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The Impact of Structural Vibration on Flying Qualities of a High Speed Civil Transport

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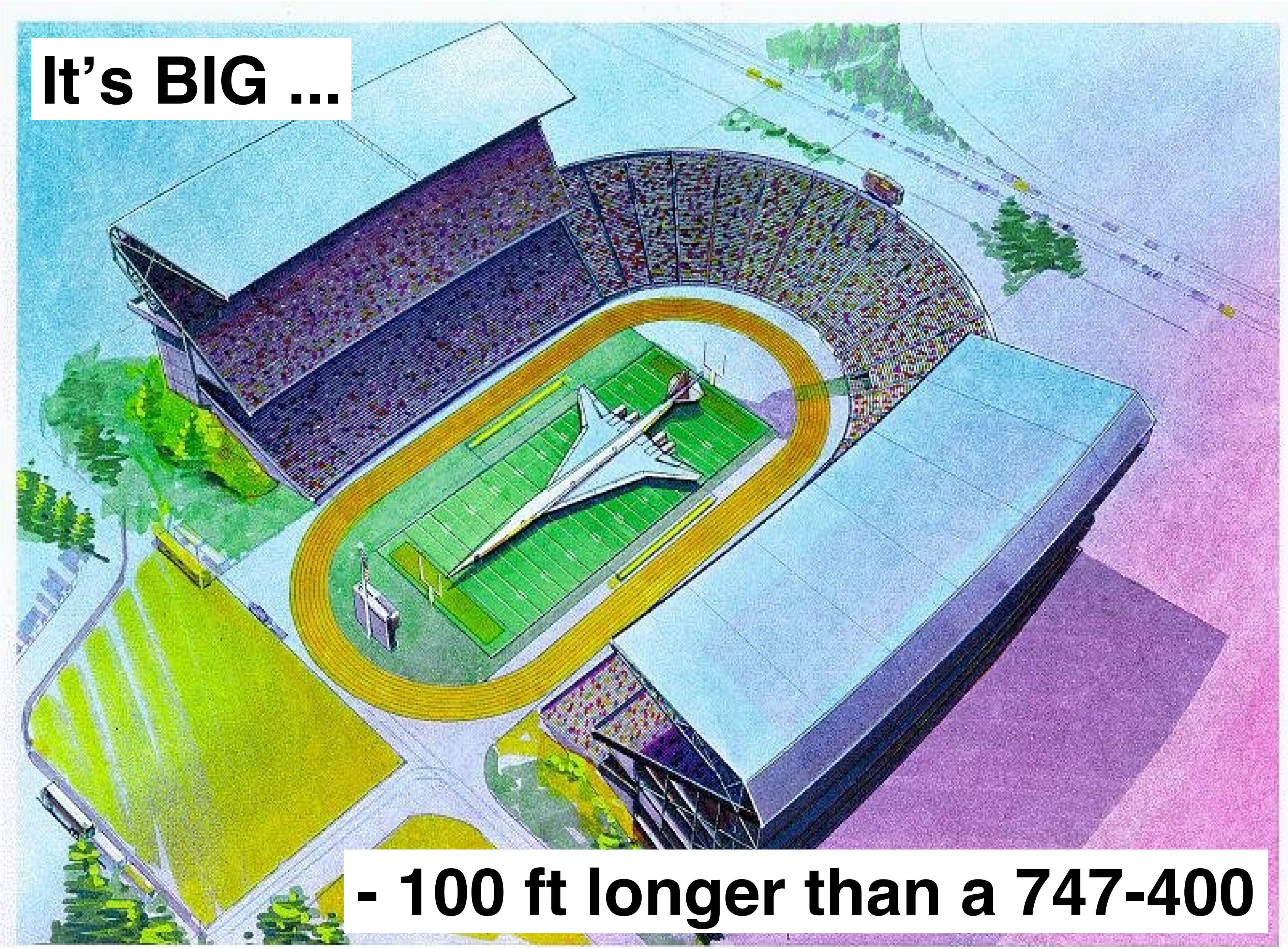
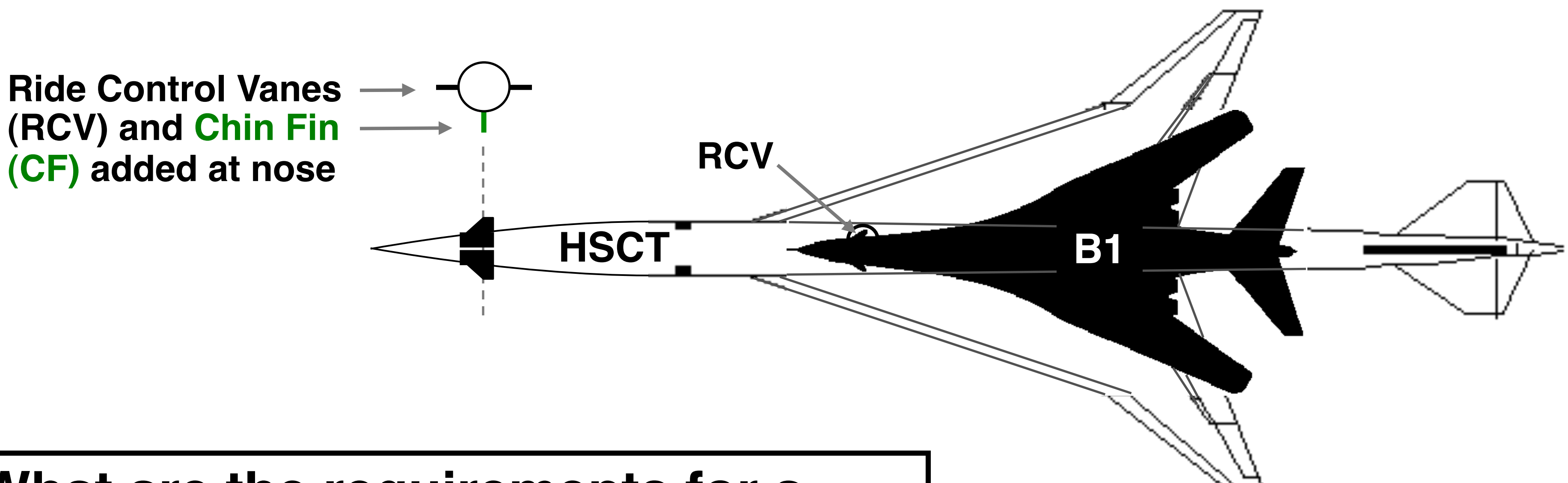

It’s BIG ...
- 100 ft longer than a 747-400

HSCT Size + Slenderness = Aeroelastic Problems

- HSCT is ~ 330 ft long with first elastic mode frequency of 1.25-1.45 Hz; typical subsonic transport is twice that.
- Simulations suggest that active structural control will be required for acceptable flying and ground handling qualities.
  - » Vibration environment at pilot station is dramatic



What are the requirements for a Structural Mode Control system?

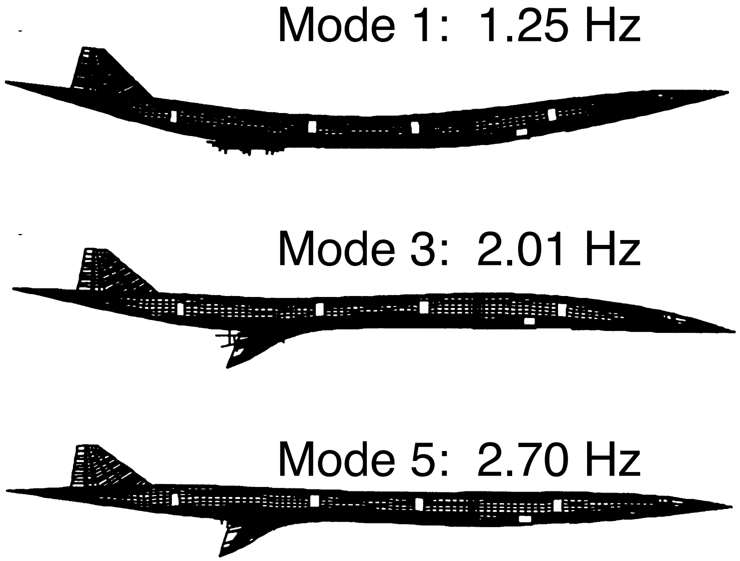
Approach & Objectives

- **Parameterize Aeroelastic Model: Directly manipulate model's dynamic characteristics to approximate the effect of various means of dealing with DASE***
  - » **Structural stiffening, Active mode suppression**
- **Perform piloted evaluation maneuvers in simulator**
  - » **Collect pilot ratings, cockpit vibration data, and simulation time histories for each parametric configuration**
- **Examine effectiveness of various means of addressing DASE**
  - » **Generate design insights**
  - » **Prescribe damping objectives for active mode control**

