Passively-Shunted Piezoelectric Damping of Centrifugally-Loaded Plates

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RELATED RESEARCH AT NASA

- **Turbomachinery blade damping research at NASA GRC**
  - *Viscoelastic damping (Kosmatka '98 – UCSD)*
  - *Impact damping (Duffy, Brown, Mehmed, Bagley '00-'04)*
  - *Plasma sprayed damping coatings (Zhu, Miller, Duffy '09)*
  - *High-temperature high-damping shape memory alloys (Duffy, Padula, Scheiman '08)*
  - *Multi-mode control with **active** piezoelectric circuits (Choi, Morrison, Min '09)*

- **High-temperature piezoelectric materials research at NASA GRC**
  - *"Microstructure-Property Relationships in Liquid Phase Sintered High-Temperature Bismuth Scandium Oxide-Lead Titanate Piezoceramics" (Sehirlioglu, Sayir, Dynys – J. Am. Ceram. Soc., 91 [9], 2910, 2008).*
  - *"High Temperature Properties of $BiScO_3$-$PbTiO_3$ Ferroelectric Ceramics" (Sehirlioglu, Sayir, Dynys – submitted to J. Appl. Phys., 2009)*

- **Application of piezoelectric materials to helicopter blades**
  - *Piezoelectric actuated flaps*
  - *Distributed piezoelectric material to adjust twist*
  - *Vibration and noise control*
  - *Ames, Langley*

PIEZOELECTRIC DAMPING RESEARCH

- **Shunted piezoelectric damping**
  - *State-of-the-art survey (Chopra '02)*
  - *Equivalent material properties (Hagood, von Flotow '91)*
  - *Types of shunt circuits (Lesieutre '98)*

- **Application of piezoelectric damping to turbomachinery blades**
  - *Passive circuit below blade platform (Hilbert, Pearson, Crawley '01)*
  - *Passive circuit on stator vanes (Cross, Fleeter '02)*
  - *Negative capacitance on beams (Livet et. al. '08)*
  - *Application to mistuning (Yu, Wang '07)*

➢ **NASA GRC – Passively-shunted piezoelectric damping for turbomachinery blade application**
  - ➢ ***Purely passive circuits – no external power required***
  - ➢ ***Centrifugal loading***

AIRCRAFT ENGINE BLADE APPLICATION

Benefits

- Reduce high cycle fatigue
  - Decrease maintenance costs, failures
- Enable lighter-weight blade designs that have lower inherent damping
  - Reduce weight and noise
  - Increase efficiency

Target applications

- Fan or cold-side compressor blade
- Titanium alloy or composite fan blade

No detrimental effect on aerodynamics

- Internal to blade or very thin surface treatment

Engine blade environment

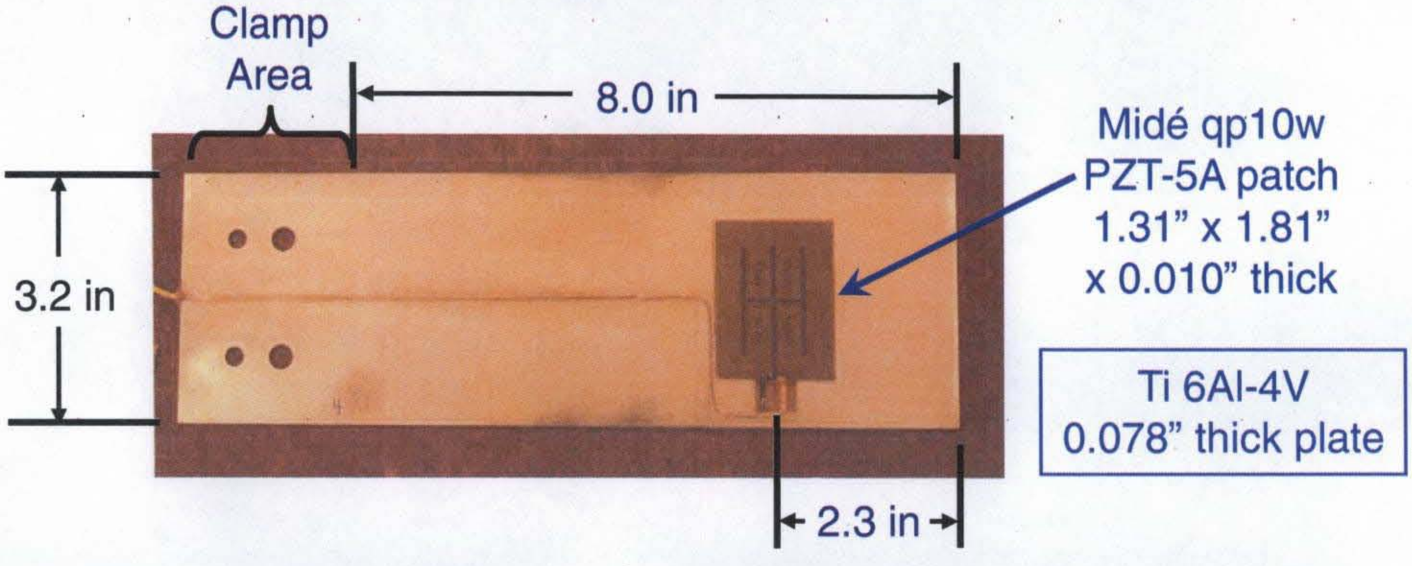
- **Temperature** – up to 600°F
- **Vibratory Strain** – less than 10^{-3}
- **Mean strain** (from centrifugal loading) – less than 10^{-3}
- **Frequency** – 100 to 10,000 Hz
- **Damping** – Loss factor $\eta < 10^{-3} \rightarrow \eta > 10^{-2}$

