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

David L. Raney, E. Bruce Jackson, Carey S. Buttrill, William M. Adams
NASA Langley Research Center
Hampton, VA

NASA Aeroservoelastic Real-Time Simulation Workshop
18-19 April 2012

Originally presented at:
AIAA Atmospheric Flight Mechanics Conference
6-9 August 2001
Montreal, Canada
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)

- Mode 1: 1.25 Hz
- Mode 3: 2.01 Hz
- Mode 5: 2.70 Hz

Antisymmetric Modes (Top View)

- Mode 2: 1.39 Hz
- Mode 4: 2.13 Hz
- Mode 6: 2.82 Hz

- 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

**active suppression:**
increase modal damping

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

**active suppression; mode-cancelling control:**
eliminate modal excitation due to surface deflections
(multi-surface mode suppression)
Variation of Structural Stiffness

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Frequency Ratio</th>
<th>Stiffness Increase</th>
<th>1st SY Mode Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>baseline</td>
<td>1.00</td>
<td>--</td>
<td>1.25 Hz</td>
</tr>
<tr>
<td>stif1</td>
<td>1.16</td>
<td>~35%</td>
<td>1.45 Hz</td>
</tr>
<tr>
<td>stif2</td>
<td>1.36</td>
<td>~85%</td>
<td>1.80 Hz</td>
</tr>
<tr>
<td>stif3</td>
<td>1.60</td>
<td>~150%</td>
<td>2.00 Hz</td>
</tr>
</tbody>
</table>

- 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

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Damping Ratio</th>
<th>Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>stiff1</td>
<td>nominal</td>
<td></td>
</tr>
<tr>
<td>damp1</td>
<td>0.07</td>
<td>SY1, AN1</td>
</tr>
<tr>
<td>damp2</td>
<td>0.15</td>
<td>SY1, AN1</td>
</tr>
<tr>
<td>damp3</td>
<td>0.30</td>
<td>SY1, AN1</td>
</tr>
<tr>
<td>damp4</td>
<td>0.30</td>
<td>SY1</td>
</tr>
<tr>
<td>damp5</td>
<td>0.30</td>
<td>AN1</td>
</tr>
<tr>
<td>damp6</td>
<td>0.07</td>
<td>SY1-2, AN1-2</td>
</tr>
<tr>
<td>damp7</td>
<td>0.15</td>
<td>SY1-2, AN1-2</td>
</tr>
<tr>
<td>damp8</td>
<td>0.30</td>
<td>SY1-2, AN1-2</td>
</tr>
<tr>
<td>damp9</td>
<td>0.30</td>
<td>SY1-2</td>
</tr>
<tr>
<td>damp10</td>
<td>0.30</td>
<td>AN1-2</td>
</tr>
</tbody>
</table>

Ny ps / Rudder (g/deg)

Nz ps / Elevator (g/deg)
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

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Modes Canceled</th>
<th>Modes Damped</th>
</tr>
</thead>
<tbody>
<tr>
<td>stif1</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>canc1</td>
<td>SY1, AN1</td>
<td>none</td>
</tr>
<tr>
<td>canc2</td>
<td>SY1, AN1</td>
<td>1-4 @ 0.07</td>
</tr>
<tr>
<td>canc3</td>
<td>SY1, AN1</td>
<td>1-4 @ 0.15</td>
</tr>
<tr>
<td>canc4</td>
<td>SY1, AN1</td>
<td>1-4 @ 0.30</td>
</tr>
</tbody>
</table>

\[ q ps / elevator transfer function poles & zeros \]
NASA LaRC Visual Motion Simulator (VMS)

Acceleration Capabilities (Single-Axis)

Surge: 
______ + 0.6g

Sway: 
______ + 0.6g

Heave: 
______ + 0.8g

Roll: 
______ + 50 deg/s²

Pitch: 
______ + 50 deg/s²

Yaw: 
______ + 50 deg/s²
Cooper-Harper Rating Scale

**Adequacy for Selected Task or Required Operation**

- **Yes**
  - Is it satisfactory without improvement?
    - Yes, Deficiencies warrant improvement
    - No, Deficiencies require improvement
- **No**
  - Is it controllable?
    - Yes, Improvement mandatory
    - No, Major deficiencies control will be lost during some portion of required operation