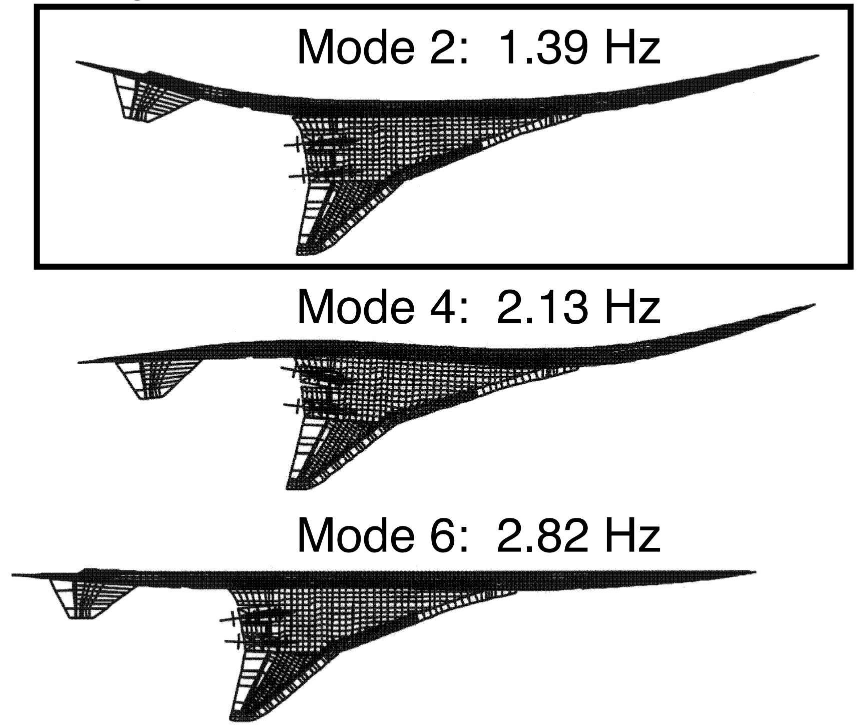
***DASE: Dynamic AeroServoElasticity**

HSCT Real-Time Dynamic Aeroelastic Model

Symmetric Modes (Side View)



Antisymmetric Modes (Top View)



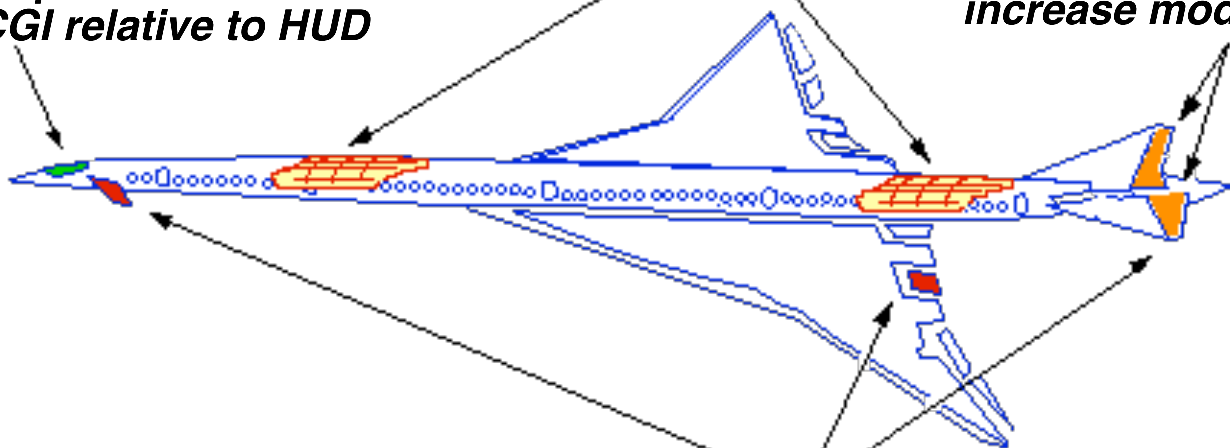
- 3 Symmetric + 3 Antisymmetric Modes
- Parameterized Modal Frequencies & Damping
- Turbulence Inputs + Control Effector Inputs
- Attitude Perturbations Represented in Visual Cues

Potential Solutions to Examine using Parameterized Model

structural stiffening:
increase modal frequencies

display compensation:
eliminate impact of visual cues by fixing CGI relative to HUD

active suppression:
increase modal damping

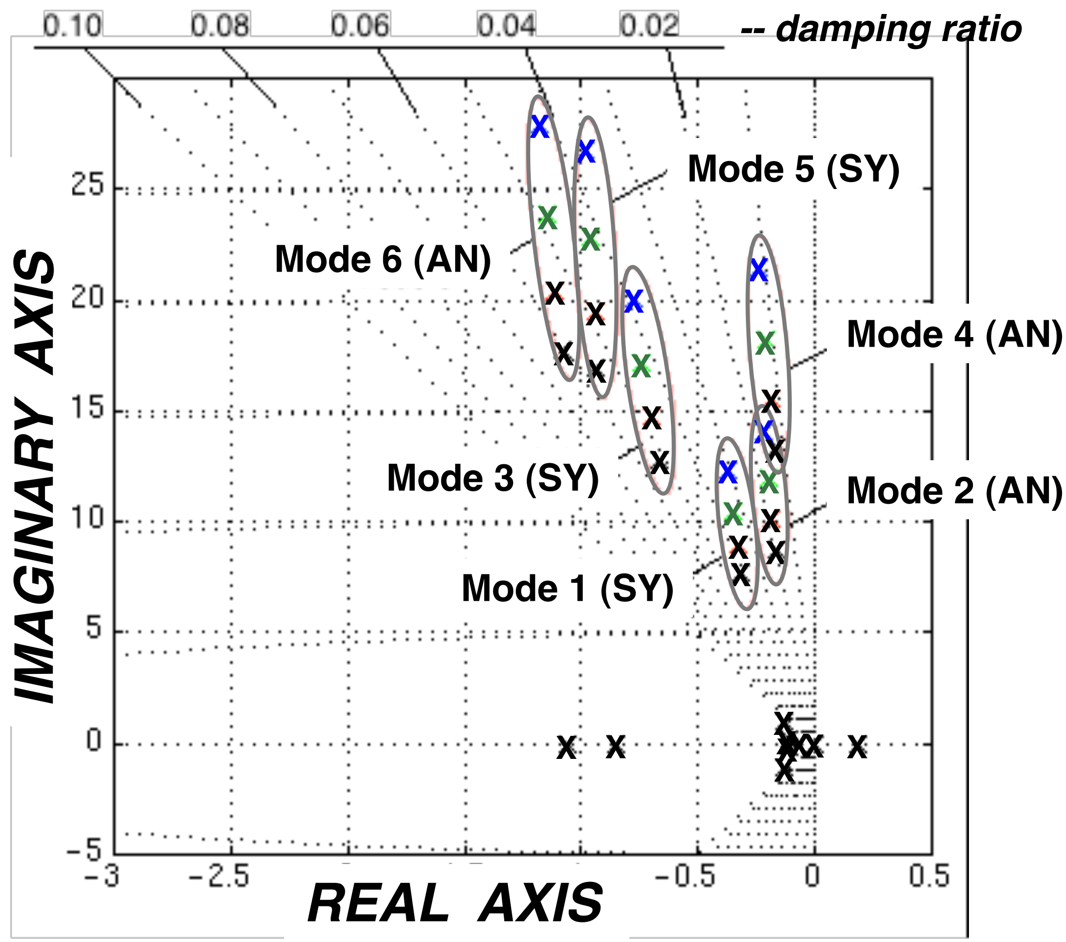


active suppression; mode-cancelling control:
eliminate modal excitation due to surface deflections (multi-surface mode suppression)

