Active Piezoelectric Vibration Control of Subscale Composite Fan Blades

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Background

• High performance fan blades
  – High excitation levels
  – Vibratory stresses → fatigue

• Incorporate damping into blades
  – Piezoelectric materials
    • Passive damping – e.g. shunt circuit
    • Active vibration control
  – Spin testing with active control
    • Surface-mounted sensors and actuators
    • Control 1st bending vibration
  – Possibility of embedding into blades
    • Protect from airflow and debris
    • Future testing
Piezoelectric Damping Research

• Basic Research
  – Chopra (2002) – survey of smart structures
  – Hagood and von Flotow (1991) – analysis of piezoelectric damping
  – Lesieutre (1998) – types of passive damping shunt circuits

• Turbomachinery Application
  – Cross and Lewis (2002) – smart materials for future engines
  – Cross and Fleeter (2002) – stator blade damping with passive shunt circuit
  – Remington et al. (2003) – stator blade actuation for noise control
  – Watanabe et al. (2008) – blade flutter control in a linear transonic cascade
  – Hohl et al. (2009) – bladed disk model with shunt circuits – analysis and testing
  – Kauffman and Lesieutre (2010) – frequency-switching for resonance avoidance

• Implementation
  – Hilbert et al. (2001) – patent for shunted piezoelectric damping of blades
  – Duffy et al. (2009) – piezoelectric plate damping under rotation
  – Siemann et al. (2009) – piezoelectric actuation of compressor blades under rotation
  – Bachmann et al. (2010) – pre-compressing piezoelectric elements to reduce centrifugal tensile stress
  – Duffy et al. (2012) – effects of embedding on composite strength
Piezoelectric Vibration Control

- $K = \text{“generalized electromechanical coupling”}$
- Damping is proportional to $K^2$
- $K^2 = \text{energy converted by the piezoelectric material into electrical energy divided by the system modal strain energy}$
- Centrifugal effects:
  - Centrifugal stiffening may increase resonance frequency, decreasing $K$
  - Modal stress contours will also change with rotational speed, affecting $K$
  - Tensile stress in the piezoelectric material due to spinning

\[
K^2 = \frac{f_{oc}^2 - f_{sc}^2}{f_{oc}^2}
\]

1B modal strain
Piezoelectric element at high strain location
Test Configuration

- Two actuators
- One sensor
- Located at high modal strain location for 1B mode
- Expected centrifugal strain at max speed of 5000 RPM is $300 \times 10^{-6}$ m/m
# Test Articles

<table>
<thead>
<tr>
<th>Blade Material</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer matrix fiber composite</td>
<td>HexPly 8551-7</td>
<td>Epoxy resin with unidirectional carbon fibers, ply stack-up</td>
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<tr>
<td></td>
<td>with IM 7 carbon fibers</td>
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<tr>
<td>Flexible, macro-fiber composite, $d_{31}$-type, 300mm (0.012&quot;) thick</td>
<td>Smart-Material Corp. Sensor: M-0714-P2 Qty:1</td>
<td>14.0 mm x 7.0 mm (0.55&quot; x 0.28&quot;) 6.5nF nominal capacitance -600x10^{-6} free strain -85N (-19 lbf) blocking force</td>
</tr>
<tr>
<td>PZT-5A (Navy Type-II PZT)</td>
<td>Smart-Material Corp. Actuators: M-2814-P2 Qty: 2</td>
<td>14.0 mm x 28.0 mm (0.55&quot; x 1.10&quot;) 25.7nF nominal capacitance -700x10^{-6} free strain -85 N (-19 lbf) blocking force</td>
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</tbody>
</table>
Dynamic Spin Rig Facility

- Two blades place opposite each other in dovetail fixtures
- Vacuum
- Excitation provided by magnetic bearings to the rotor
- Slip ring
- 0-5000 RPM for this test
- Instrumentation
  - Piezoelectric sensor on each blade
  - Two piezoelectric actuators on each blade
  - Endevco model 25A accelerometer on blade fixture
- Equipment
  - Data Physics SignalCalc Mobilyzer provided excitation voltage, also measured response from sensors
  - dSPACE control system
  - Midé Piezoelectric amplifiers
Dynamic Spin Rig Facility
Spin Test

