AIAA 2001-4006

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

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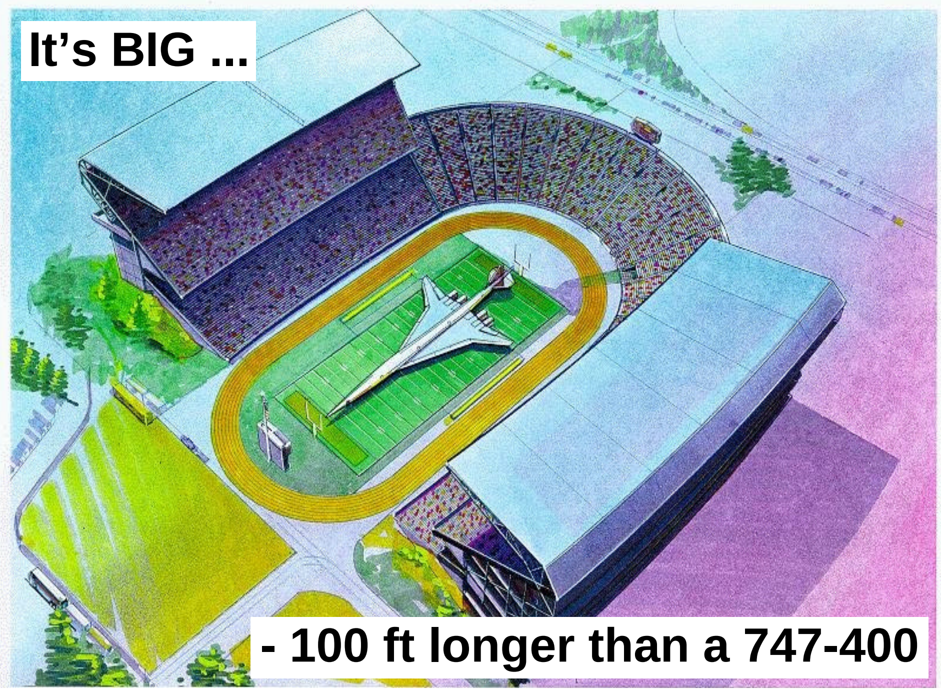
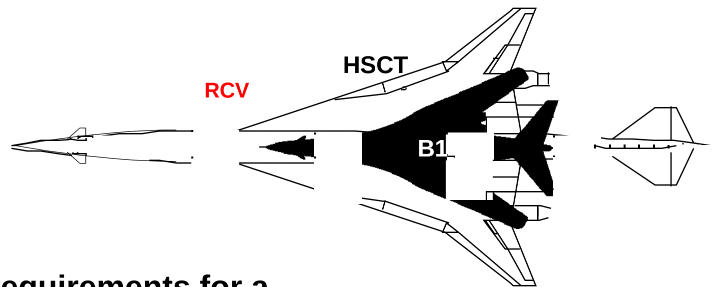
AIAA Atmospheric Flight Mechanics Conference
6-9 August 2001
Montreal, Canada



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

Ride Control Vanes (RCV) and Chin Fin (CF) added at nose



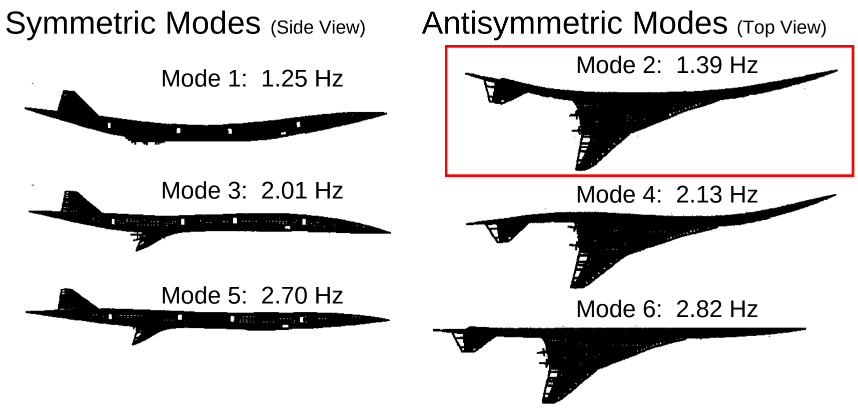
What are the requirements for a Structural Mode Control system?

