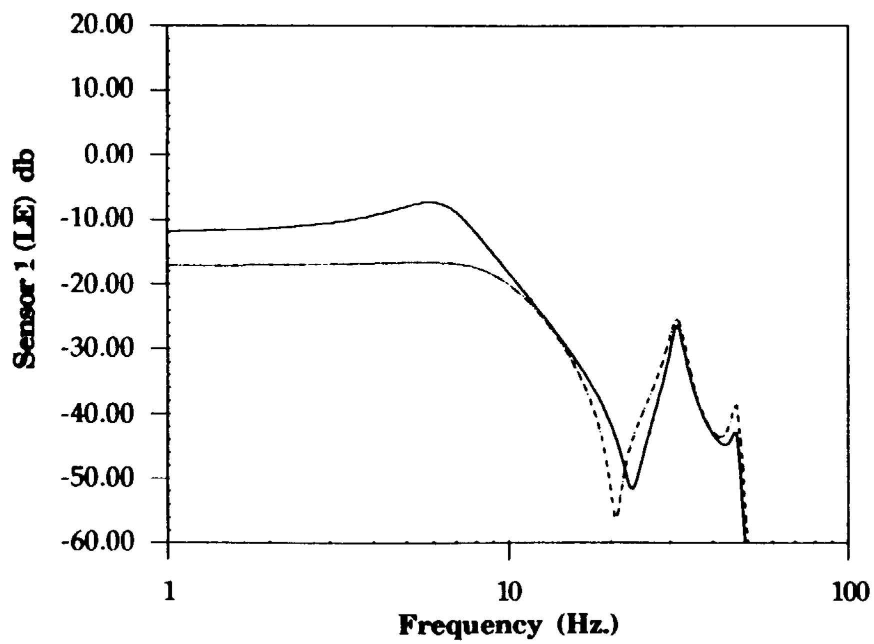




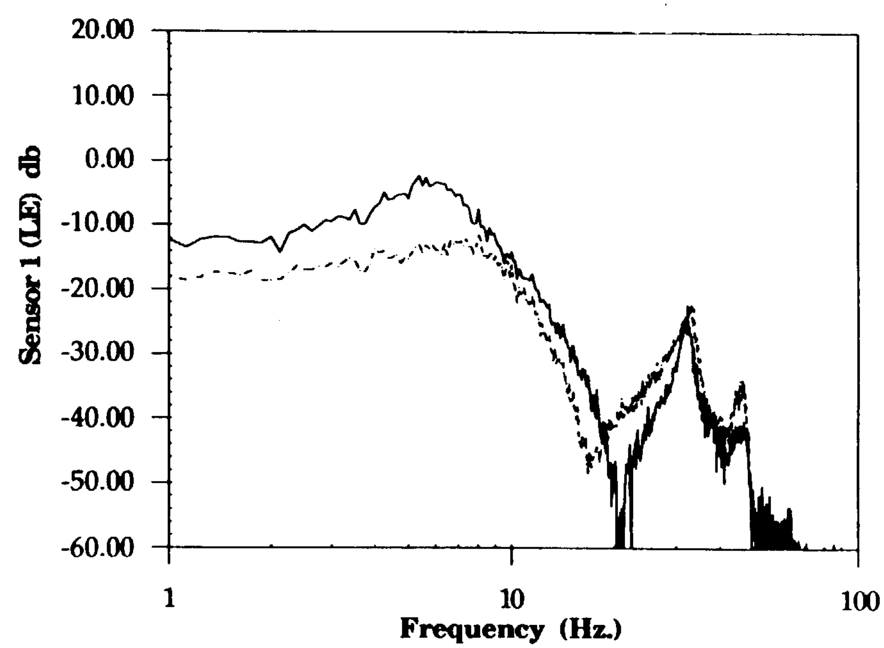
WIND TUNNEL GUST ALLEVIATION: OPEN AND CLOSED LOOP RESPONSE AT 60 MPH

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

Analytic Model

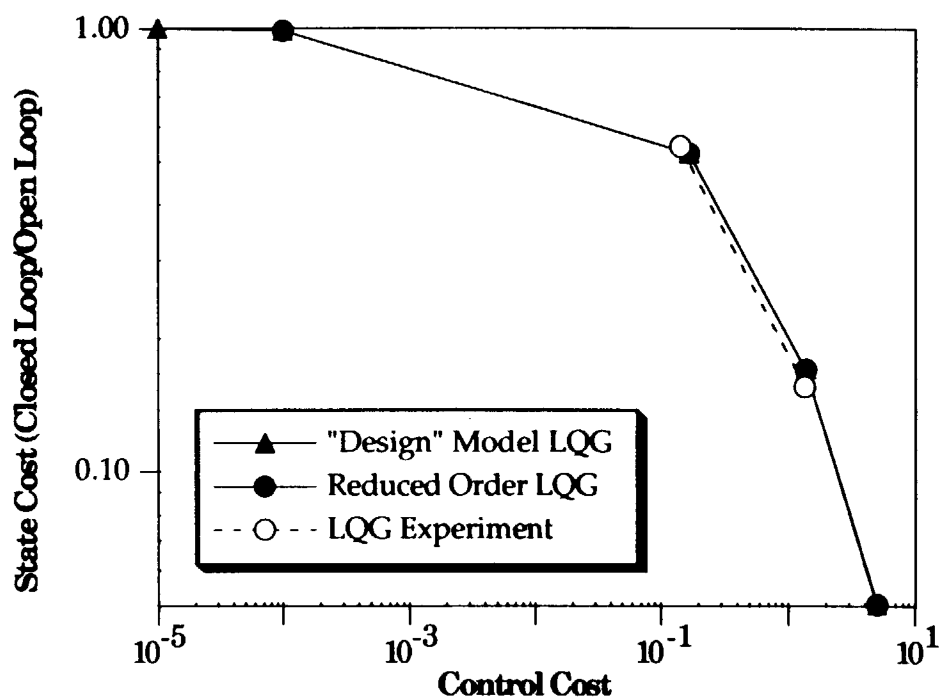


