Active Piezoelectric Vibration Control of Subscale Composite Fan Blades

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Background

GEAviation.com

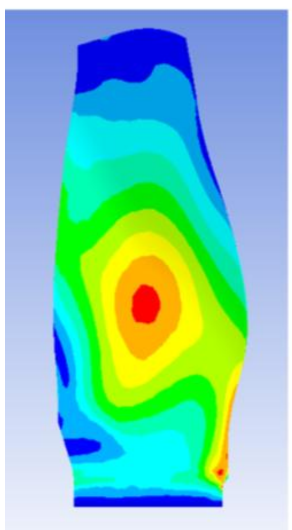
- High performance fan blades
  - High excitation levels
  - Vibratory stresses → fatigue
- Incorporate damping into blades
  - Piezoelectric materials
    - Passive damping – e.g. shunt circuit
    - Active vibration control
  - Spin testing with active control
    - Surface-mounted sensors and actuators
    - Control 1st bending vibration
  - Possibility of embedding into blades
    - Protect from airflow and debris
    - Future testing

Piezoelectric Damping Research

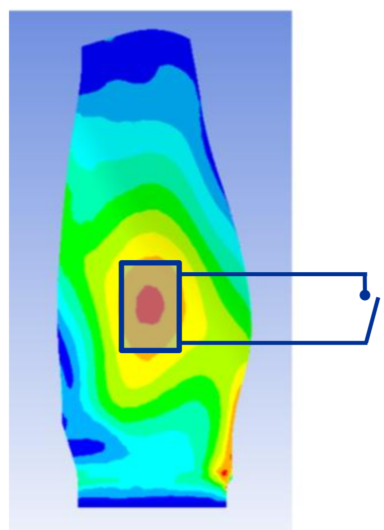
- Basic Research
  - Chopra (2002) – survey of smart structures
  - Hagood and von Flotow (1991) – analysis of piezoelectric damping
  - Lesieutre (1998) – types of passive damping shunt circuits
- Turbomachinery Application
  - Cross and Lewis (2002) – smart materials for future engines
  - Cross and 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
  - Struzik and Wang, Yu and Wang (2007,2009) – piezoelectric circuits for mistuning and damping
  - 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 = "generalized electromechanical coupling"
- Damping is proportional to K^2
- K^2 = 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



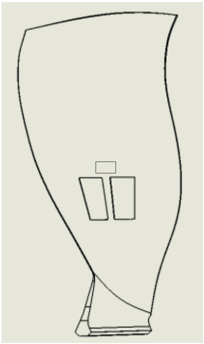
1B modal strain



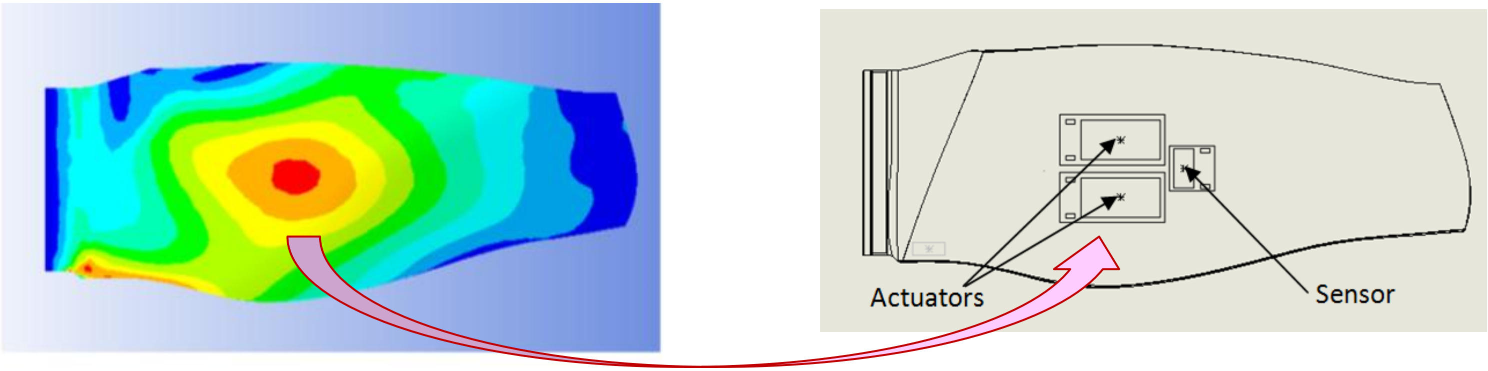
Piezoelectric element
at high strain location