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

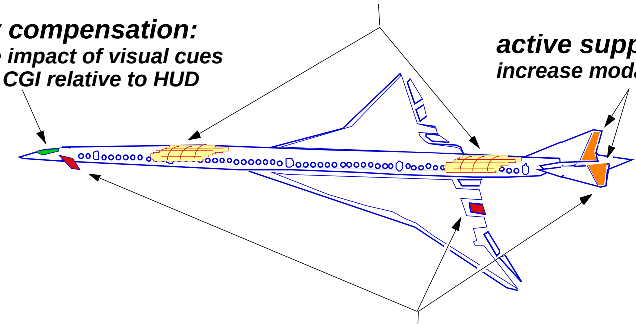
*DASE: Dynamic AeroServoElasticity

HSCT Real-Time Dynamic Aeroelastic Model



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

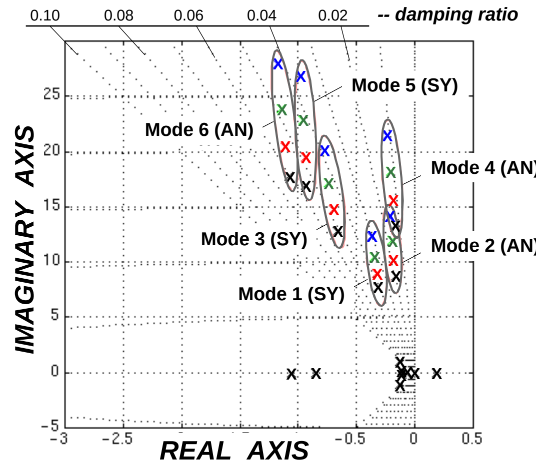
Potential Solutions to Examine using Parameterized Model



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

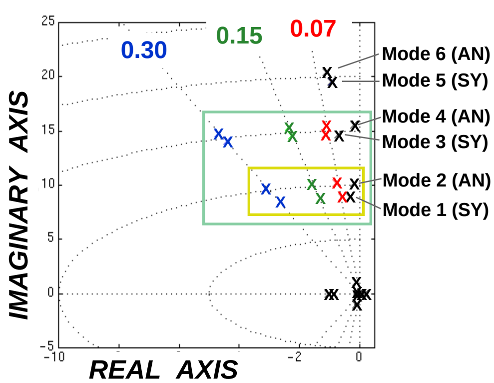
- **Directly manipulate model to simulate frequency increases due to stiffer structure**
- **All structural modes are lightly damped**
- **No consideration of associated weight penalties**