Bench-Top Experiments



WIND TUNNEL GUST ALLEVIATION: STATE COST VERSUS CONTROL COST AT 60 MPH

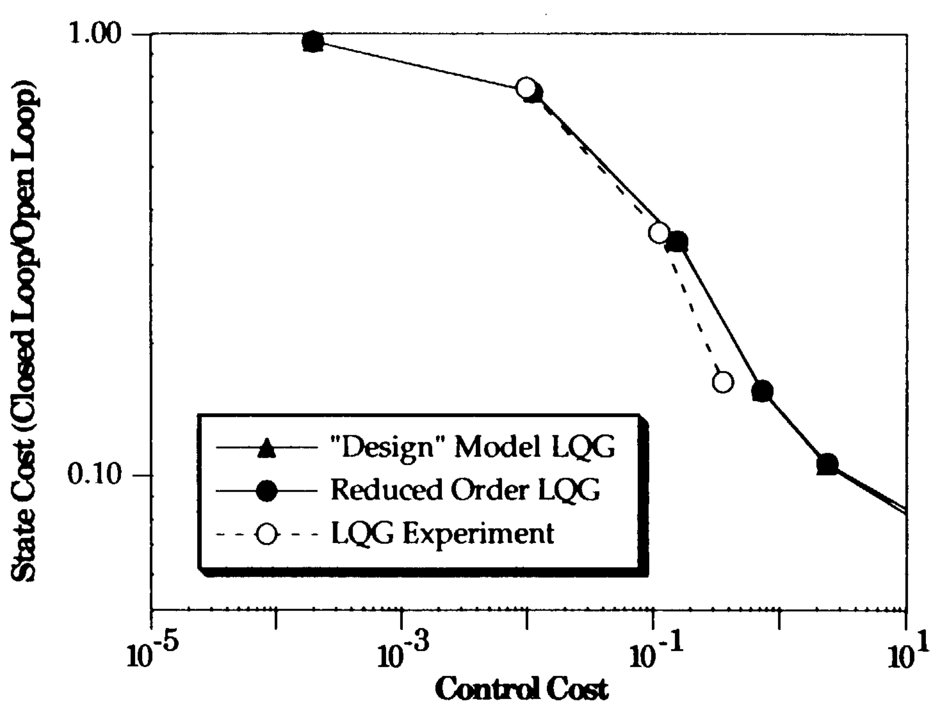
- **Aluminum Bench Mark Specimen**
- **Reduced Order LQG Design:** **Sensor Noise = 0.5%**