Variation of Structural Stiffness

Configuration	Frequency Ratio	Stiffness Increase	1st SY Mode Frequency
baseline	1.00	--	1.25 Hz
stif1	1.16	~35%	1.45 Hz
stif2	1.36	~85%	1.80 Hz
stif3	1.60	~150%	2.00 Hz

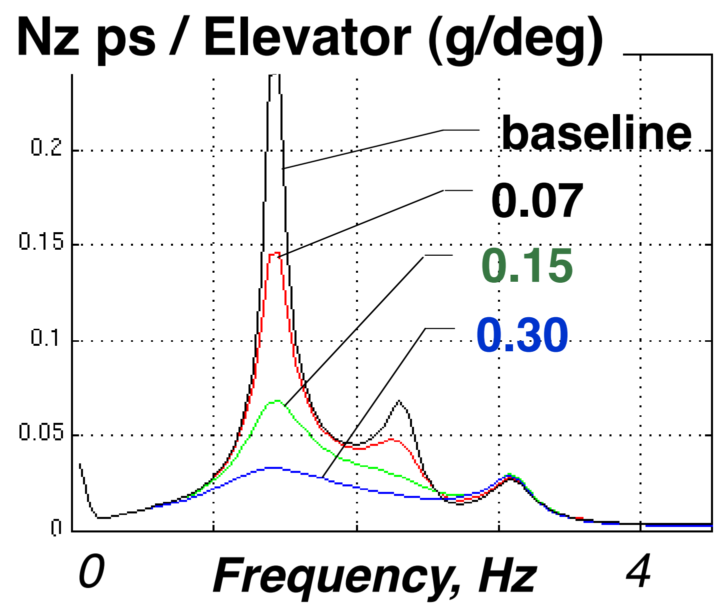
- **Directly manipulate model to simulate frequency increases due to stiffer structure**
- **All structural modes are lightly damped**
- **No consideration of associated weight penalties**

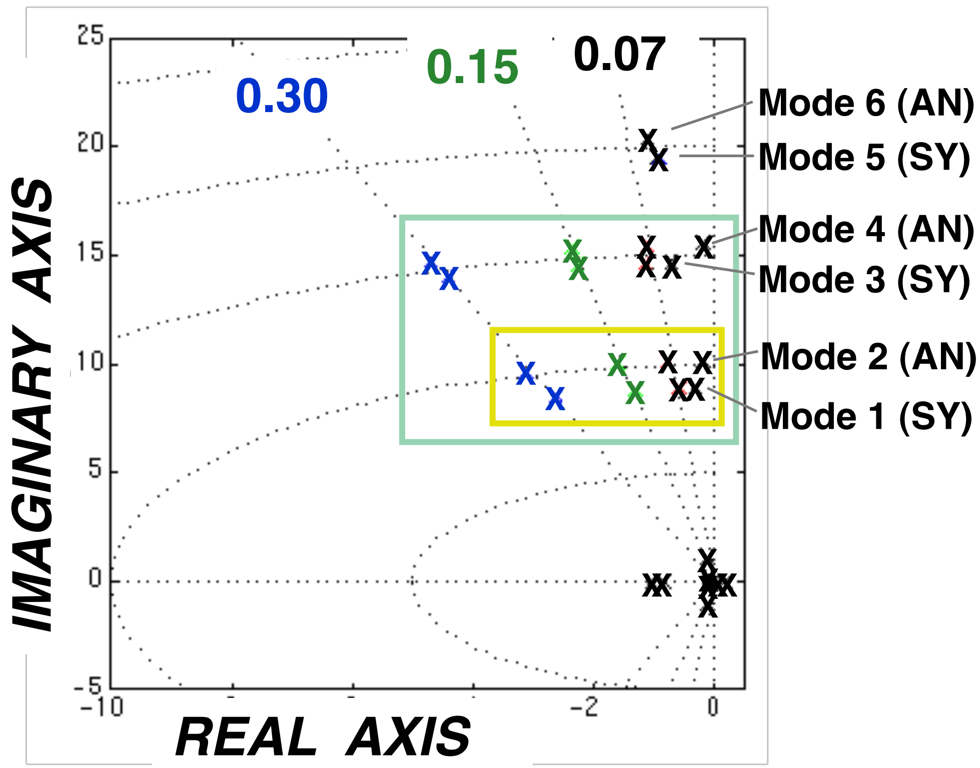


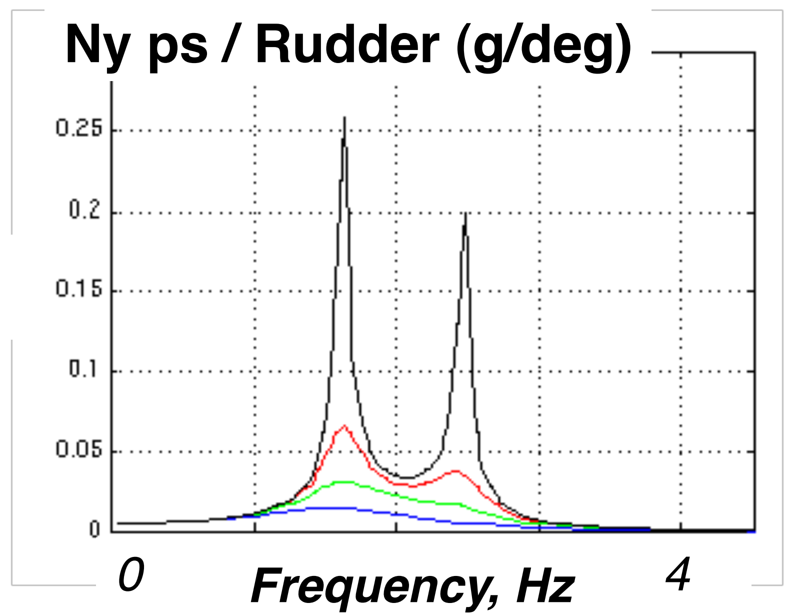
Variation of Modal Damping

Examine effect of Damping Level, Frequency Range, Symmetric vs Antisymmetric

Configuration	Damping Ratio	Modes
stif1	nominal	—
damp1	0.07	SY1, AN1
damp2	0.15	SY1, AN1
damp3	0.30	SY1, AN1
damp4	0.30	SY1
damp5	0.30	AN1
damp6	0.07	SY1-2, AN1-2
damp7	0.15	SY1-2, AN1-2
damp8	0.30	SY1-2, AN1-2
damp9	0.30	SY1-2
damp10	0.30	AN1-2