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

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 $300x10^{-6}$ m/m



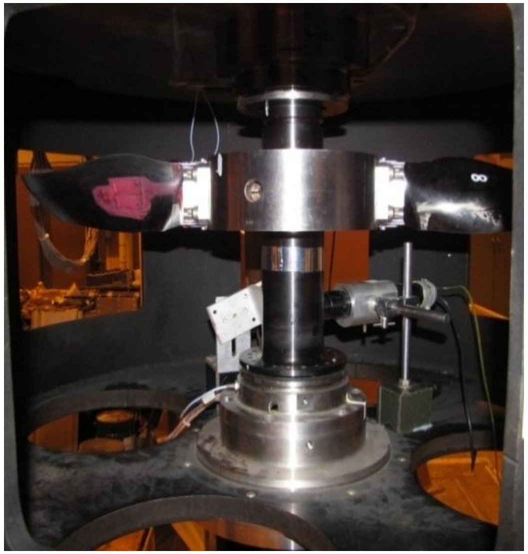
Test Articles

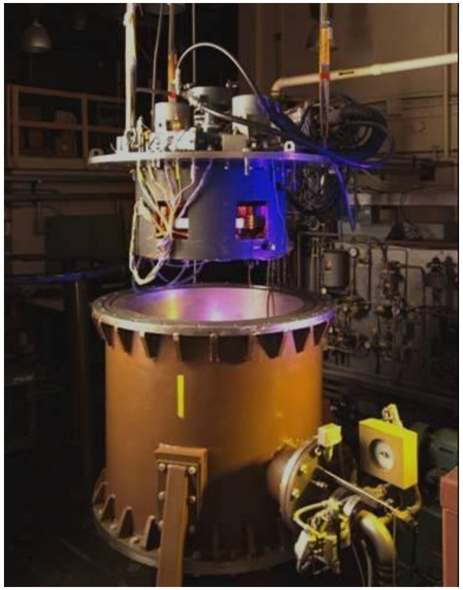
Blade Material	Type	Description
Polymer matrix fiber composite	HexPly 8551-7 with IM 7 carbon fibers	Epoxy resin with unidirectional carbon fibers, ply stack-up
Piezoelectric Materials	**Type**	**Description**
Flexible, macro-fiber composite, d_{31}-type, 300mm (0.012”) thick PZT-5A (Navy Type-II PZT)	Smart-Material Corp. Sensor: M-0714-P2 Qty:1	14.0 mm x 7.0 mm (0.55” x 0.28”) 6.5nF nominal capacitance -600×10^{-6} free strain -85N (-19 lbf) blocking force
	Smart-Material Corp. Actuators: M-2814-P2 Qty: 2	14.0 mm x 28.0 mm (0.55” x 1.10”) 25.7nF nominal capacitance -700×10^{-6} free strain -85 N (-19 lbf) blocking force

GEnx Subscale Composite Fan Blade

Piezoelectric Actuator

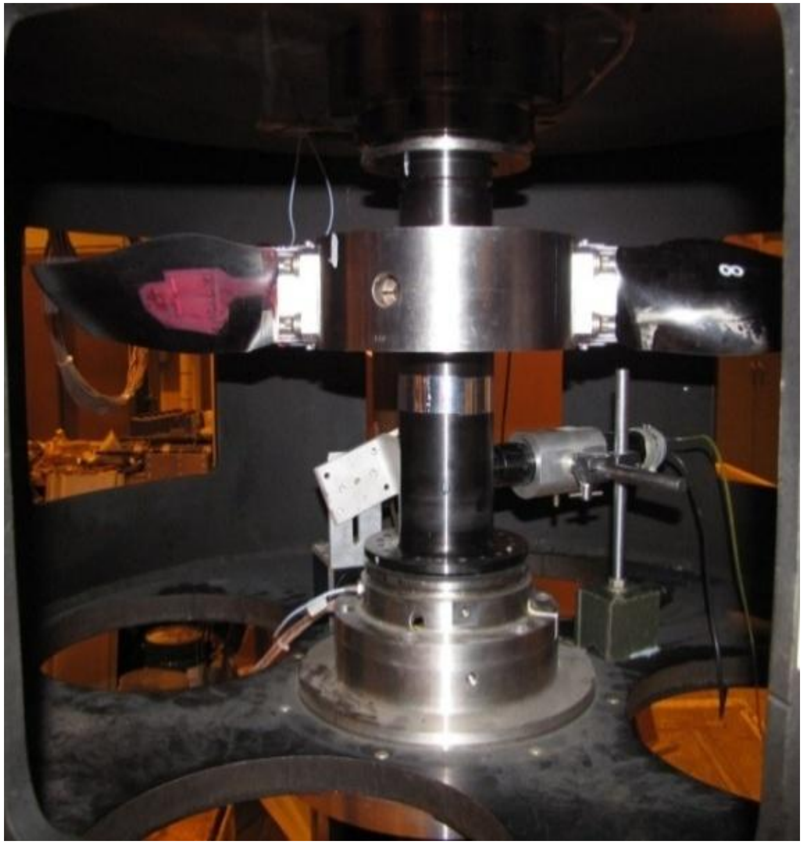
Dynamic Spin Rig Facility

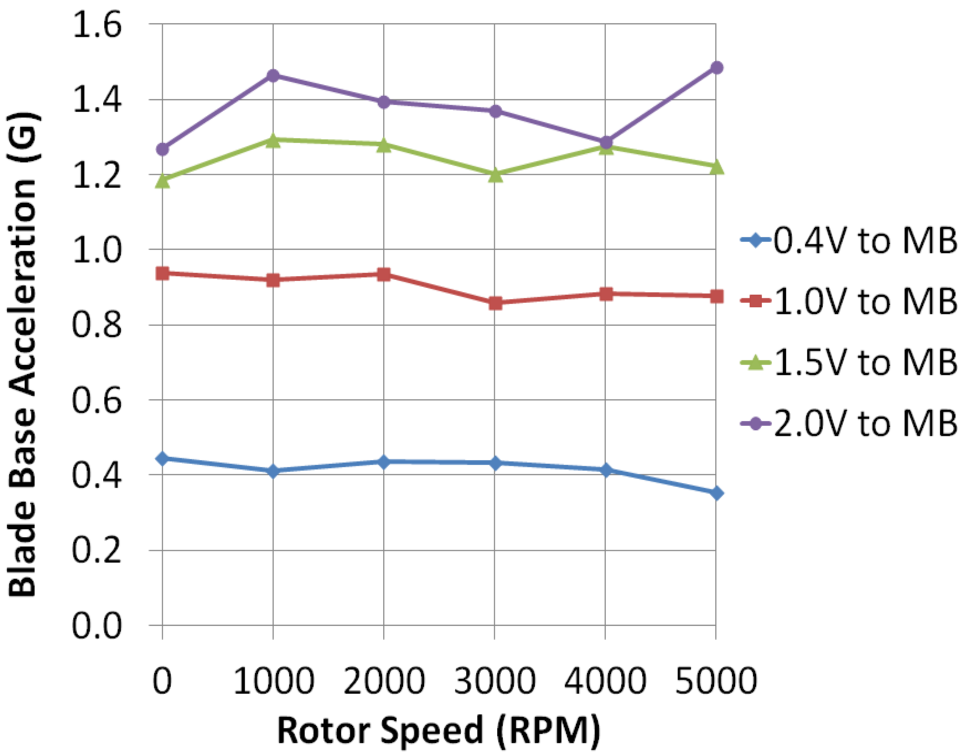




- Two blades place opposite each other in dovetail fixtures
- Vacuum
- Excitation provided by magnetic bearings to the rotor
- Slip ring
- 0- 5000 RPM for this test
- Instrumentation
  - Piezoelectric sensor on each blade
  - Two piezoelectric actuators on each blade
  - Endevco model 25A accelerometer 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