- **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%**

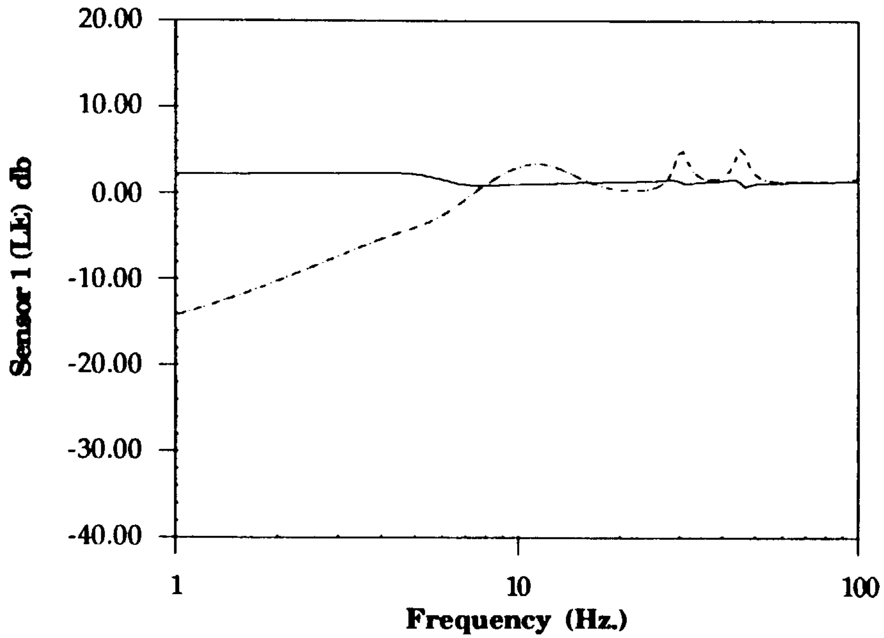


- **State Cost Reduced by 84% (8 db RMS)**

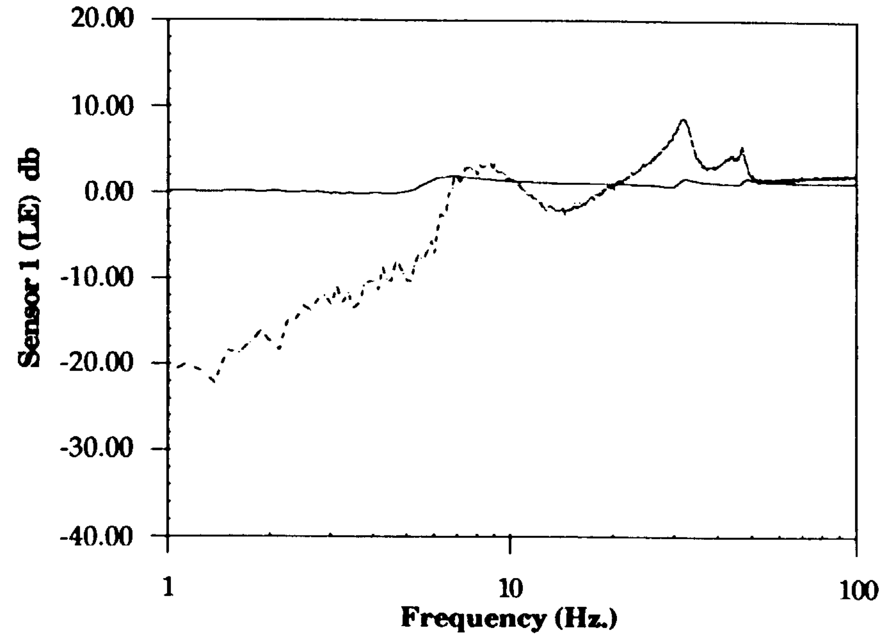
WIND TUNNEL COMMAND FOLLOWING: OPEN AND CLOSED LOOP ERROR AT 60 MPH

Graphite/Epoxy Bend/Twist Coupled Specimen: Low Bandwidth

Analytic Model



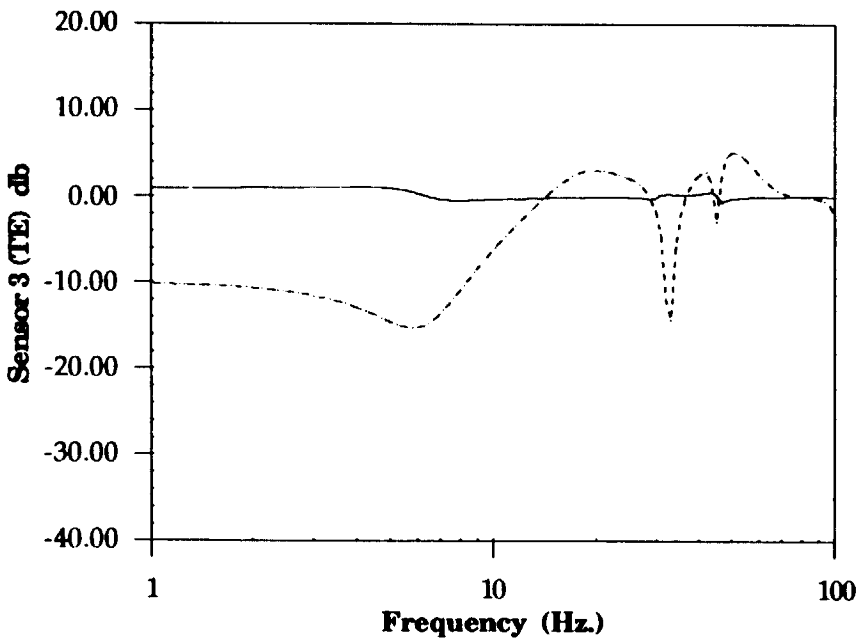