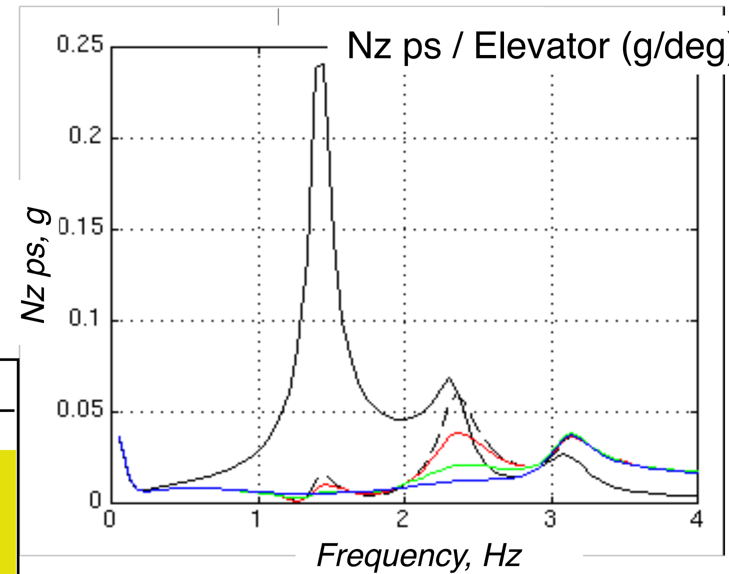




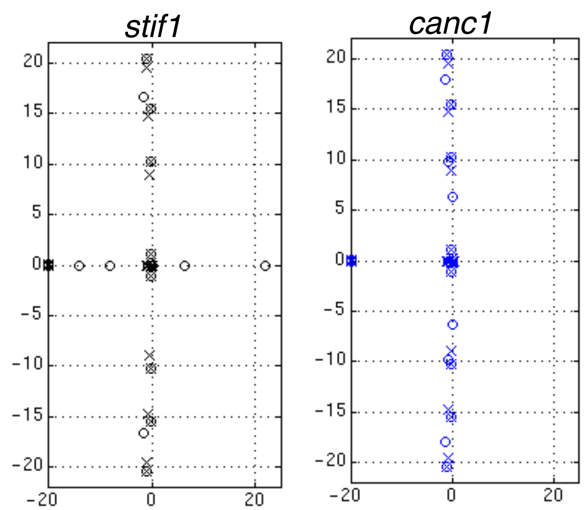
Impact of Modal Cancellation*

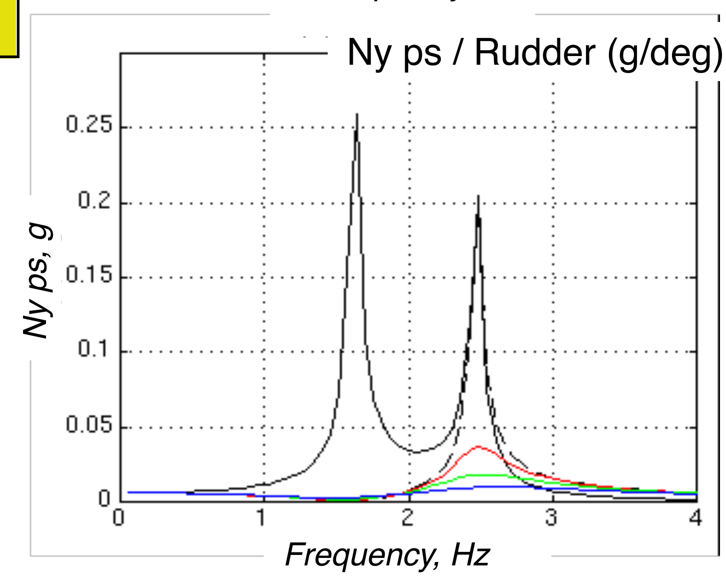
- **Examine effect of Cancellation at each Damping Level**
  - » ***Cancellation: Eliminate control effector excitation of 1st SY & 1st AN modes**
  - » **Probably requires distributed effectors: canard and chin fin**

Configuration	Modes Canceled	Modes Damped
stif1	none	none
canc1	SY1, AN1	none
canc2	SY1, AN1	1-4 @ 0.07
canc3	SY1, AN1	1-4 @ 0.15
canc4	SY1, AN1	1-4 @ 0.30



q ps / elevator transfer function poles & zeros



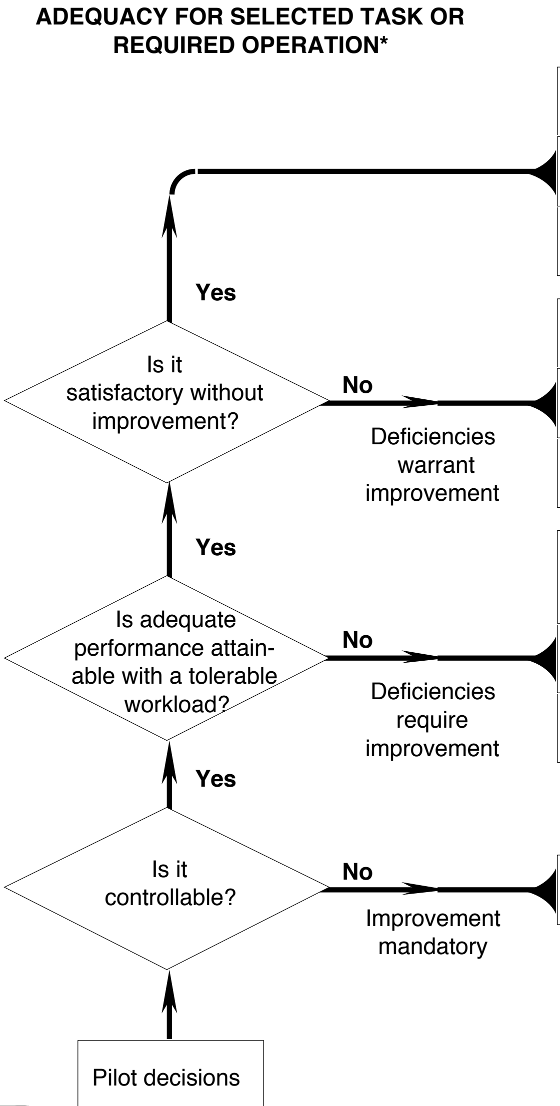


NASA LaRC Visual Motion Simulator (VMS)

Acceleration Capabilities (Single-Axis)

Surge:	*± 0.6g*
Sway:	*± 0.6g*
Heave:	*± 0.8g*
Roll:	*± 50 deg/s*^{2}
Pitch:	*± 50 deg/s*^{2}
Yaw:	*± 50 deg/s*^{2}

Cooper-Harper Rating Scale



AIRCRAFT CHARACTERISTICS	DEMAND ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*	CHR	
Excellent Highly desirable	Pilot compensation not a factor for desired performance	1	Level 1
Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2	Level 1
Fair - Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3	Level 1
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4	Level 2
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5	Level 2
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6	Level 2
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question.	7	Level 3
Major deficiencies	Considerable pilot compensation is required for control	8	Level 3
Major deficiencies	Intense pilot compensation is required to retain control	9	Level 3
Major deficiencies	Control will be lost during some portion of required operation	10	

*Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

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Control Influence Rating Scale

DASE INFLUENCE ON PILOT'S CONTROL INPUTS	CIR
Pilot does not alter control inputs as a result of aircraft flexibility.	1
Pilot intentionally modifies control inputs to avoid excitation of flexible modes.	2
Cockpit vibrations impact precision of voluntary control inputs.	3
Cockpit vibrations cause occasional involuntary control inputs.	4
Cockpit vibrations cause frequent involuntary control inputs.	5
Cockpit vibrations cause sustained involuntary control inputs or loss of control.	6

CIR targets voluntary/ involuntary modification of pilot's control inputs due to cockpit vibration

- *Acceptable - No Improvement Necessary*
- *Marginal - Improvement Desired/Warranted*
- *Unacceptable - Improvement Required/Mandatory*

Ride Quality Rating Scale

DASE INFLUENCE ON RIDE QUALITY	RQR
Cockpit vibrations do not impact ride quality.	1
Cockpit vibrations are perceptible but not objectionable - no improvement necessary.	2
Cockpit vibrations are mildly objectionable - improvement desired.	3
Cockpit vibrations are moderately objectionable - improvement warranted.	4
Cockpit vibrations are highly objectionable - improvement required.	5
Cockpit vibrations cause abandonment of task - improvement required.	6

RQR targets degradation of general comfort level due to cockpit vibration

- *Acceptable - No Improvement Necessary*
- *Marginal - Improvement Desired/Warranted*
- *Unacceptable - Improvement Required/Mandatory*