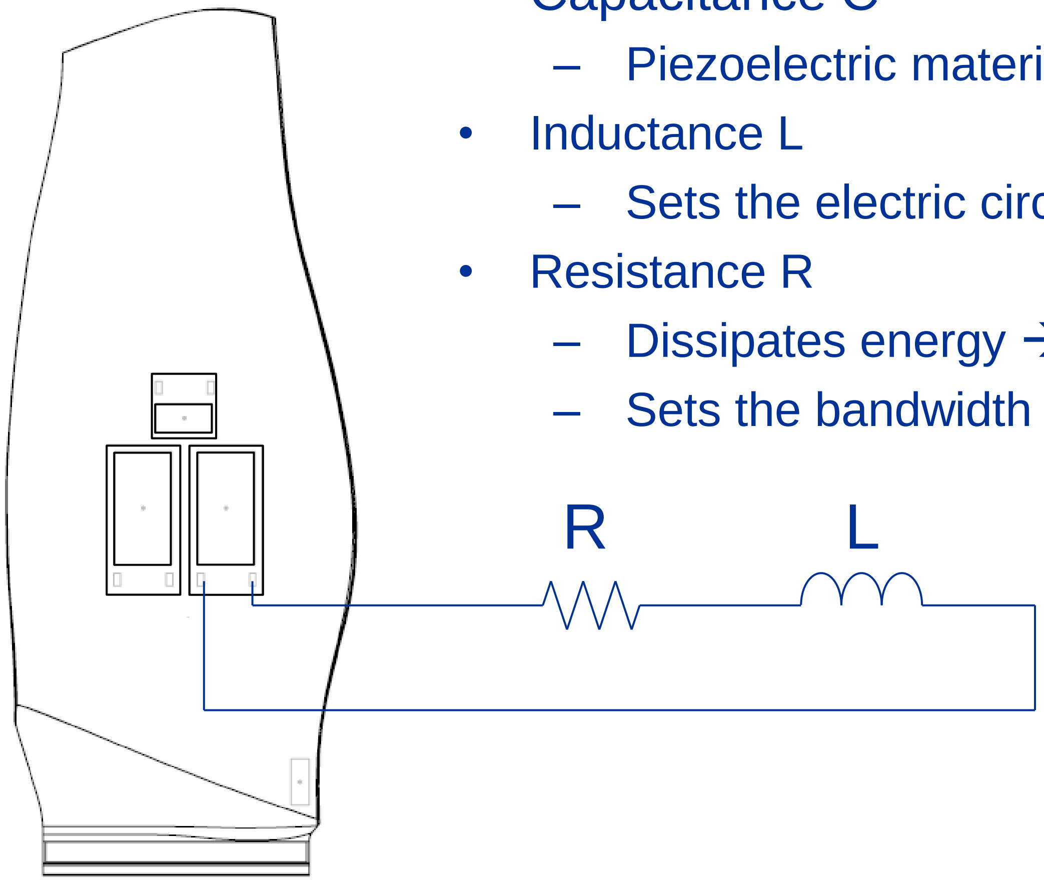


Spin Test

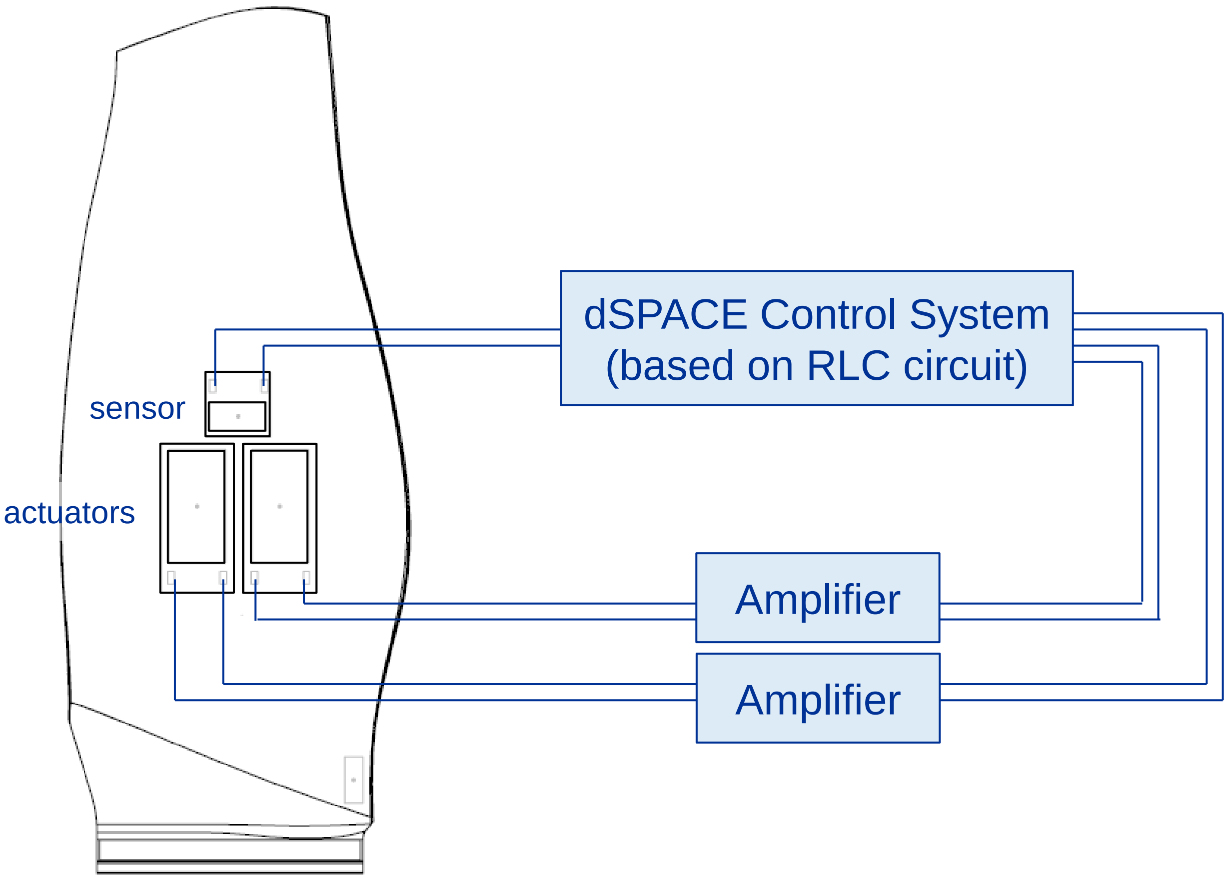
- Piezoelectric Sensor
  - Measure response to magnetic bearing excitation – no control
- Piezoelectric Actuator
  - Measure response to piezoelectric actuator excitation – no control
- Open Loop Control
  - Magnetic bearing excitation
  - Piezoelectric actuator at same frequency as excitation, phase 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