**Aircraft Characteristics**

- Excellent
  - Highly desirable
  - Pilot compensation not a factor for desired performance
- Good
  - Negligible deficiencies
  - Pilot compensation not a factor for desired performance
- Fair - Some mildly unpleasant deficiencies
  - Minimal pilot compensation required for desired performance
- Minor but annoying deficiencies
  - Desired performance requires moderate pilot compensation
- Moderately objectionable deficiencies
  - Adequate performance requires considerable pilot compensation
- Very objectionable but tolerable deficiencies
  - Adequate performance requires extensive pilot compensation
- Major deficiencies
- Major deficiencies
  - Considerable pilot compensation is required for control
- Major deficiencies
  - Intense pilot compensation is required to retain control
- Major deficiencies
  - Control will be lost during some portion of required operation

**Demand on the Pilot in Selected Task or Required Operation**

- Level 1
  - CHR 1
- Level 2
  - CHR 2
- Level 3
  - CHR 3

**Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.**
## Control Influence Rating Scale

### DASE INFLUENCE ON PILOT'S CONTROL INPUTS

<table>
<thead>
<tr>
<th>CIR</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pilot does not alter control inputs as a result of aircraft flexibility.</td>
</tr>
<tr>
<td>2</td>
<td>Pilot intentionally modifies control inputs to avoid excitation of flexible modes.</td>
</tr>
<tr>
<td>3</td>
<td>Cockpit vibrations impact precision of voluntary control inputs.</td>
</tr>
<tr>
<td>4</td>
<td>Cockpit vibrations cause occasional involuntary control inputs.</td>
</tr>
<tr>
<td>5</td>
<td>Cockpit vibrations cause frequent involuntary control inputs.</td>
</tr>
<tr>
<td>6</td>
<td>Cockpit vibrations cause sustained involuntary control inputs or loss of control.</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>RQR</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cockpit vibrations do not impact ride quality.</td>
</tr>
<tr>
<td>2</td>
<td>Cockpit vibrations are perceptible but not objectionable - no improvement necessary.</td>
</tr>
<tr>
<td>3</td>
<td>Cockpit vibrations are mildly objectionable - improvement desired.</td>
</tr>
<tr>
<td>4</td>
<td>Cockpit vibrations are moderately objectionable - improvement warranted.</td>
</tr>
<tr>
<td>5</td>
<td>Cockpit vibrations are highly objectionable - improvement required.</td>
</tr>
<tr>
<td>6</td>
<td>Cockpit vibrations cause abandonment of task - improvement required.</td>
</tr>
</tbody>
</table>

**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

<table>
<thead>
<tr>
<th>INFLUENCE ON PILOT’S CONTROL INPUTS</th>
<th>CIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control inputs are not modified due to vibration</td>
<td>1</td>
</tr>
<tr>
<td>Intentional modification of inputs to avoid excitation</td>
<td>2</td>
</tr>
<tr>
<td>Vibrations impact precision of voluntary inputs</td>
<td>3</td>
</tr>
<tr>
<td>Vibrations cause occasional involuntary inputs</td>
<td>4</td>
</tr>
<tr>
<td>Vibrations cause frequent involuntary inputs</td>
<td>5</td>
</tr>
<tr>
<td>Sustained involuntary inputs or loss of control</td>
<td>6</td>
</tr>
</tbody>
</table>

![Graph showing Control Influence Ratings 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

Voluntary Inputs

**Input Contamination**

**Power Spectra**

- **Lateral Stick Deflections (+1)**
- **Lateral Cockpit Acceleration Cmd (g)**

**Mode 2**

~1.7 Hz

(1st AN)

Sustained Feedback of Cockpit Vibrations

Langley Research Center
High Speed Research

Frequency, Hz

0
1
2
3
4

Frequency, Hz

0
1
2
3
4

Frequency, Hz

0
0
2
4

Frequency, Hz

0
0
2
4
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 $> 0.15$

• 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

pilot station displacement, in

- frequency, rad/sec
- phase lag, deg
- pilot station g due to DASE

DASE:
1.25 - 2.82 Hz

NASA TN D-7349, 1973
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

- Subjective measure of acceptability based on pilots’ assessment of ride quality
- Tasks were performed in mild turbulence ($\sigma = 3$ ft/s)
DASE Influence Rating Scales

**DASE Influence on Pilot’s Control Inputs**

- 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)

**DASE Influence on Ride Quality**

- 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)

- **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)
Biodynamic Coupling Incidents for 3 Pilots

- **Stick**
- **Accels**

**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