Evaluation Maneuvers

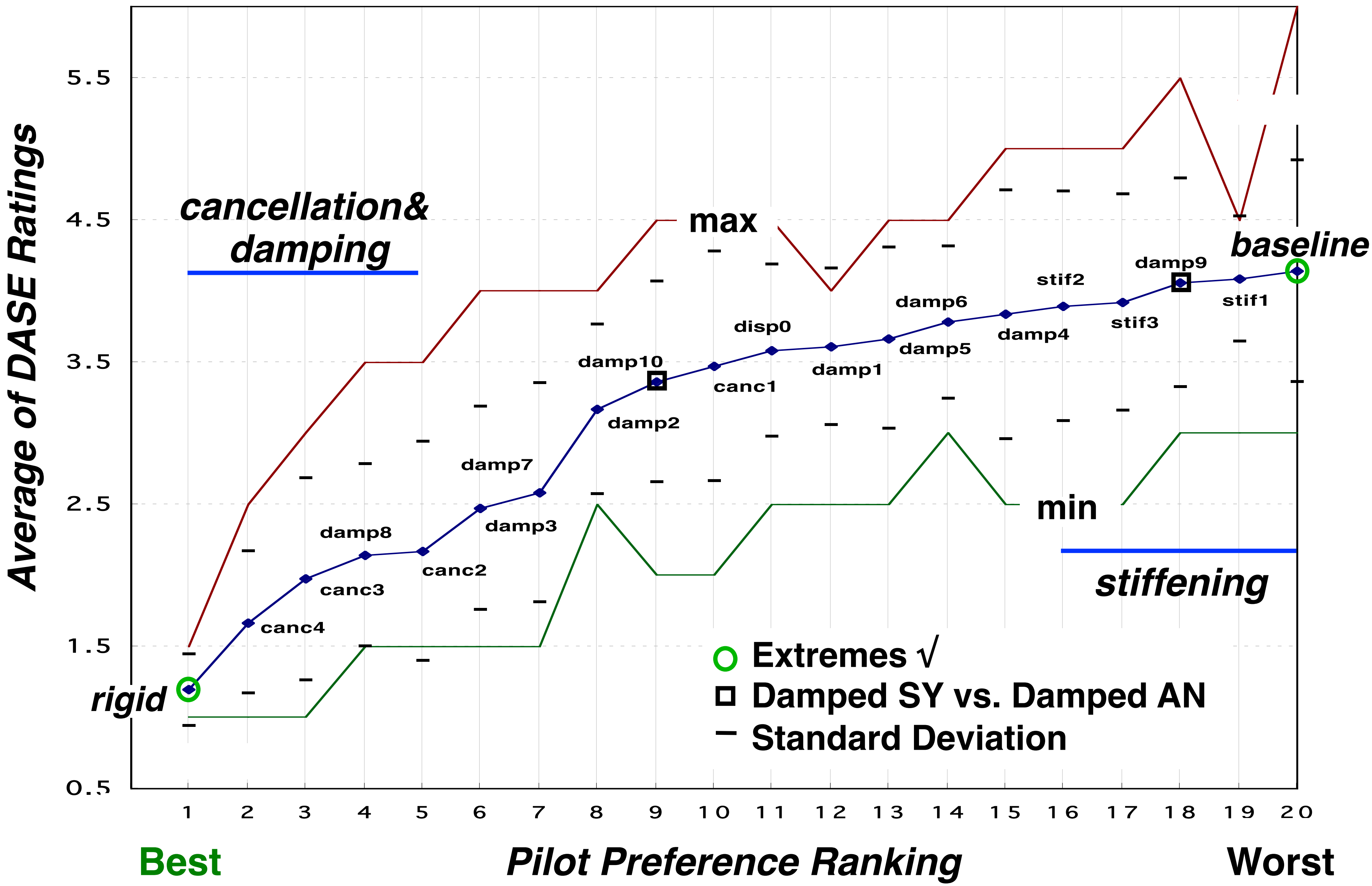
1) Straight-in (Nominal) Approach and Landing

2) Offset Approach and Landing

3) Composite Flight Director Tracking Task

- *(2) and (3) were fairly aggressive, high-gain tasks*
- *Six evaluation pilots participated representing NASA (2), Calspan (1), FAA (1), Boeing Seattle & Longbeach (2)*

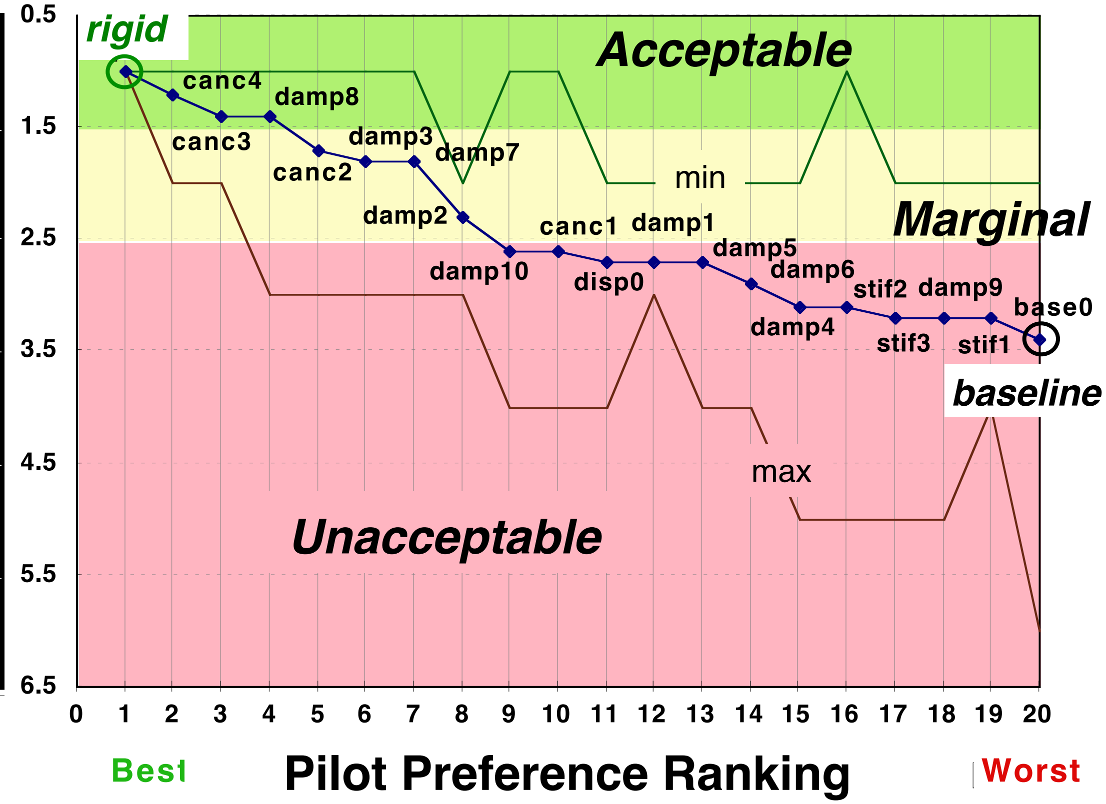
Configuration Descriptions Ranked in Order of Pilot Preference Based on Average of DASE Ratings



Control Influence Ratings vs Pilot Preference

INFLUENCE ON PILOT'S CONTROL INPUTS	CIR
Control inputs are not modified due to vibration	1
Intentional modification of inputs to avoid excitation	2
Vibrations impact precision of voluntary inputs	3
Vibrations cause occasional involuntary inputs	4
Vibrations cause frequent involuntary inputs	5
Sustained involuntary inputs or loss of control	6

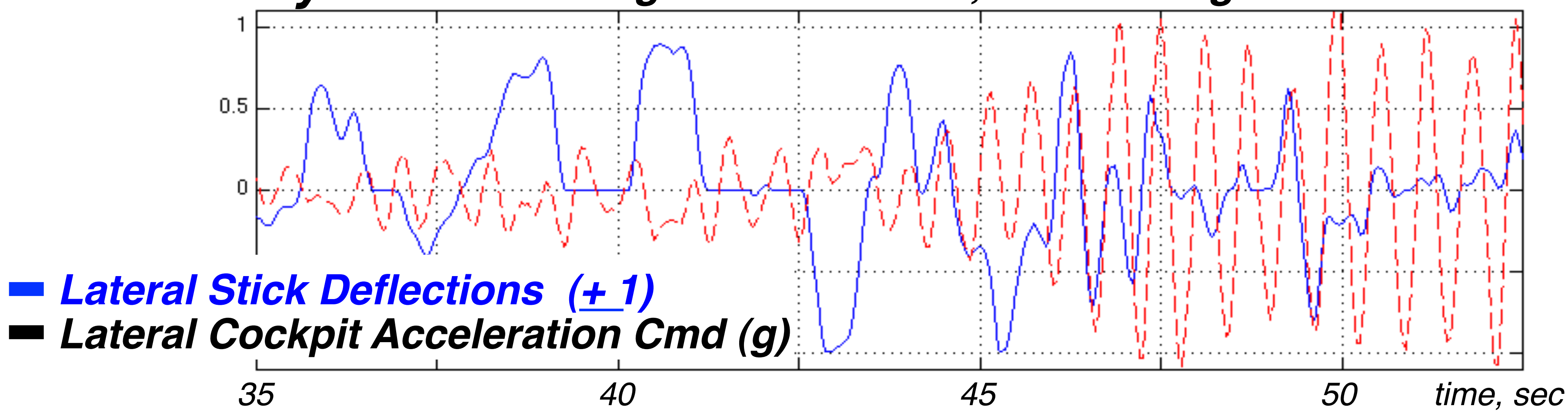
Average Control Influence Rating vs Pilot Preference