Note: loss factor $\eta = Q^{-1} = 2\zeta$

PASSIVE SHUNT TEST GOALS

- **Centrifugal loading**
  - Maintain material and adhesive integrity
  - Maintain circuit and wiring integrity
  - Centrifugal strain
- **Shunt circuit implementation**
  - Fully passive (no external power source)
  - Small circuit size
  - Maintain damping level over speed range
- **Target modes**
  - Tip modes (e.g. 3^{rd} bending – 3B)
- **Not addressed in this phase of the program:**
  - Realistic implementation (e.g. surface vs. recessed mounting, piezo thickness, composite blades)
  - Room temperature testing only (PZT-5A – 600°F Curie temp)

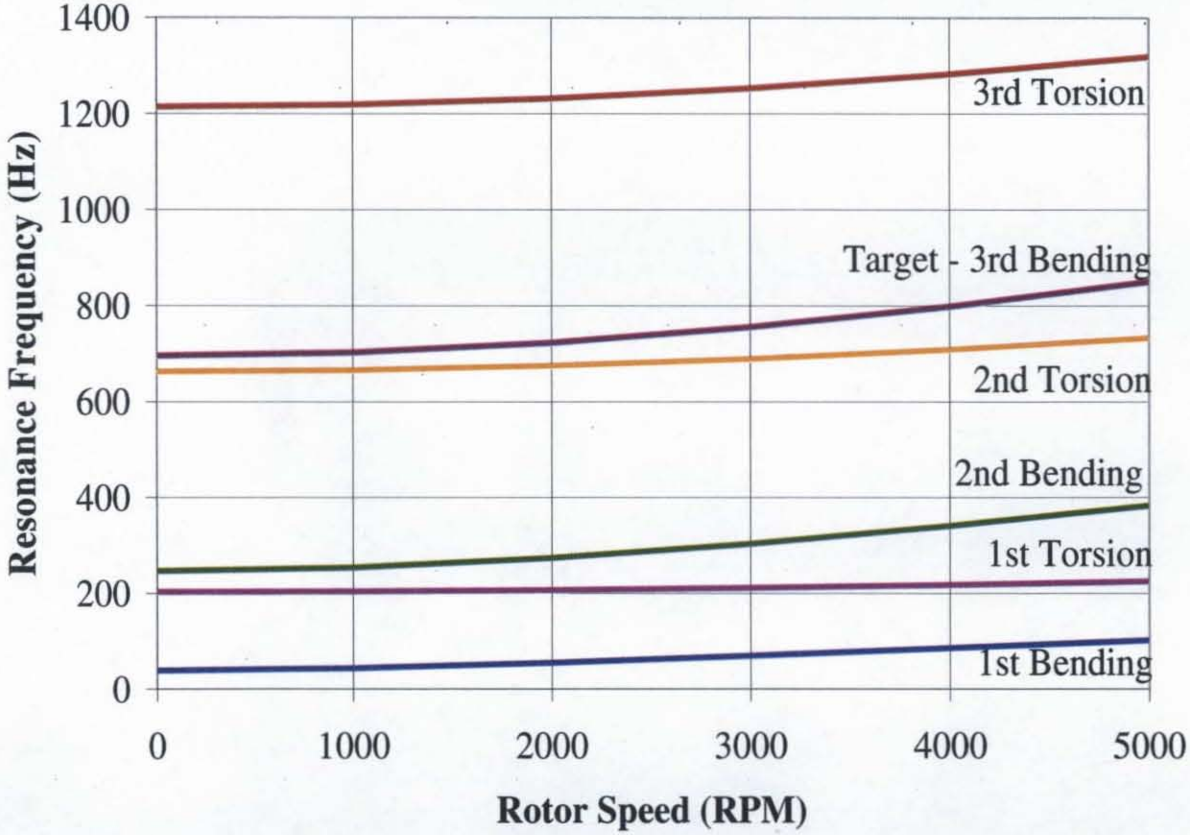
TEST ARTICLE



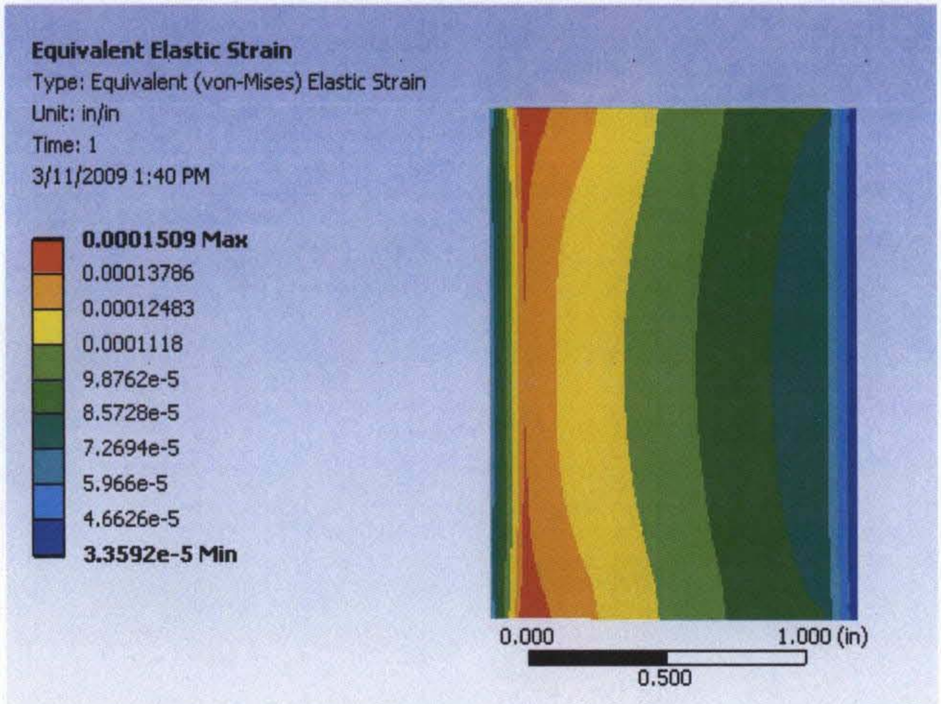
3B Mode – Modal Deformation

3B Mode – von Mises Modal Strain

EFFECT OF CENTRIFUGAL LOADING



EFFECT OF CENTRIFUGAL LOADING



Centrifugal strain in piezoelectric patch at 4krpm

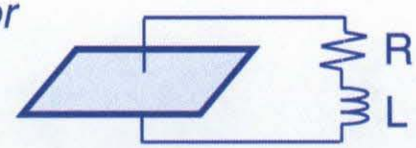
150×10^{-6} max

(500×10^{-6} allowable)