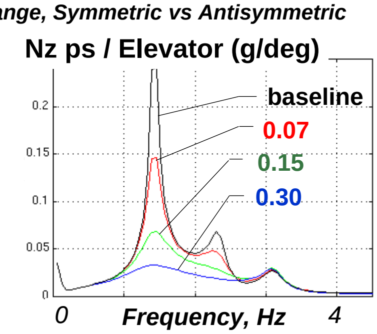


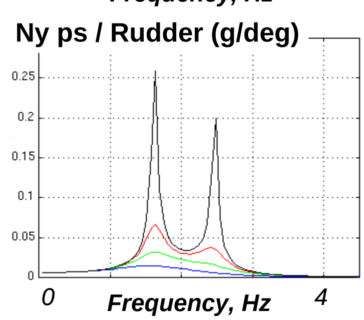
Variation of Modal Damping

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



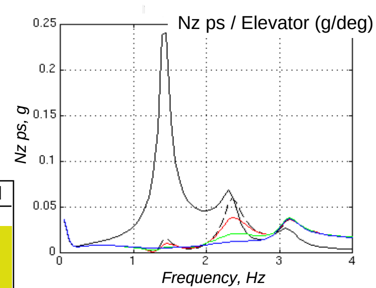




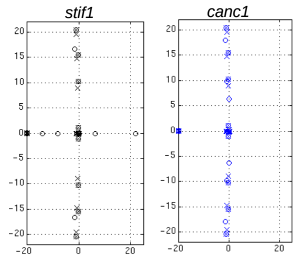
Impact of Modal Cancellation*

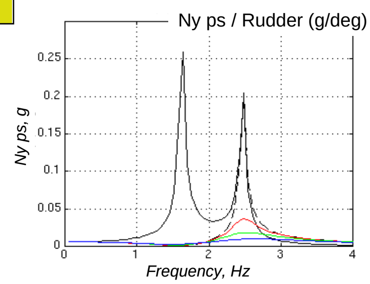
- Examine effect of Cancellation at each Damping Level
  - » *Cancellation: Eliminate control effector excitation of 1st SY & 1st AN modes
  - » Probably requires distributed effectors: canard and chin fin

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



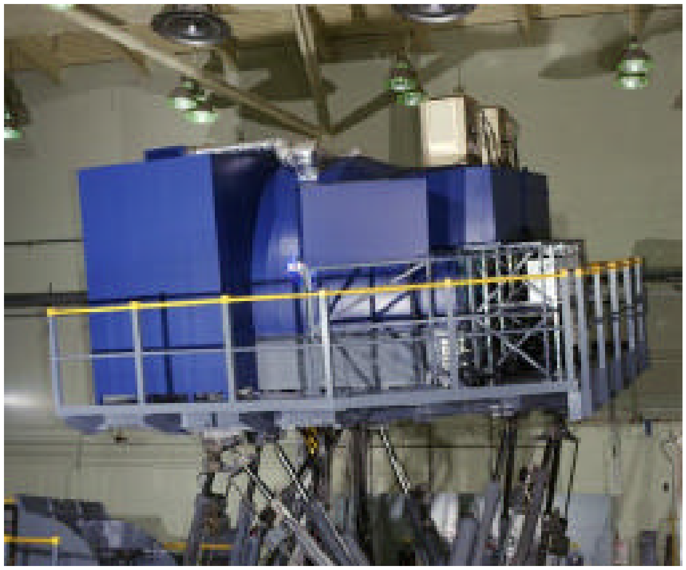


Data Collected

- » 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)

NASA LaRC Visual Motion Simulator (VMS)



Acceleration Capabilities (Single-Axis)