Bench-Top Experiments



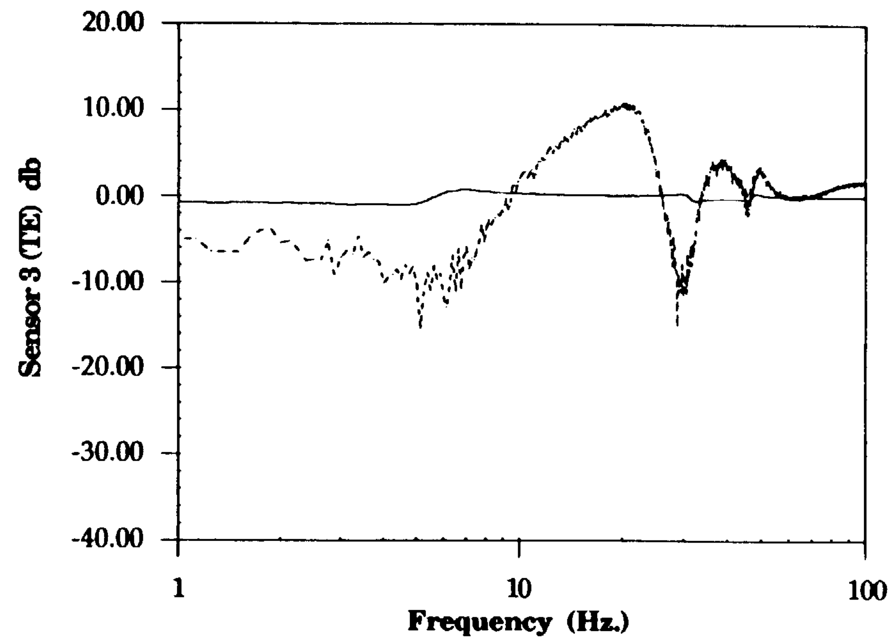
WIND TUNNEL COMMAND FOLLOWING: OPEN AND CLOSED LOOP ERROR AT 60 MPH

Graphite/Epoxy Bend/Twist Coupled Specimen: High Bandwidth

Analytic Model

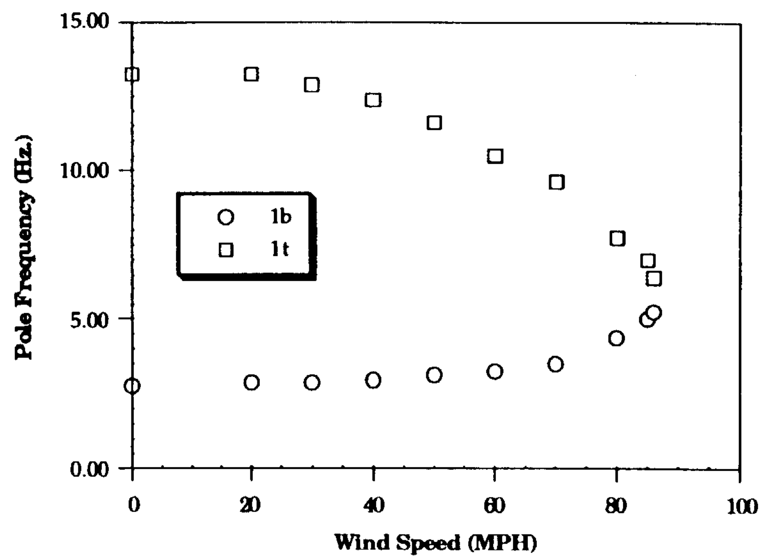


Bench-Top Experiments



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



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**