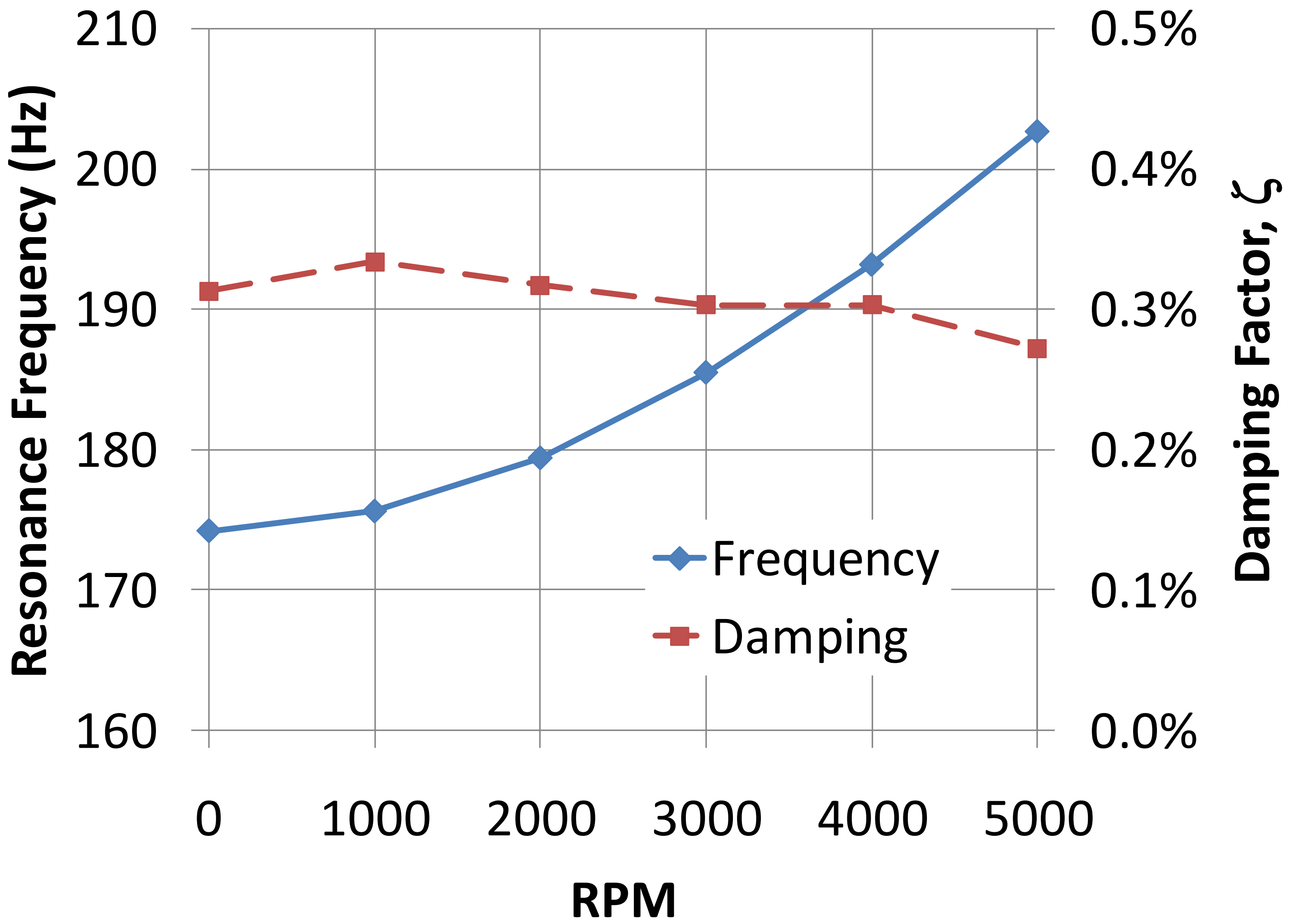
- Closed-loop control based on RLC circuit
- Capacitance C
  - Piezoelectric material property
- Inductance L
  - Sets the electric circuit frequency
- Resistance R
  - Dissipates energy → damping
  - Sets the bandwidth