PASSIVE SHUNT CIRCUITS

- **Resistive Circuit (R-Circuit)**
  - *Energy dissipated through the resistor*
  - *Broad frequency range, lower damping*

- **Tuned Resonant Circuit (RL-Circuit)**
  - *Tuned to resonance frequency through the inductor*
  - *Higher damping at target frequency*
  - *Inductor is a simple coiled wire – **fully passive***



Test	Shunt Circuit Configuration	Shunt Resistance	Shunt Inductance
Stationary 0 rpm (Shaker)	3B-O-S 3B-S-S 3B-R-S 3B-RL-S	Open circuit Short circuit 0-22 kΩ 0-22 kΩ	--- --- --- 0.38H, 0.69H, 1.27H
Centrifugal (Spin Rig)	3B-O-C 3B-R-C	Open circuit 4.12 kΩ	--- ---

AIR-CORE INDUCTOR

Optimal inductor for 700-800Hz

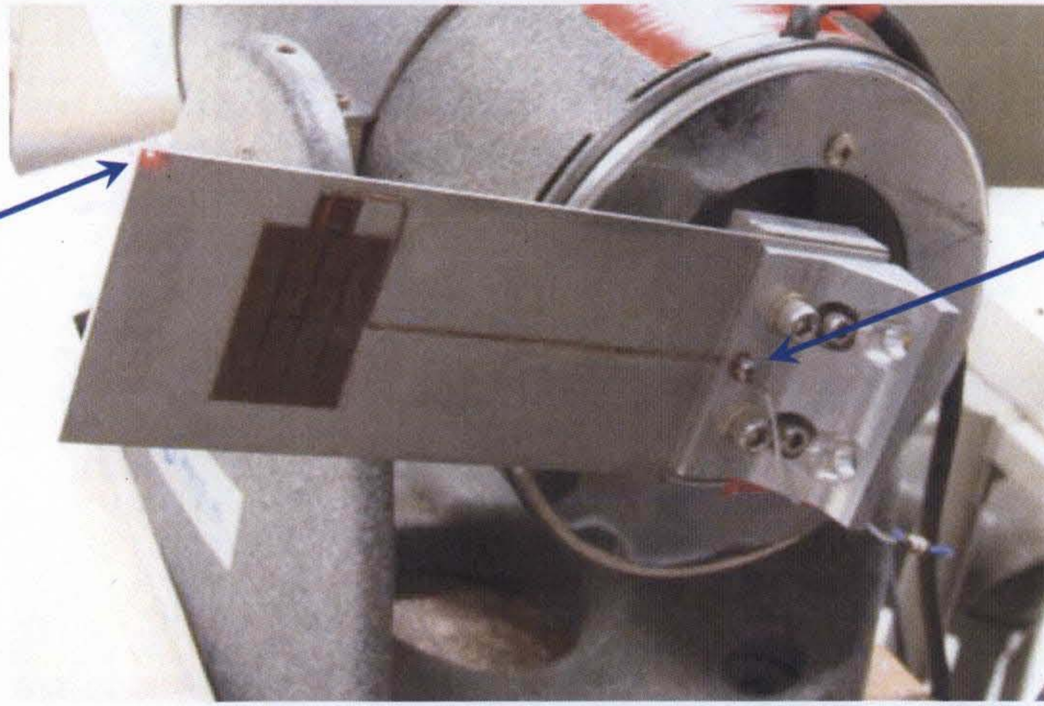
0.69 H wound inductor:

- *34-gauge wire*
- *0.75-inch inner diameter*
- *2.6-inch outer diameter*
- *0.30-inch length*
- *510 Ω*
- *Packing factor could be improved*
- ***Too large for blade application***

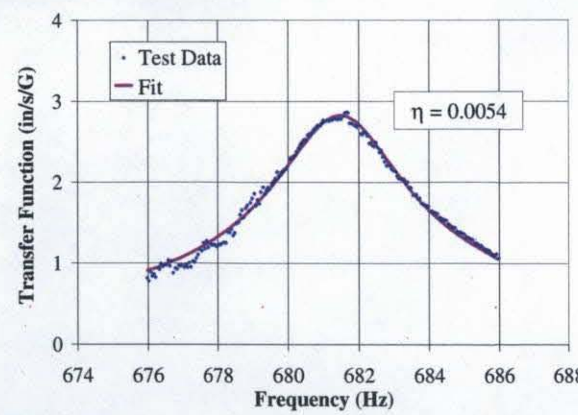
Inductor size required for higher frequencies:

- *2000 Hz – 0.1 H*
- *5000 Hz – 0.015 H*

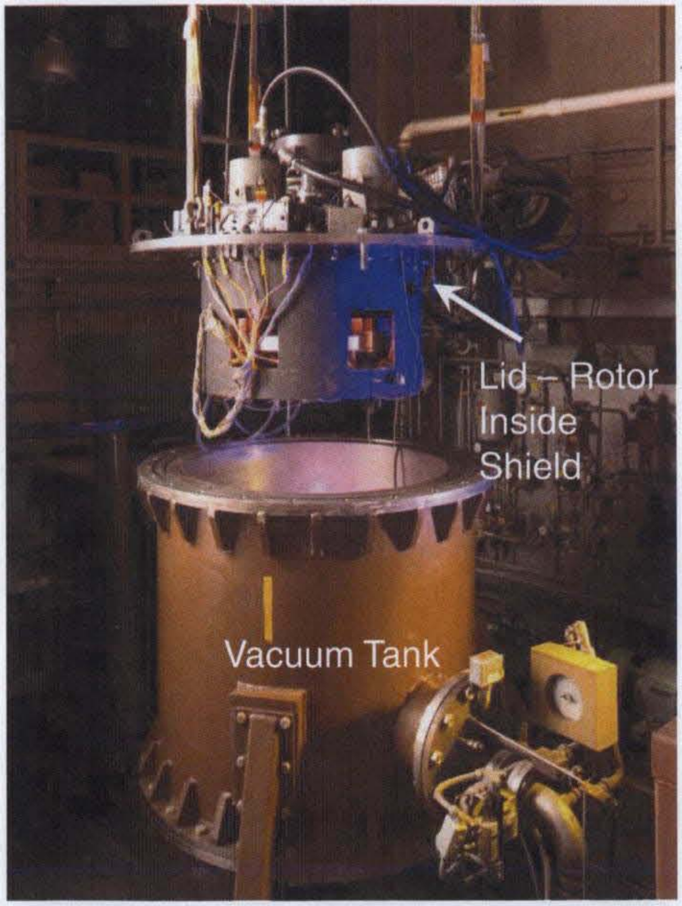
SHAKER TEST



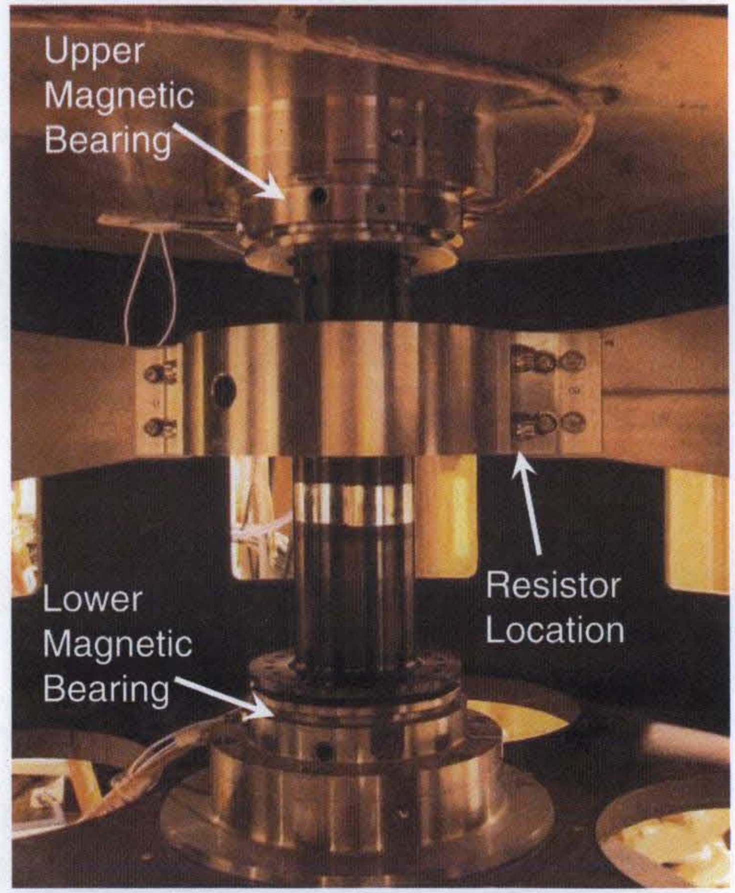
- MB Dynamics PM100 100-lb shaker
- Columbia model 6062-HT accelerometer
- Polytec OFV-505 laser vibrometer with an OFV-5000 controller
- HP 3566A analyzer – signal to shaker, transfer functions