Surge:
± 0.6g

Sway:
± 0.6g

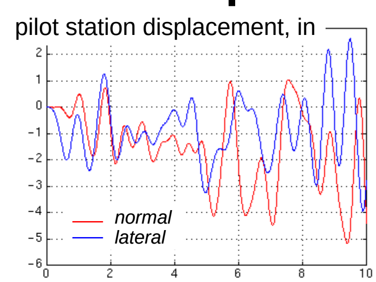
Heave:
± 0.8g

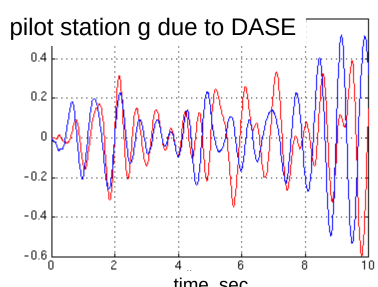
Roll:
± 50 deg/s ^{2}

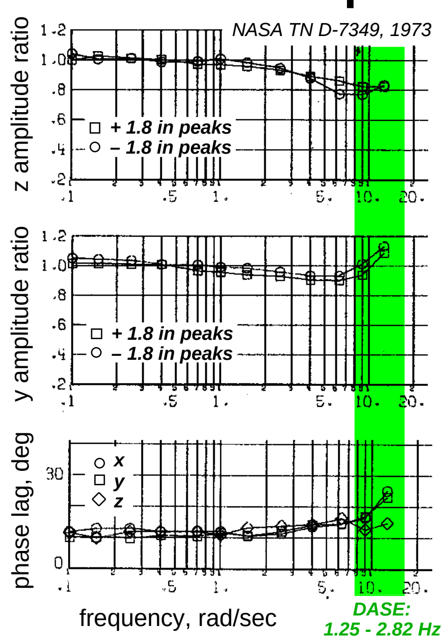
Pitch:
± 50 deg/s ^{2}

Yaw:
± 50 deg/s ^{2}

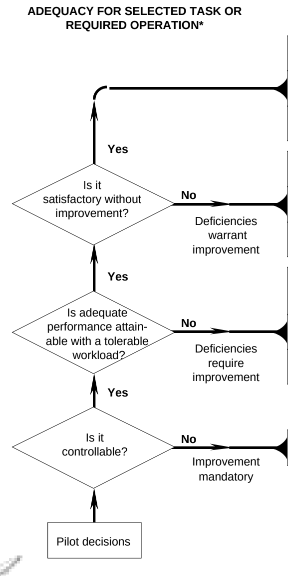
DASE Responses vs LaRC VMS Specs







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	Acceptable
Pilot intentionally modifies control inputs to avoid excitation of flexible modes.	2	Marginal
Cockpit vibrations impact precision of voluntary control inputs.	3	Unacceptable
Cockpit vibrations cause occasional involuntary control inputs.	4	Unacceptable
Cockpit vibrations cause frequent involuntary control inputs.	5	Unacceptable
Cockpit vibrations cause sustained involun-tary control inputs or loss of control.	6	Unacceptable

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

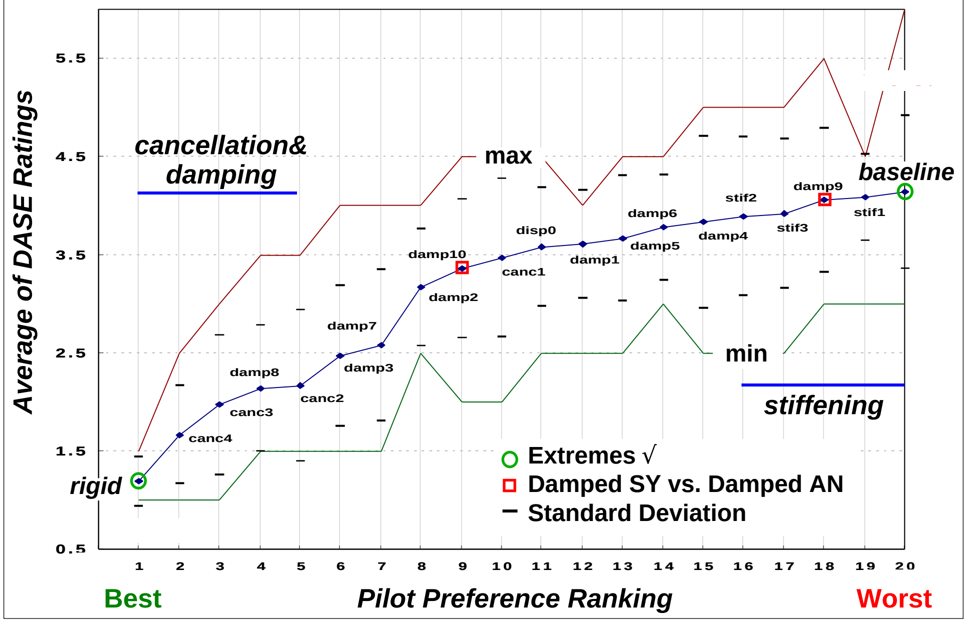
- *Acceptable - No Improvement Necessary*
- *Marginal - Improvement Desired/Warranted*
- *Unacceptable - Improvement Required/Mandatory*