• Piezoelectric Sensor
  – Measure response to magnetic bearing excitation – no control
• Piezoelectric Actuator
  – Measure response to piezoelectric actuator excitation – no control
• Open Loop Control
  – Magnetic bearing excitation
  – Piezoelectric actuator at same frequency as excitation, phase chosen to reduce blade response
• Closed Loop Control
  – Based on a tuned RLC circuit (Choi 2008)
  – Implemented in dSPACE control code
  – Amplified signal (from amplifier and within control code)
Passive RLC Shunt Circuit

- Closed-loop control based on RLC circuit
- Capacitance C
  - Piezoelectric material property
- Inductance L
  - Sets the electric circuit frequency
- Resistance R
  - Dissipates energy → damping
  - Sets the bandwidth
Closed-Loop Control System

dSPACE Control System (based on RLC circuit)

Amplifier

Amplifier

sensor

actuators
Blade Resonance Frequency/Damping

![Graph showing the relationship between frequency and damping factor with respect to RPM. The graph displays a trend of increasing resonance frequency and damping factor as RPM increases.](image-url)
Generalized Electromechanical Coupling

\[ K^2 = \frac{f_{oc}^2 - f_{sc}^2}{f_{oc}^2} \]
Piezoelectric Patch as Sensor

- Excitation provided by magnetic bearings
- Strain measured by piezoelectric sensor
- Strain should be proportional to $K$

- Piezoelectric sensor – voltage output proportional to strain
- Average strain over sensor area
Piezoelectric Patch as Actuator

• Excitation provided by piezoelectric actuator
• Strain measured by piezoelectric sensor
• Strain should be proportional to $K$

• Piezoelectric excitation levels much lower than magnetic bearing excitation levels (60 microstrain versus 250 microstrain)
Open Loop Vibration Control

- 0.4 V to MB, Actuator 2
- 0.4 V to MB, Actuator 3
- 0.4 V to MB, Actuators 2&3
- 1.0 V to MB, Actuator 2
- 1.0 V to MB, Actuator 3
- 1.0 V to MB, Actuators 2&3
Closed Loop Control

Reduced Response from Single Actuator

Sensor Strain (Microstrain) vs RPM

- 0.4 V to MB - Baseline
- 1.0 V to MB - Baseline
- 1.5 V to MB - Baseline
- 2.0 V to MB - Baseline
- 0.4 V to MB - Control
- 1.0 V to MB - Control
- 1.5 V to MB - Control
- 2.0 V to MB - Control

3000 RPM

Sensor Strain (Microstrain) vs Voltage Amplitude to MB

- None
- Actuator 2
- Actuator 3
- Actuators 2 and 3
Damping from Closed Loop Control

- Control system is simulated RLC circuit with amplification
- \( R = 2500\Omega \), bandwidth \( \sim 4 \) Hz
- \( L \) changes with blade frequency
- Low excitation level – voltage to actuators below max allowable
Conclusions

• Spin test conclusions
  – Successful demonstration of open and closed loop control of blade vibration over a rotational speed range
    • Up to 1% damping at 0 RPM, 0.5% damping at 5000 RPM
  – Piezoelectric patches operated as designed under centrifugal and vibrational load
  – Damping shown to be proportional to $K^2$

• Maximize $K$ to maximize damping
  – Effect of target resonance mode
  – $K$ is proportional to piezoelectric material elastic modulus and thickness (to first order)
  – $K$ is proportional to material electromechanical coupling, $k$
    • Single crystal material
    • $d_{33}$ versus $d_{31}$ type actuators
  – Optimize coverage area
Complementary Research at NASA GRC

• Composites with embedded piezoelectric materials – component strength and fatigue properties
  – Material coupon testing (Duffy 2012)
• Subscale composite fan blades with embedded piezoelectric sensors and actuators
  – Blades currently being fabricated – vibration testing
• Piezoelectric material property variation with temperature
  – New material compositions
• Power transmission to piezoelectric actuators from the stationary frame
  – Collaboration with Mesa Systems Co. to develop inductive power transmission device
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