NASA GRC DYNAMIC SPIN FACILITY

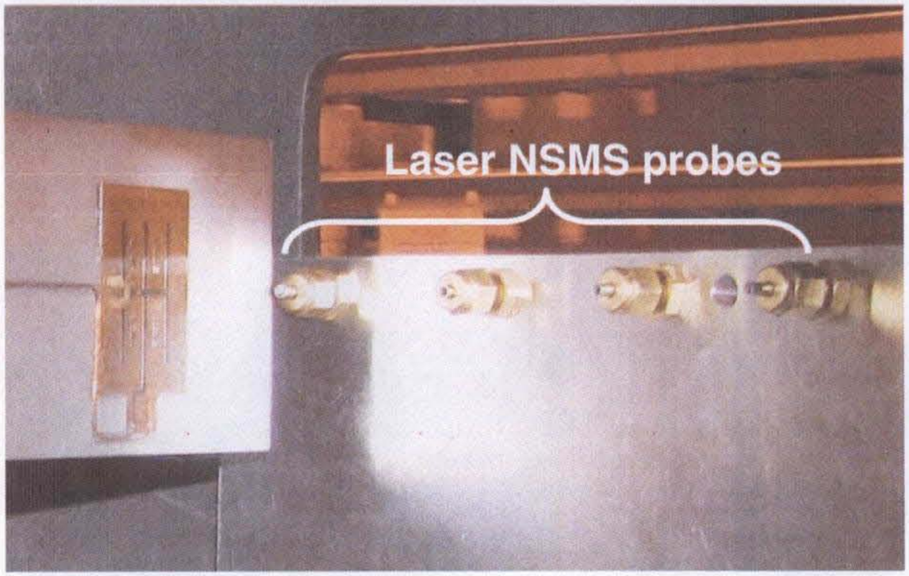


Dynamic Spin Facility



Rotor with Tapered Test Plates

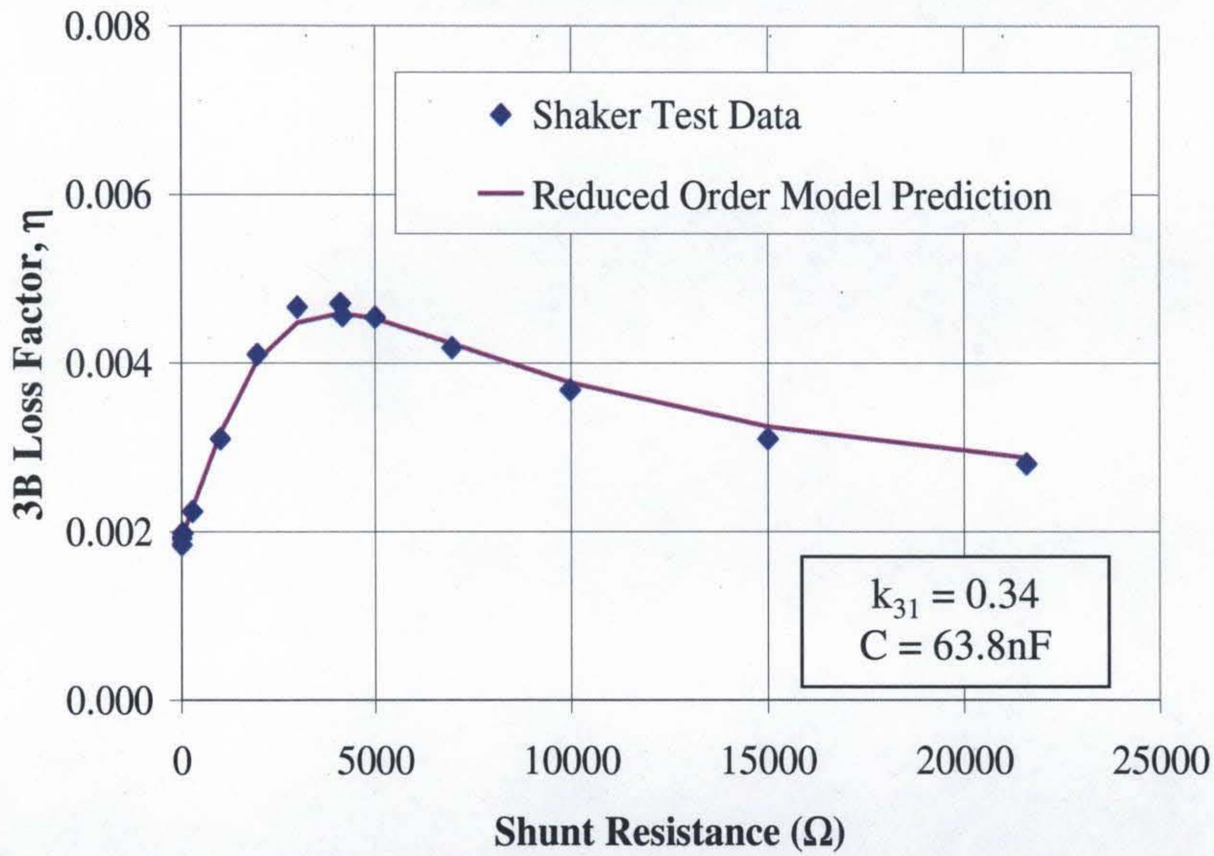
NASA GRC DYNAMIC SPIN FACILITY



- **Vacuum** – 0.01 psia
- **Spin speed** – up to 4000 rpm in this test (20,000 rpm max for facility)
- **Excitation system** – Actively controlled magnetic bearings provide excitation to rotor with approximately 1 kHz bandwidth
- **Excitation type** – engine order frequency, rotating with blades, approximately one-g
- **Instrumentation** – Laser NSMS system, IFOSYS probes, Hood measurement and analysis software