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



DASE Influence Rating Scales

DASE INFLUENCE ON PILOT'S CONTROL INPUTS	CIR
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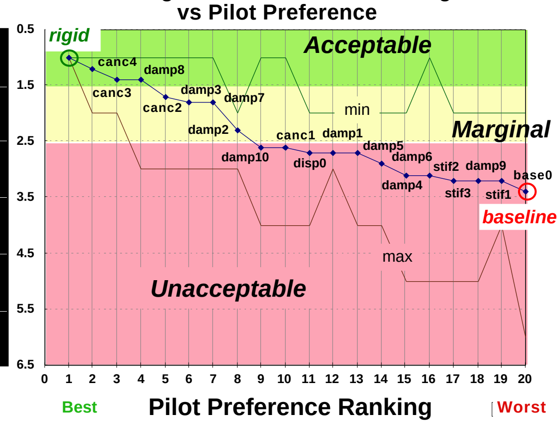
Acceptable - No Improvement Necessary
Marginal - Improvement Desired/Warranted
Unacceptable - Improvement Required/Mandatory

- **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)**

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

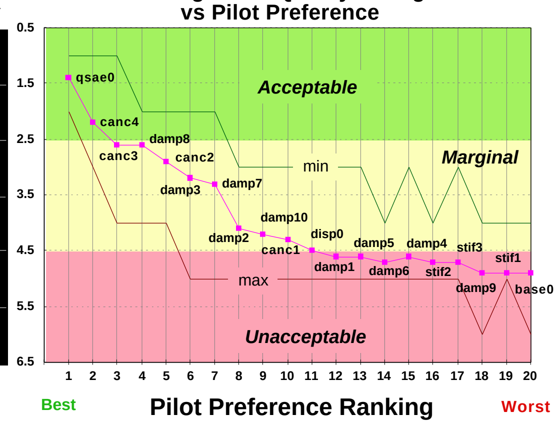


- **Subjective measure of acceptability based on pilots' assessment of vibration impact on manual control inputs**
- **Pilots were sometimes unaware of input contamination due to cockpit vibrations -> CIR assessments may be optimistic**

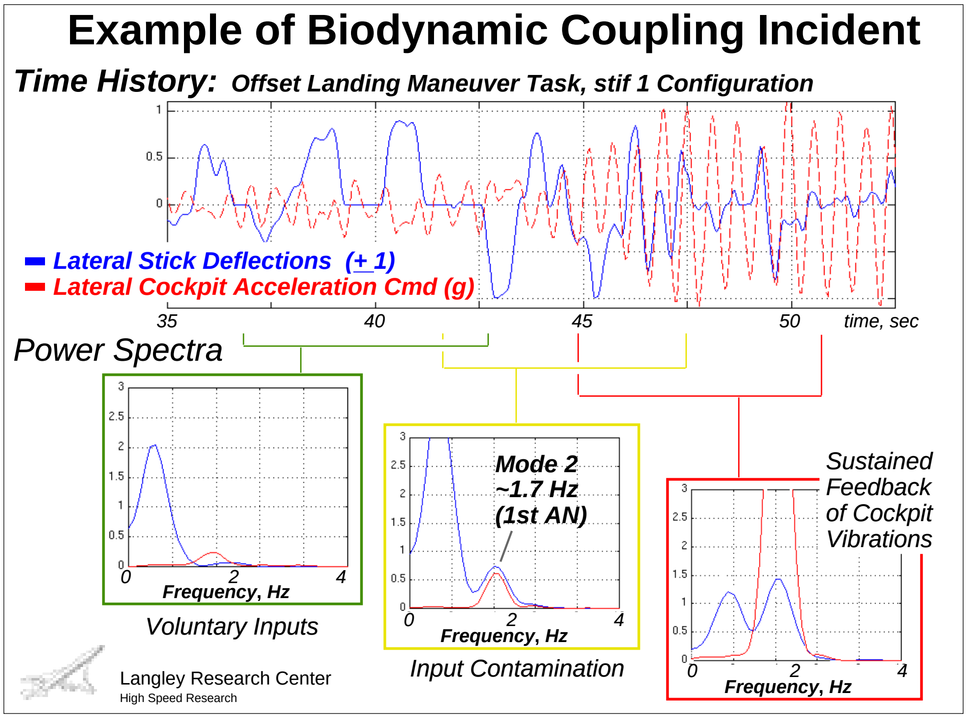
Ride Quality Ratings vs Pilot Preference