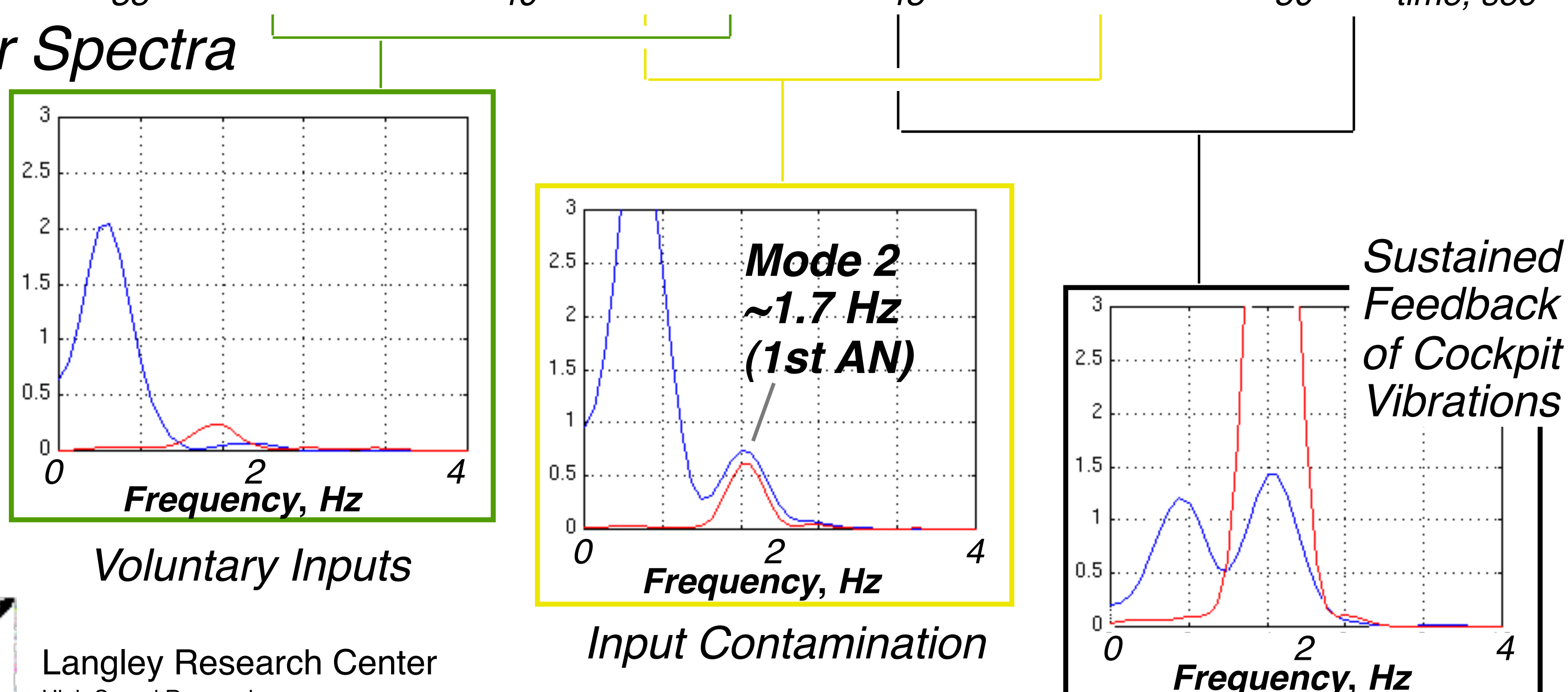
- **Subjective measure of acceptability based on pilots' assessment of vibration impact on manual control inputs**
- **Pilots were sometimes unaware of input contamination due to cockpit vibrations -> CIR assessments may be optimistic**

Example of Biodynamic Coupling Incident

Time History: ***Offset Landing Maneuver Task, stif 1 Configuration***



Power Spectra



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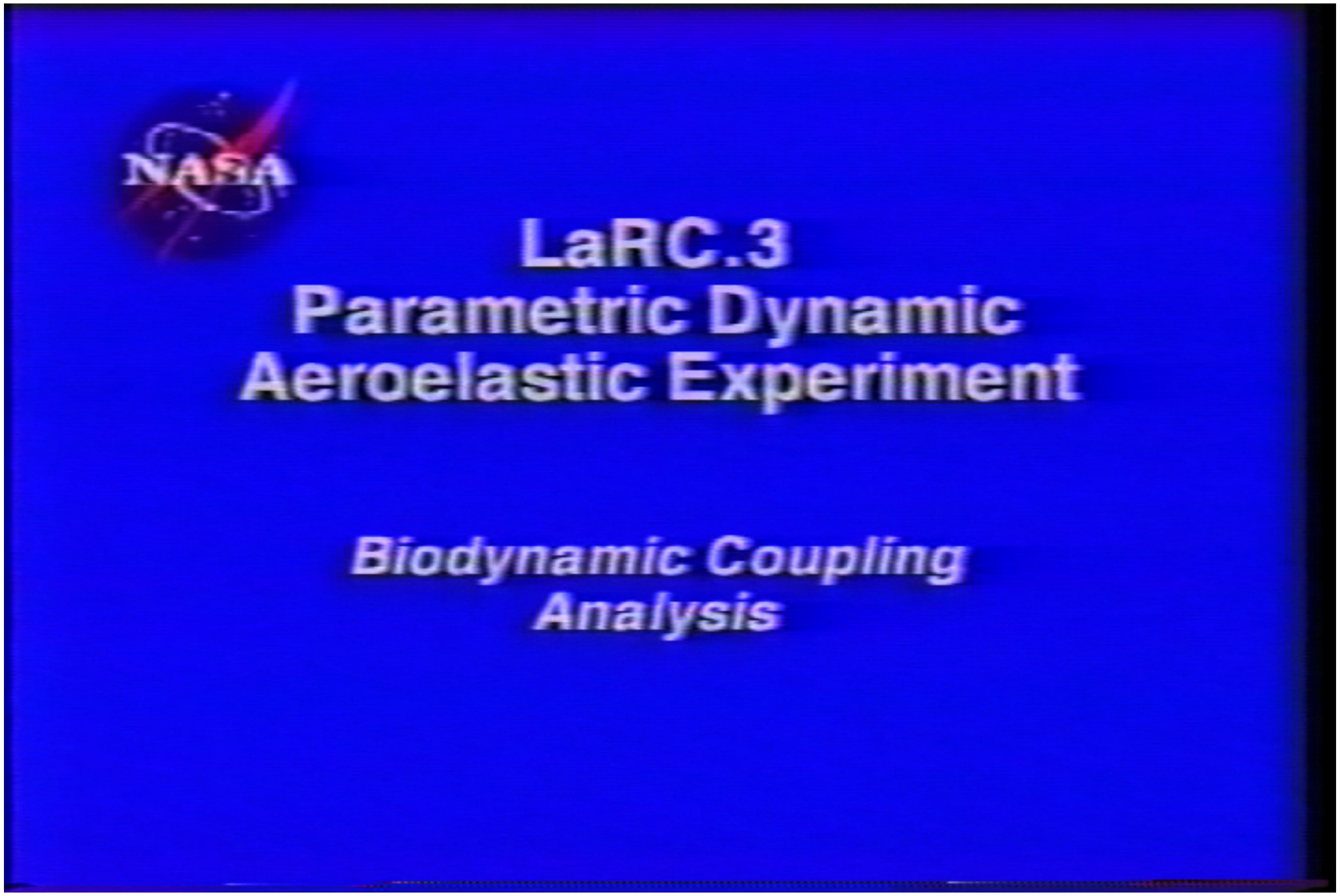
Video of Biodynamic Coupling Incidents