SHAKER TEST RESULTS

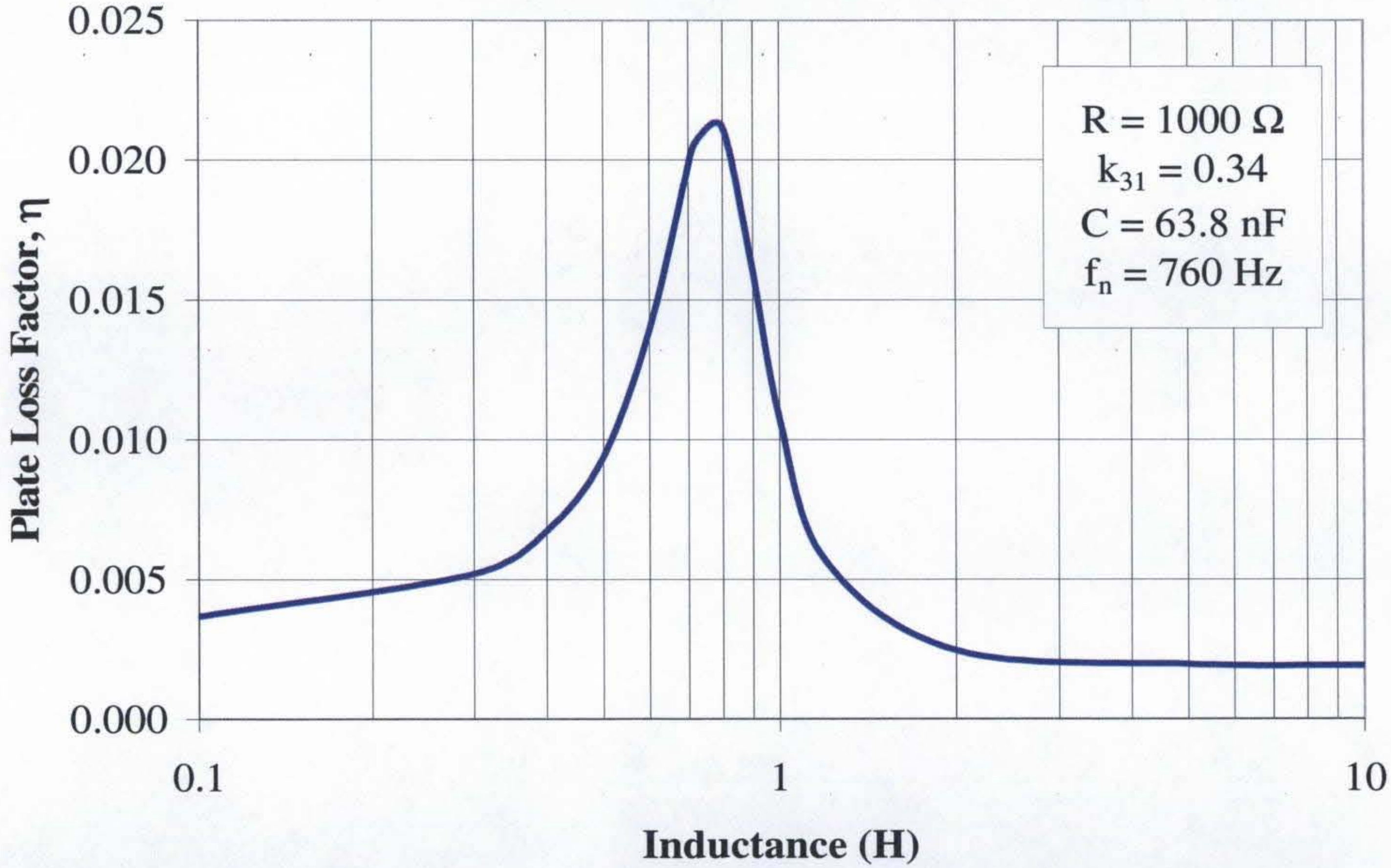
3B-R-S – R-CIRCUIT RESULTS



Damping target of $\eta = 0.01$ not achieved with resistor alone

DAMPING PREDICTION

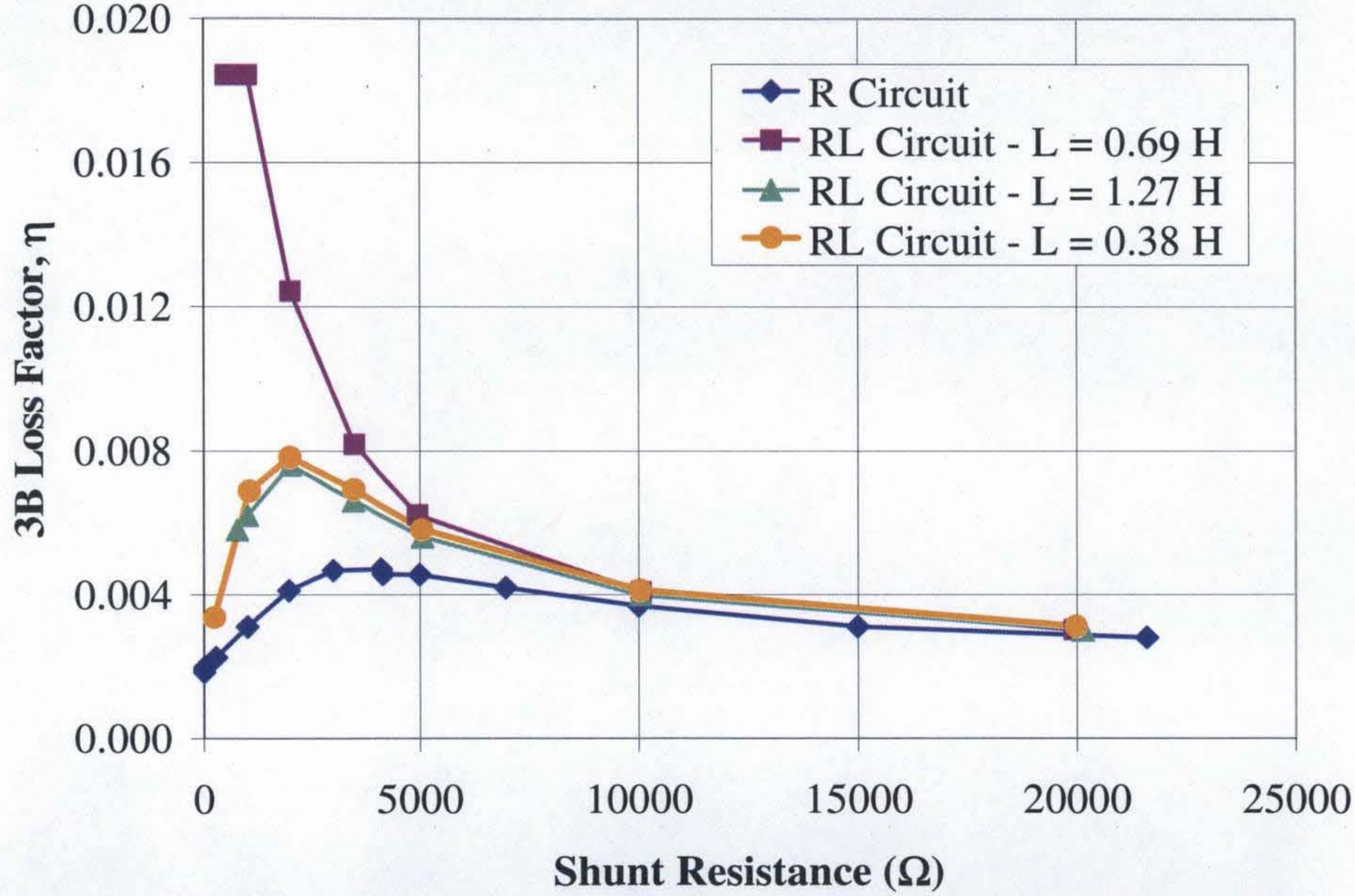
3B-RL-S – RL CIRCUIT PREDICTIONS



Predictions show L = 0.52–1.0 H range to give η = 0.01 at 760 Hz

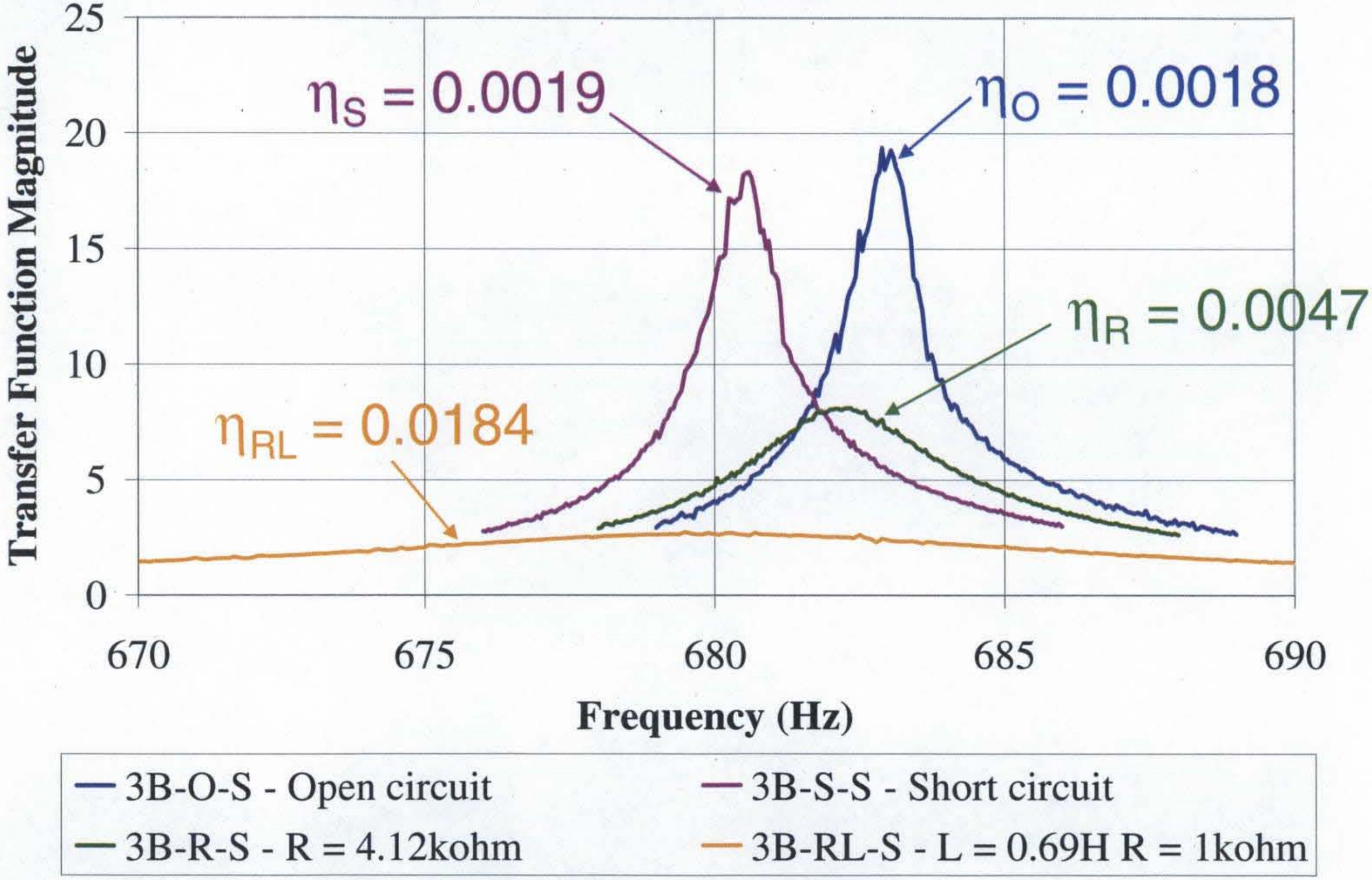