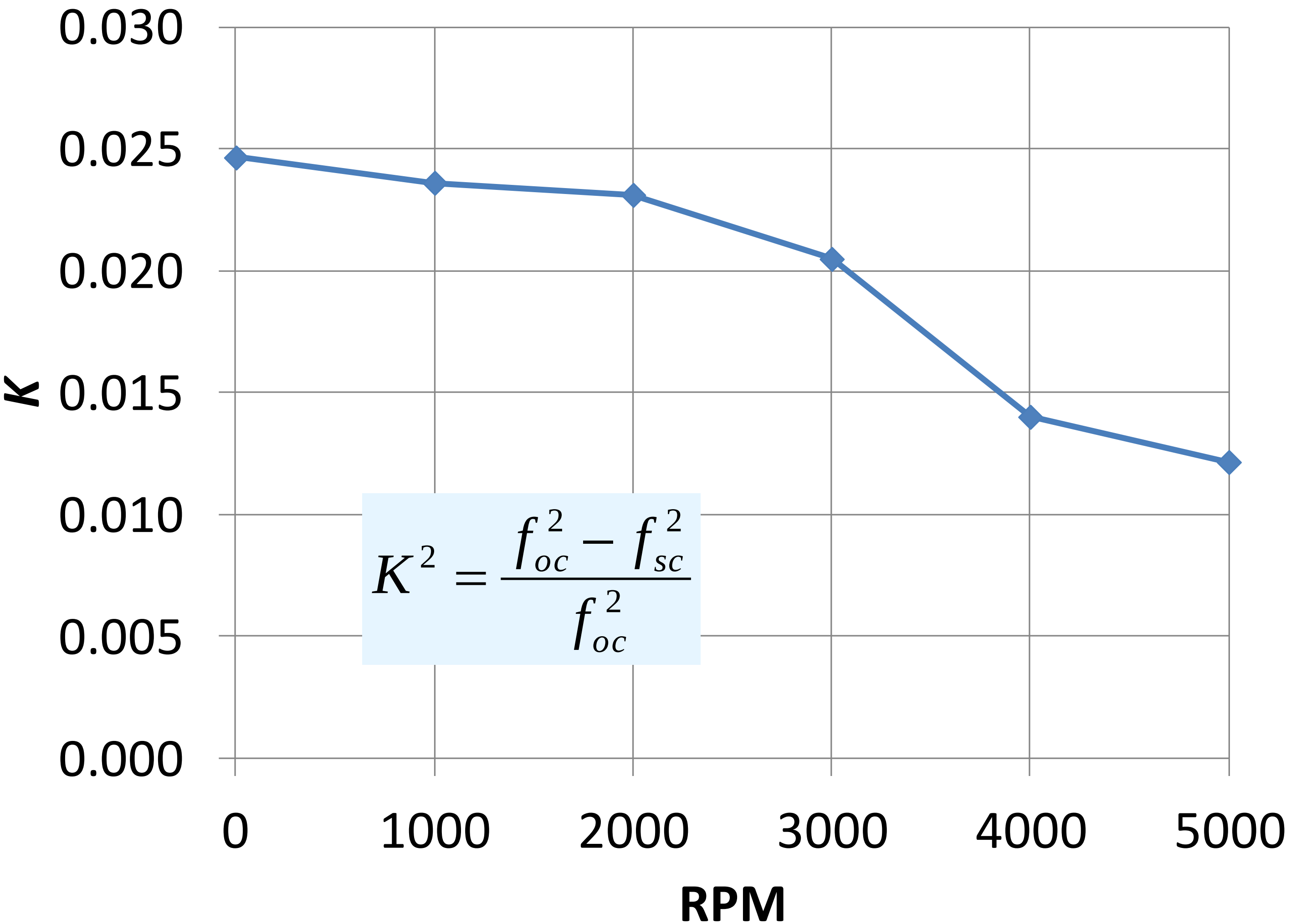
Closed-Loop Control System



Blade Resonance Frequency/Damping

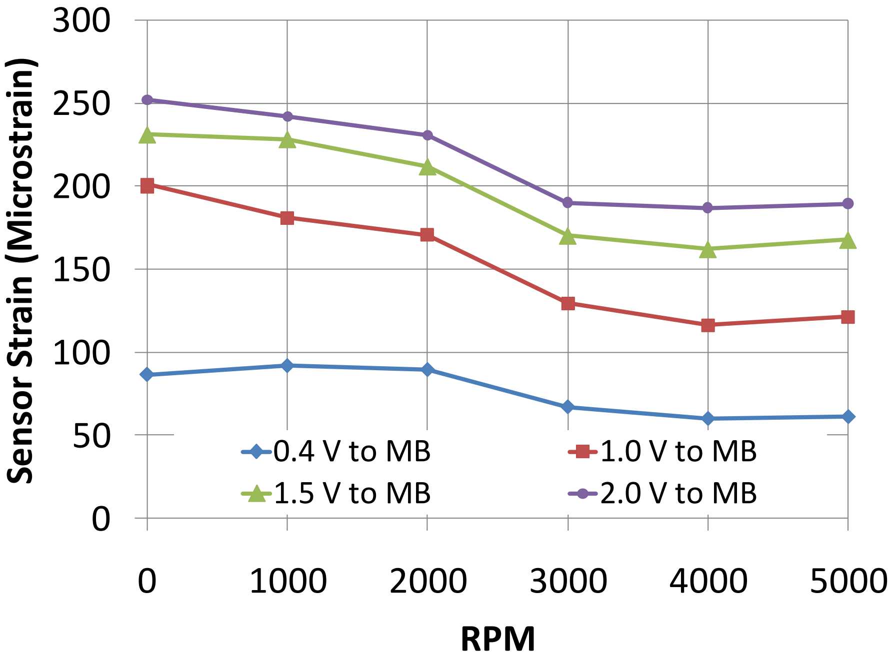


Generalized Electromechanical Coupling



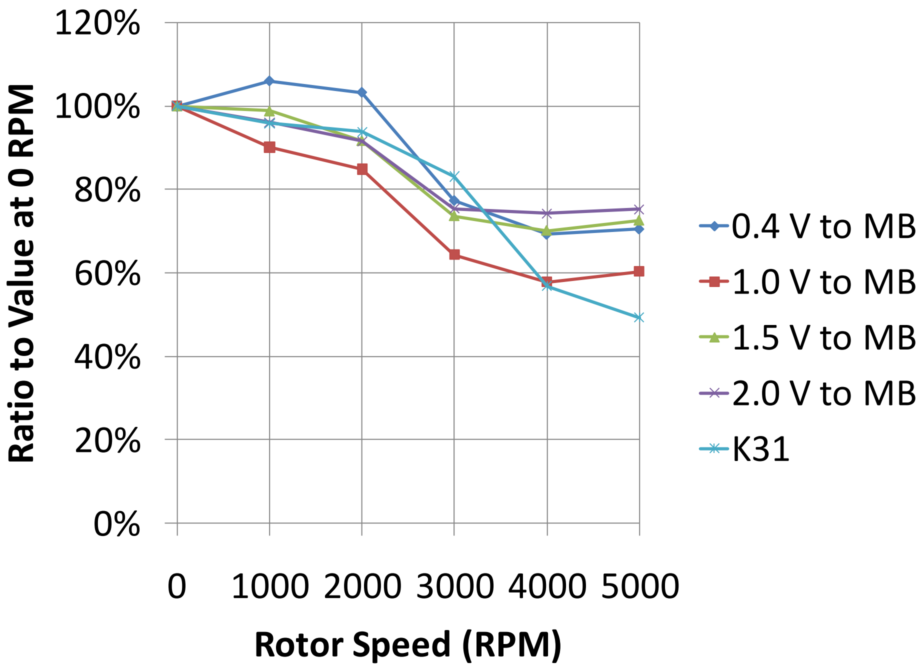
$$K^2 = \frac{f_{oc}^{\,2} - f_{sc}^{\,2}}{f_{oc}^{\,2}}$$

Piezoelectric Patch as Sensor