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)**


Example of Biodynamic Coupling Incident
Time History: Offset Landing Maneuver Task, stif 1 Configuration
Lateral Stick Deflections (± 1)
Lateral Cockpit Acceleration Cmd (g)
35
40
45
50
time, sec
Power Spectra
Frequency, Hz
Voluntary Inputs
Mode 2
~1.7 Hz
(1st AN)
Input Contamination
Sustained
Feedback
of Cockpit
Vibrations
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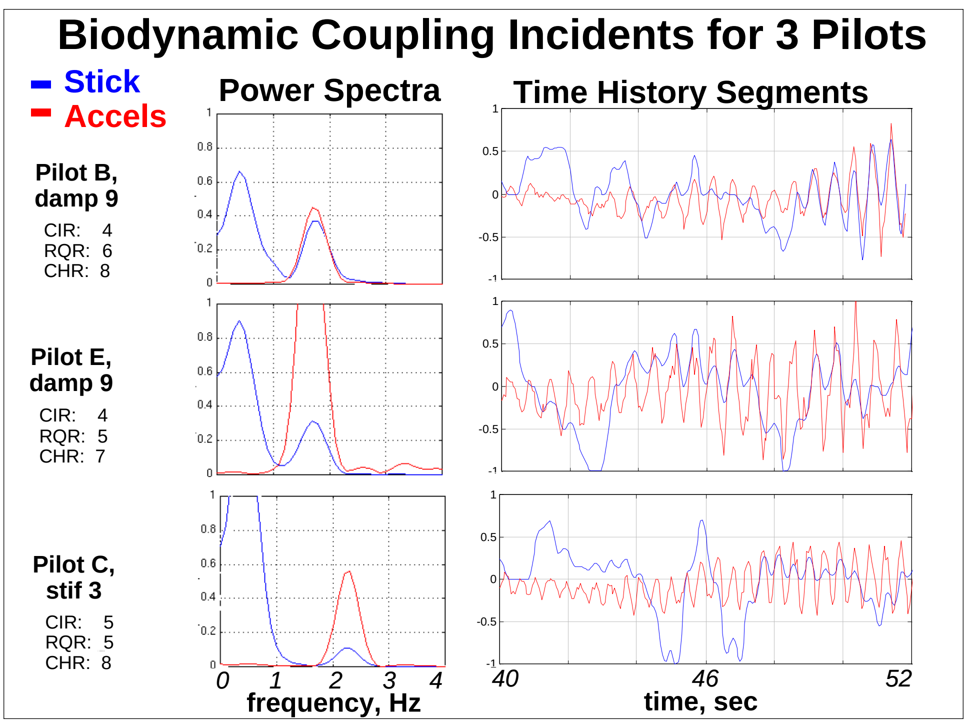
Biodynamic Coupling Incidents for 3 Pilots
Stick
Accels
Power Spectra
Time History Segments
Pilot B,
damp 9
CIR: 4
RQR: 6
CHR: 8
Pilot E,
damp 9
CIR: 4
RQR: 5
CHR: 7
Pilot C,
stif 3
CIR: 5
RQR: 5
CHR: 8
0 1 2 3 4
frequency, Hz
40
46
52
time, sec

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**

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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**

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