Concluding Remarks

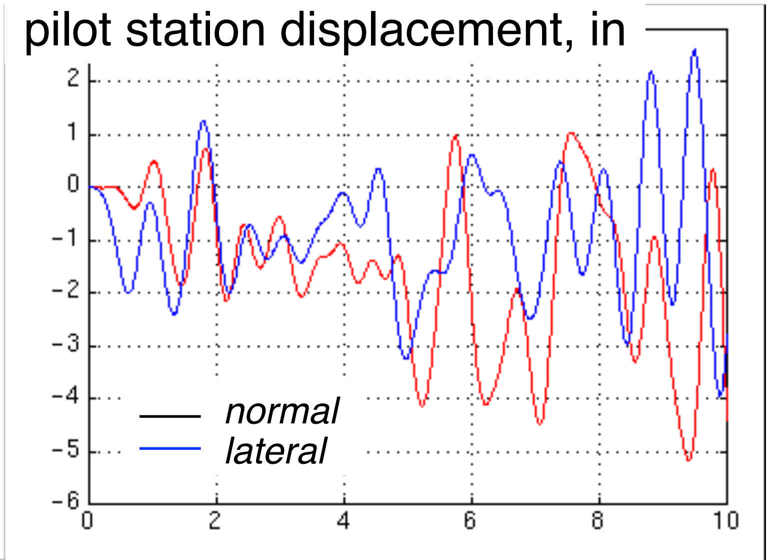
- **At least 3 of the 6 pilots encountered BDC at some point in the experiment**
  - » **Triggered by high-gain maneuvering (firm grip on stick is a crucial ingredient)**
  - » **Always dangerous, sometimes catastrophic (not just an annoyance)**
  - » **Influenced by inceptor design, control law design, piloting style & physical characteristics**
    - **Aileron-Rudder Interconnect (ARI) is implicated in coupling**
  - » **No BDC events were observed when modal damping was $\geq$ 0.15**
- **Some provision must be made to ensure that BDC never occurs**
  - » **Flight-critical mode suppression?**
  - » **Consider BDC susceptibility in control inceptor design**

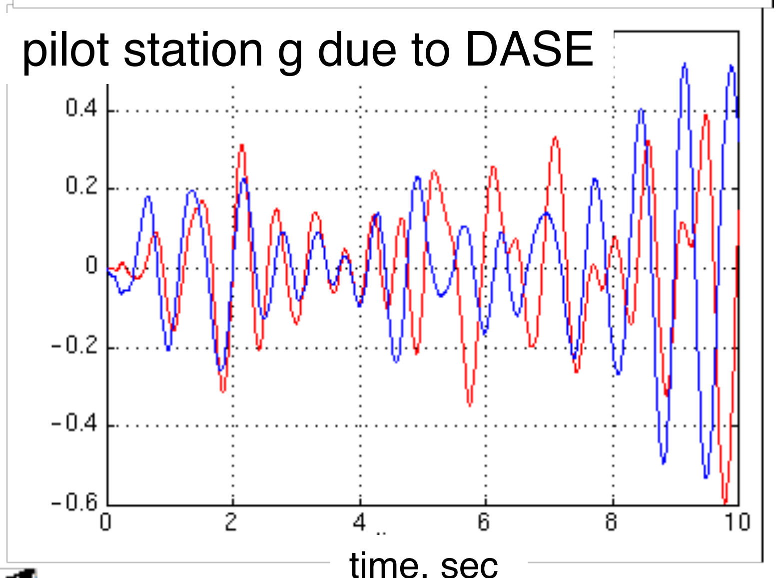
Concluding Remarks (continued)

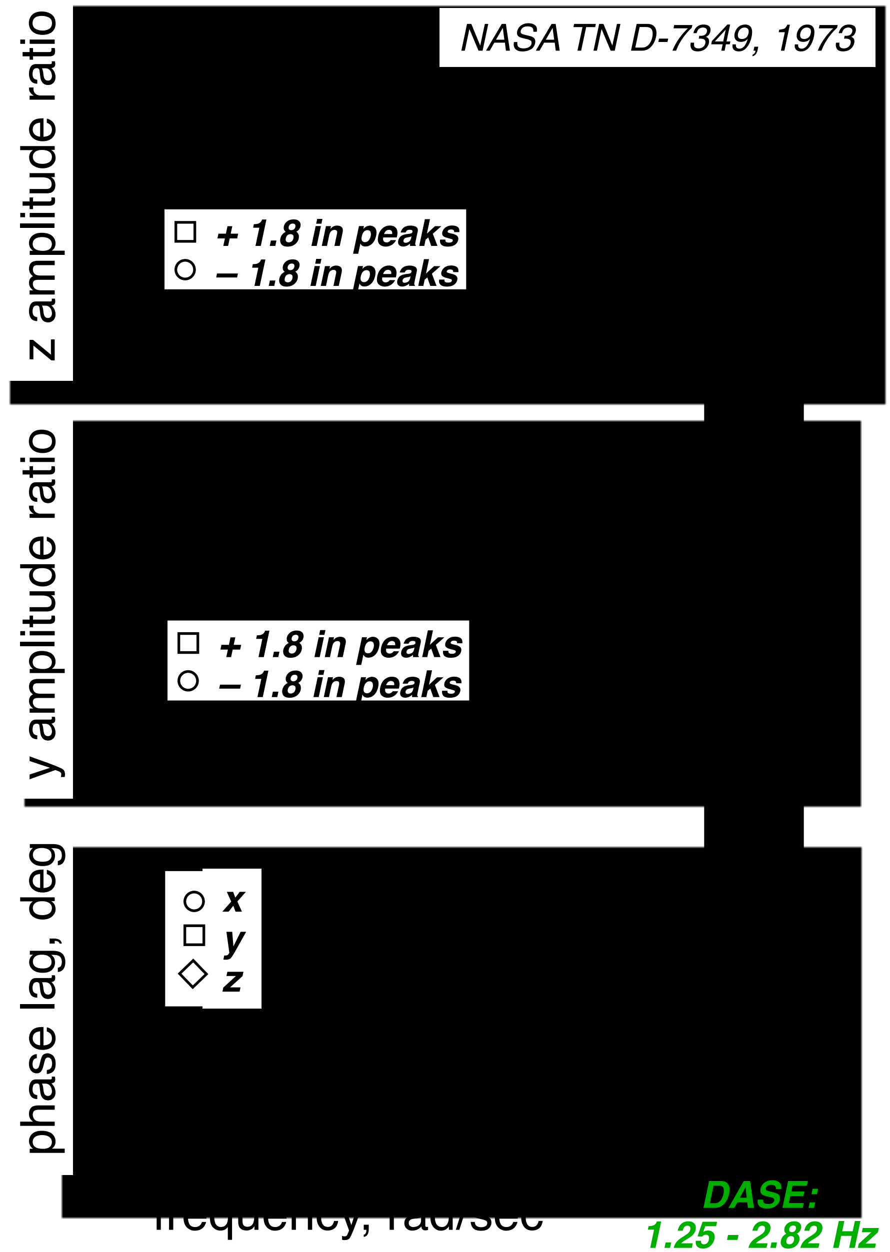
- **Antisymmetric modes were highly problematic**
  - » Symmetric (longitudinal) mode suppression not sufficient
- **Structural Stiffening and Display Compensation did not appear to solve problem**
- **Damping and Modal Cancellation were both highly beneficial**
- **Design Insights**
  - » Use Filtered Air Data - “noisy” surface deflections will kill ride quality by exciting high frequency modes
  - » Watch Aileron/Rudder Interconnect (implicated in BDC)
  - » Minimal damping suggestions:
    - 0.3 nominal on 1st & 2nd AN and 1st & 2nd SY modes
    - 0.15 reversion (failure) - or other measures sufficient to prevent BDC; Prioritize AN over SY if necessary

Additional Charts

DASE Responses vs LaRC VMS Specs







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Data Collected

- » Videotape of cockpit and pilot's hand on control stick
- » Time history data of all relevant flight dynamic simulation parameters
- » Transcribed micro-cassette recordings of pilot comments immediately following flights