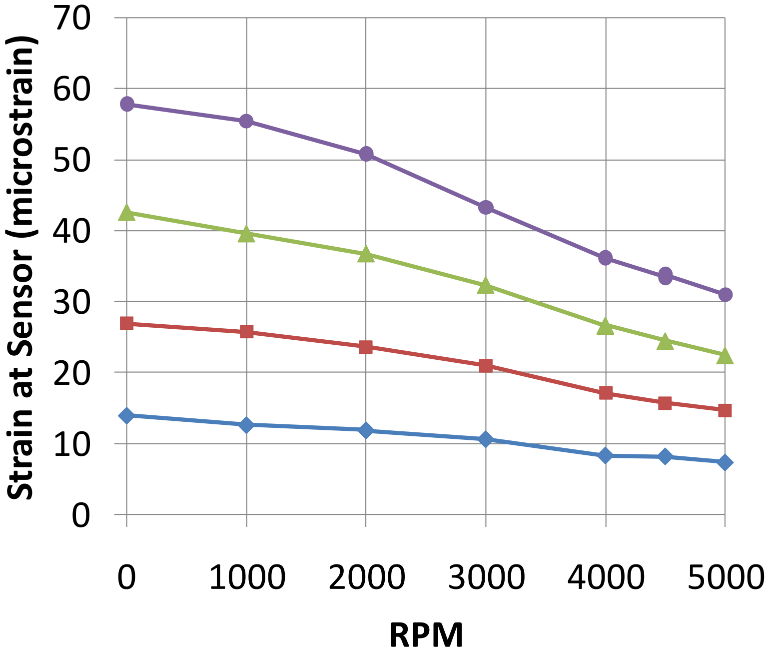


- Excitation provided by magnetic bearings
- Strain measured by piezoelectric sensor
- Strain should be proportional to K

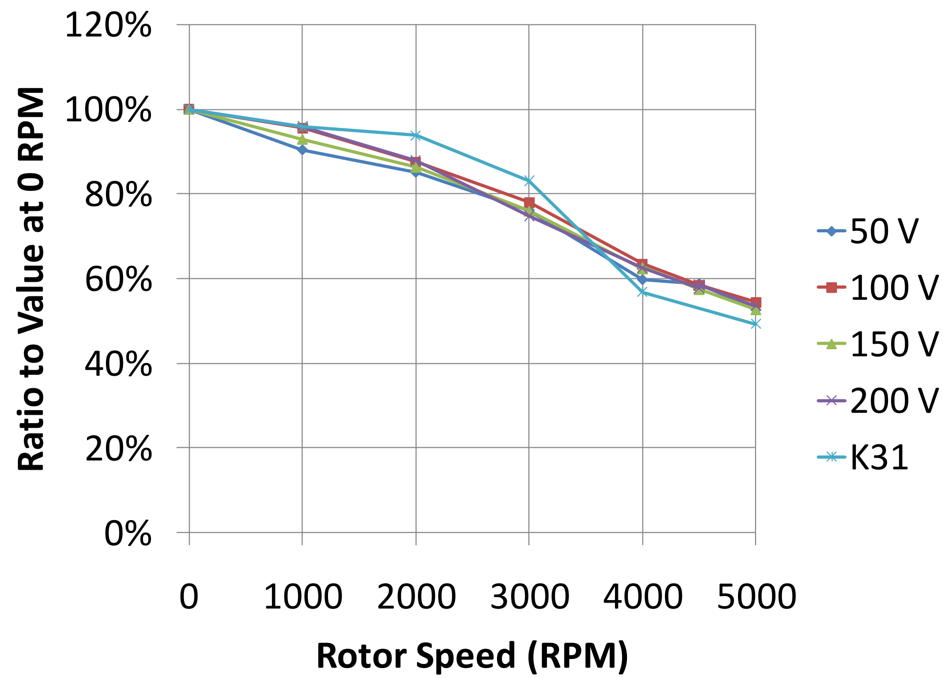
- Piezoelectric sensor – voltage output proportional to strain
- Average strain over sensor area



Piezoelectric Patch as Actuator

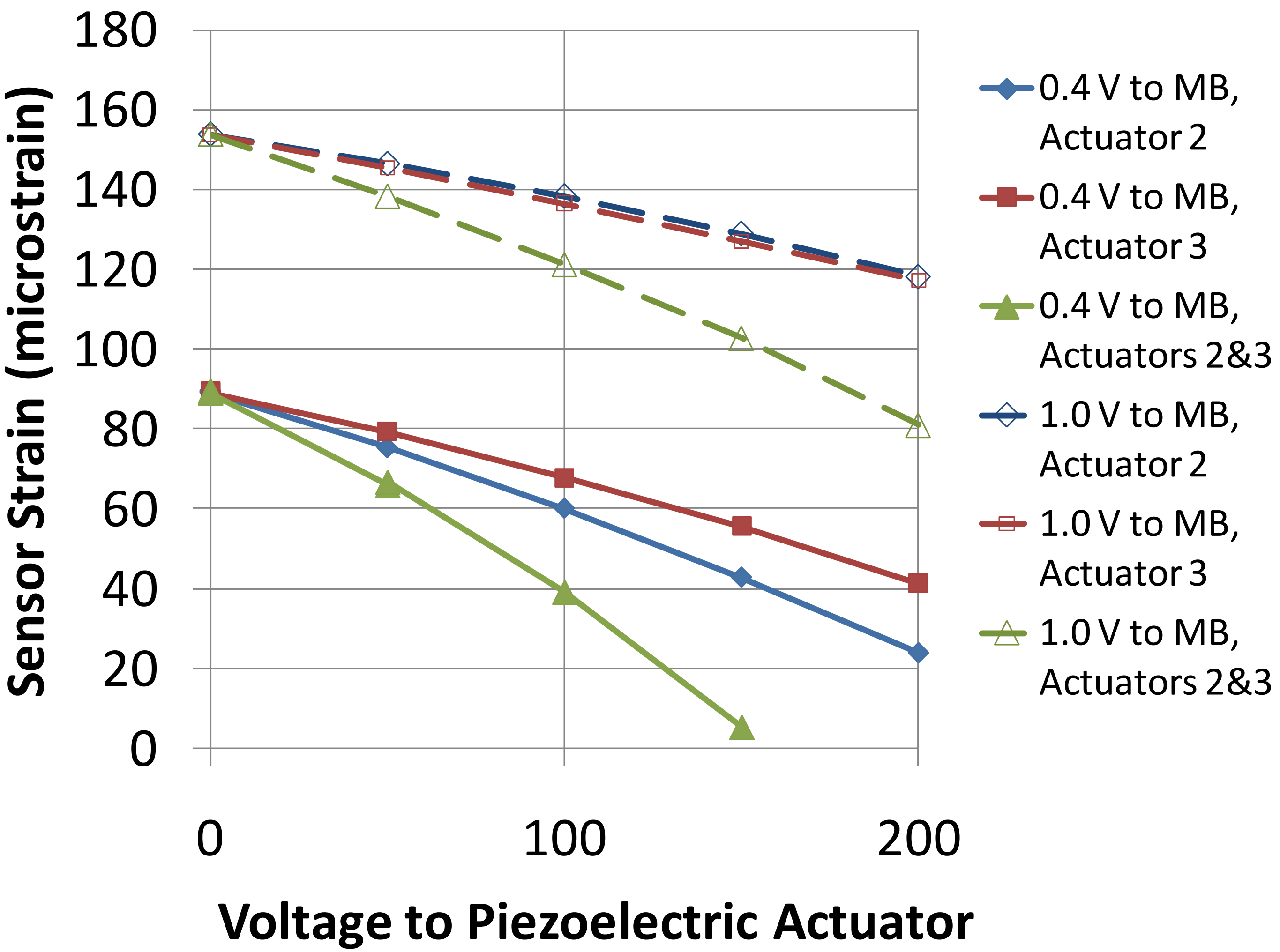


- Excitation provided by piezoelectric actuator
- Strain measured by piezoelectric sensor
- Strain should be proportional to K



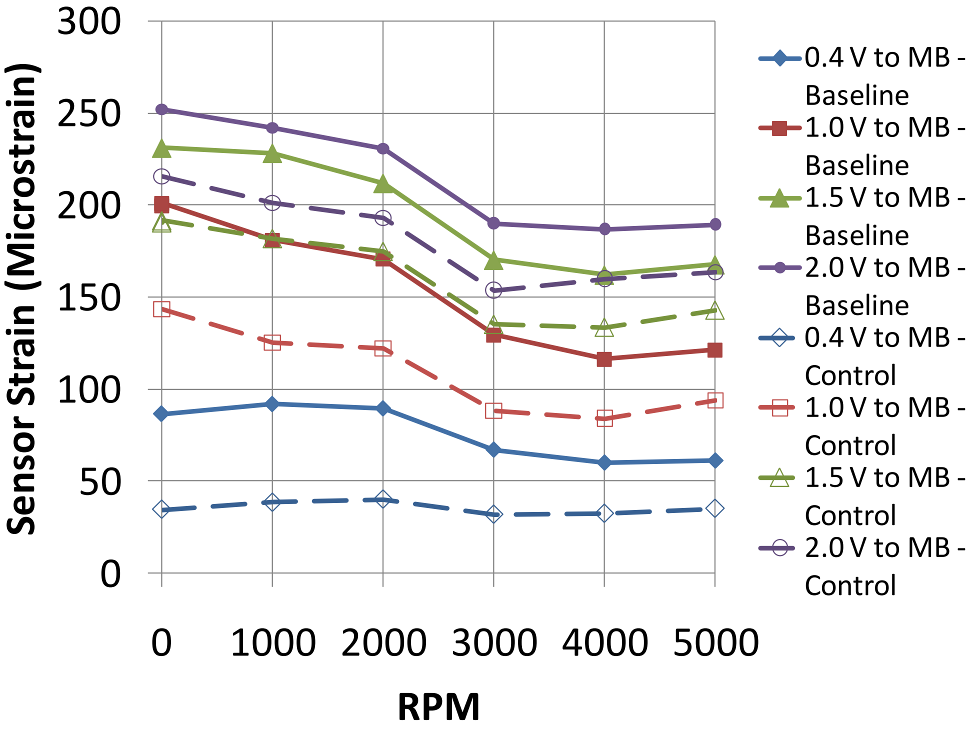
- Piezoelectric excitation levels much lower than magnetic bearing excitation levels (60 microstrain versus 250 microstrain)