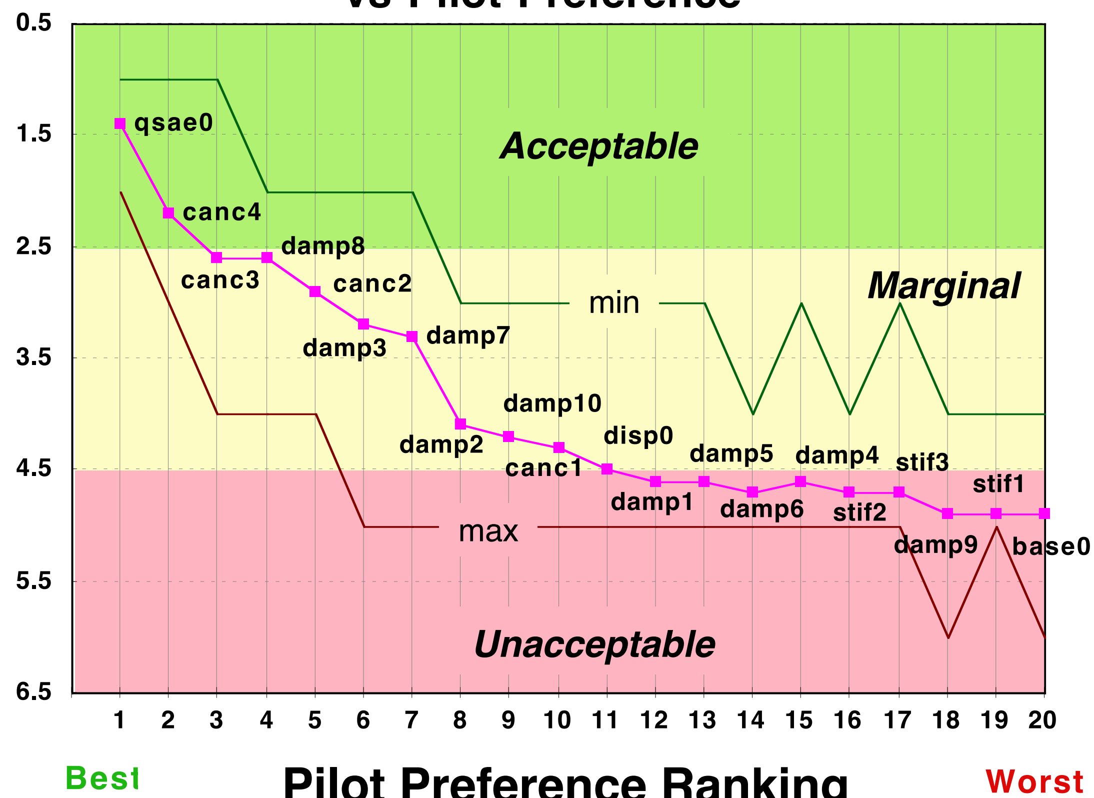
- ***Quantitative Evaluation Measures***
  - » Touchdown dispersions and sink rates
  - » Flight director tracking tolerances
  - » Spectral analysis of pilot stick inputs
- ***Subjective Evaluation Measures***
  - » Cooper-Harper Flying Qualities Ratings (CHR)
  - » "Ride Quality Rating" (RQR) - identifies DASE influence on comfort & ride quality
  - » "Control Influence Rating" (CIR) - identifies voluntary/ involuntary (biodynamic) modification of pilot's control inputs
  - » Pilot option for task abandonment (pilot discomfort, imminent loss of control)

Ride Quality Ratings vs Pilot Preference

DASE INFLUENCE ON RIDE QUALITY

DASE influence on ride quality	RQR
Cockpit vibrations do not impact ride quality	1
Perceptible but not objectionable	2
Mildly objectionable - improvement desired	3
Moderately objectionable - improvement warranted	4
Highly objectionable - improvement required	5
Task abandoned - improvement mandatory	6

Average Ride Quality Rating vs Pilot Preference



- **Subjective measure of acceptability based on pilots' assessment of ride quality**
- **Tasks were performed in mild turbulence (σ = 3 ft/s)**

DASE Influence Rating Scales

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Acceptable - No Improvement Necessary
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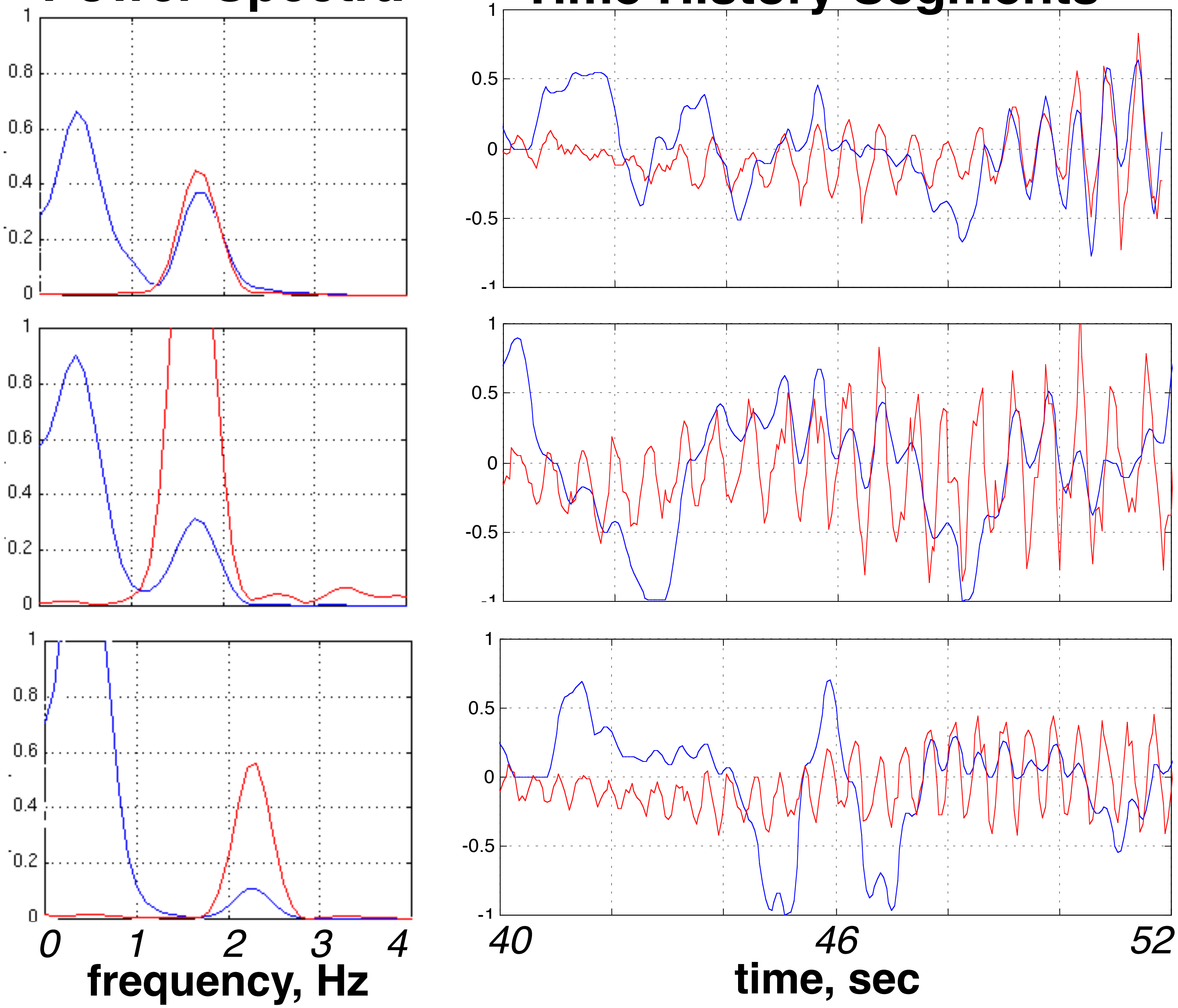
- **Targets pilot's perception of dynamic aeroelastic effects**
- **Supplements CHR (Discriminates SCAS deficiencies from DASE effects)**
- **"Control Influence Rating" (CIR) - identifies voluntary/ involuntary (biodynamic) modification of pilot's control inputs**
- **"Ride Quality Rating" (RQR) - identifies DASE influence on comfort & ride quality**
- **Pilot option for task abandonment (pilot discomfort, imminent loss of control)**

Biodynamic Coupling Incidents for 3 Pilots

– Stick
– Accels

Power Spectra **Time History Segments**



Pilot B, damp 9

CIR: 4
RQR: 6
CHR: 8

Pilot E, damp 9

CIR: 4
RQR: 5
CHR: 7

Pilot C, stif 3

CIR: 5
RQR: 5
CHR: 8