Open Loop Vibration Control

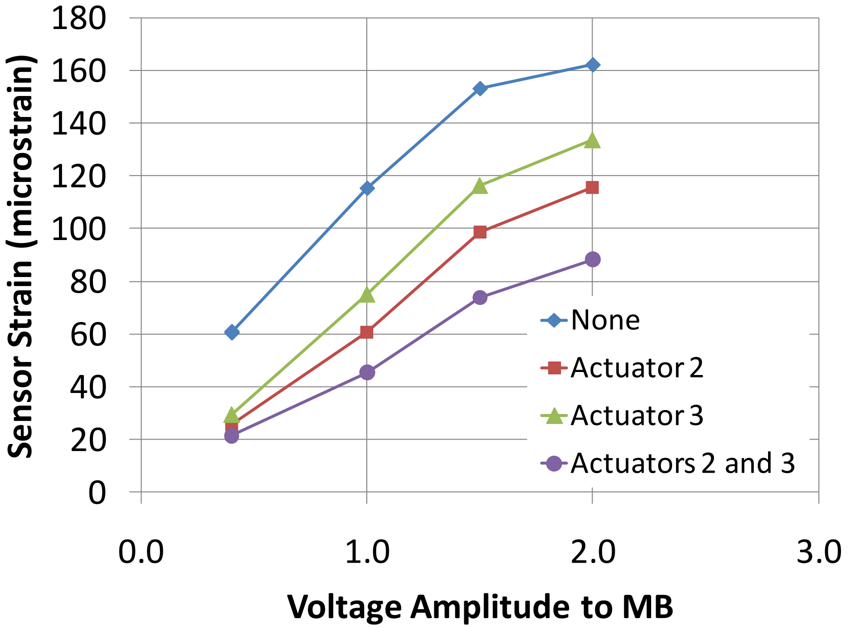


Closed Loop Control

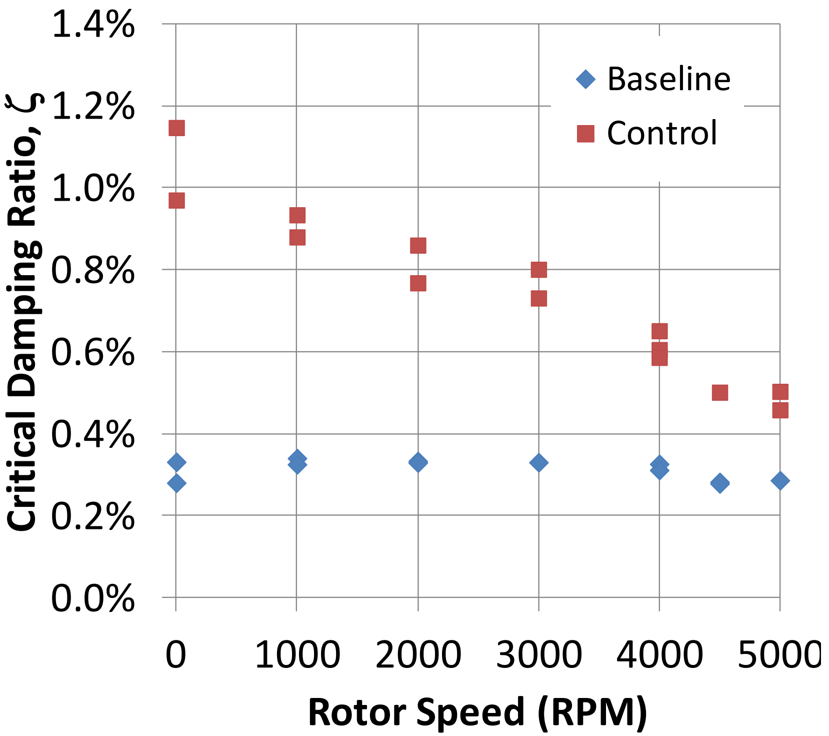
Reduced Response from Single Actuator



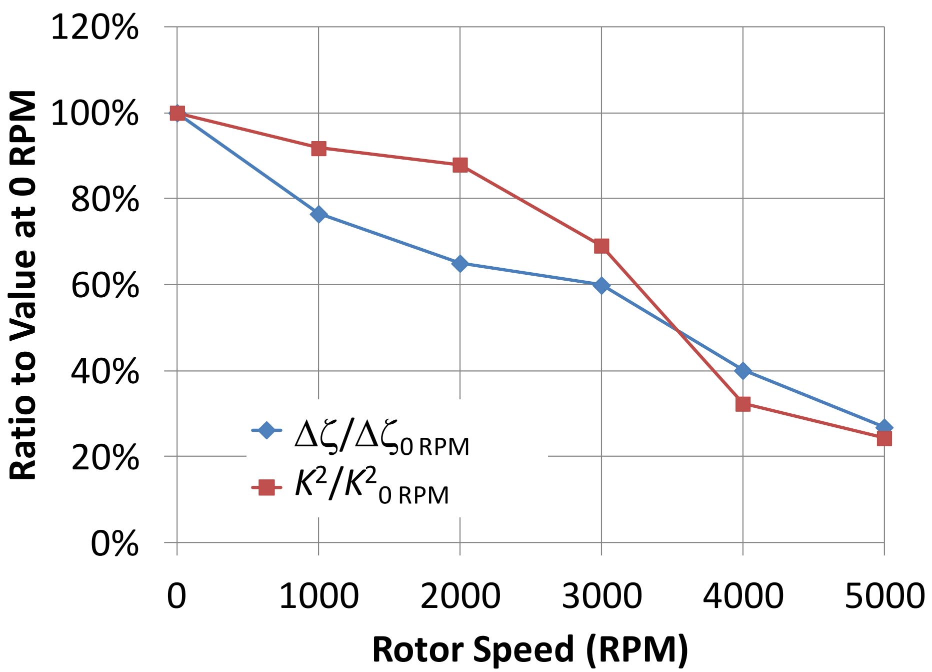
3000 RPM



Damping from Closed Loop Control



- Control system is simulated RLC circuit with amplification
- R = 2500Ω, bandwidth ~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

Acknowledgments

- NASA Fundamental Aeronautics Program, Subsonic Fixed Wing Project
- Space Act Agreement – NASA Glenn Research Center and GE Aviation

- Thanks to Jeff Kauffman (Penn State University) and Carlos Morrison (NASA Glenn) for their assistance during testing