SHAKER TEST RESULTS

3B-R-S & 3B-RL-S – R & RL CIRCUIT RESULTS



Testing shows L = 0.69 H gives $\eta > 0.01$ at 0 rpm

SHAKER TEST RESULTS



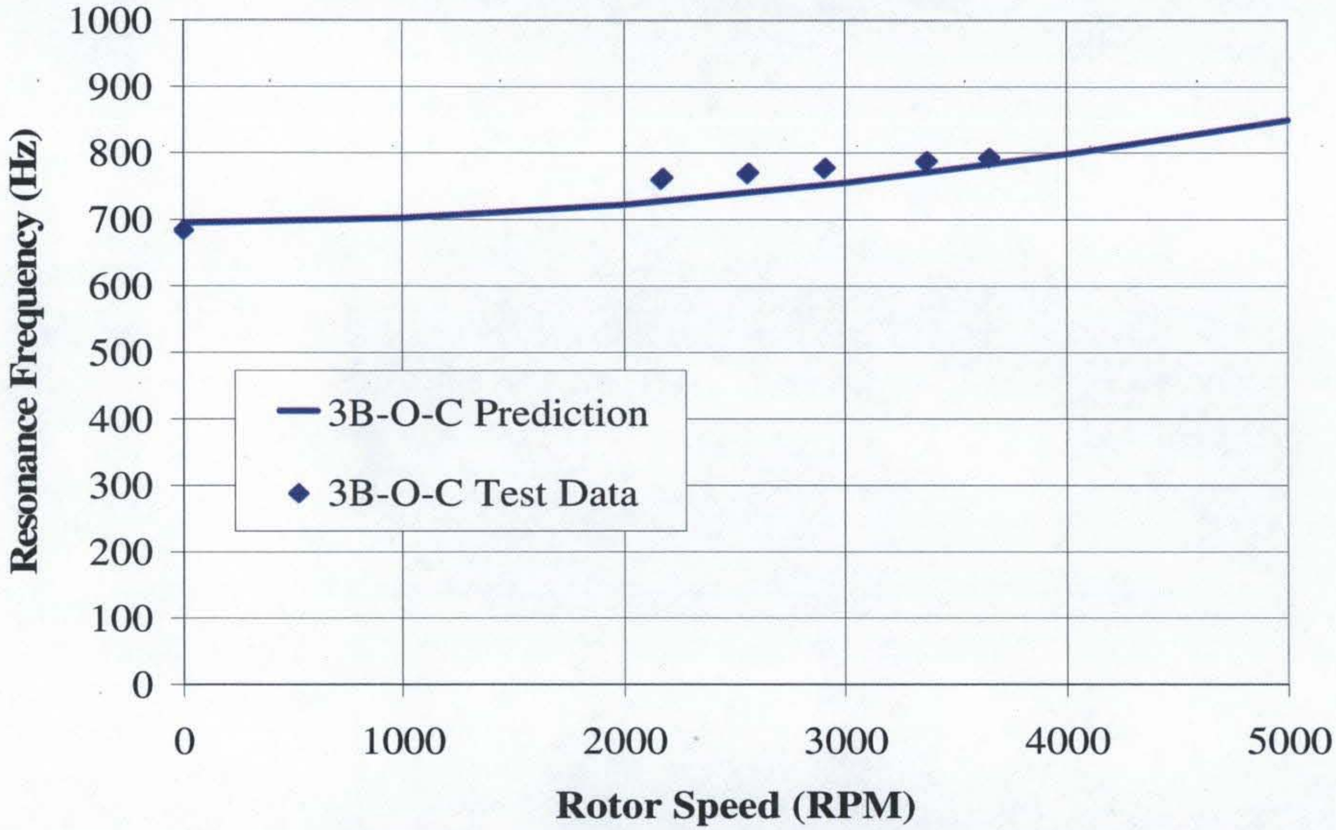
Target $\eta > 0.010$

SHAKER TEST RESULTS

	Transfer Function			Tip Velocity Measurement		
Configuration	3B Frequency (Hz)	3B Loss Factor η	3B Loss Factor Increase $\Delta\eta$	3B Frequency (Hz)	3B Loss Factor η	3B Loss Factor Increase $\Delta\eta$
3B-O-S Open Circuit	683.0	0.0018	---	684.4	0.0047	---
3B-S-S Short Circuit	680.6	0.0019	0.0001	682.0	0.0044	-0.0003
3B-R-S R-Circuit	682.3	0.0047	0.0029	683.7	0.0072	0.0025
3B-RL-S RL-Circuit	680.1	**0.0184**	0.0166	681.2	0.0206	0.0159

SPIN TEST RESULTS

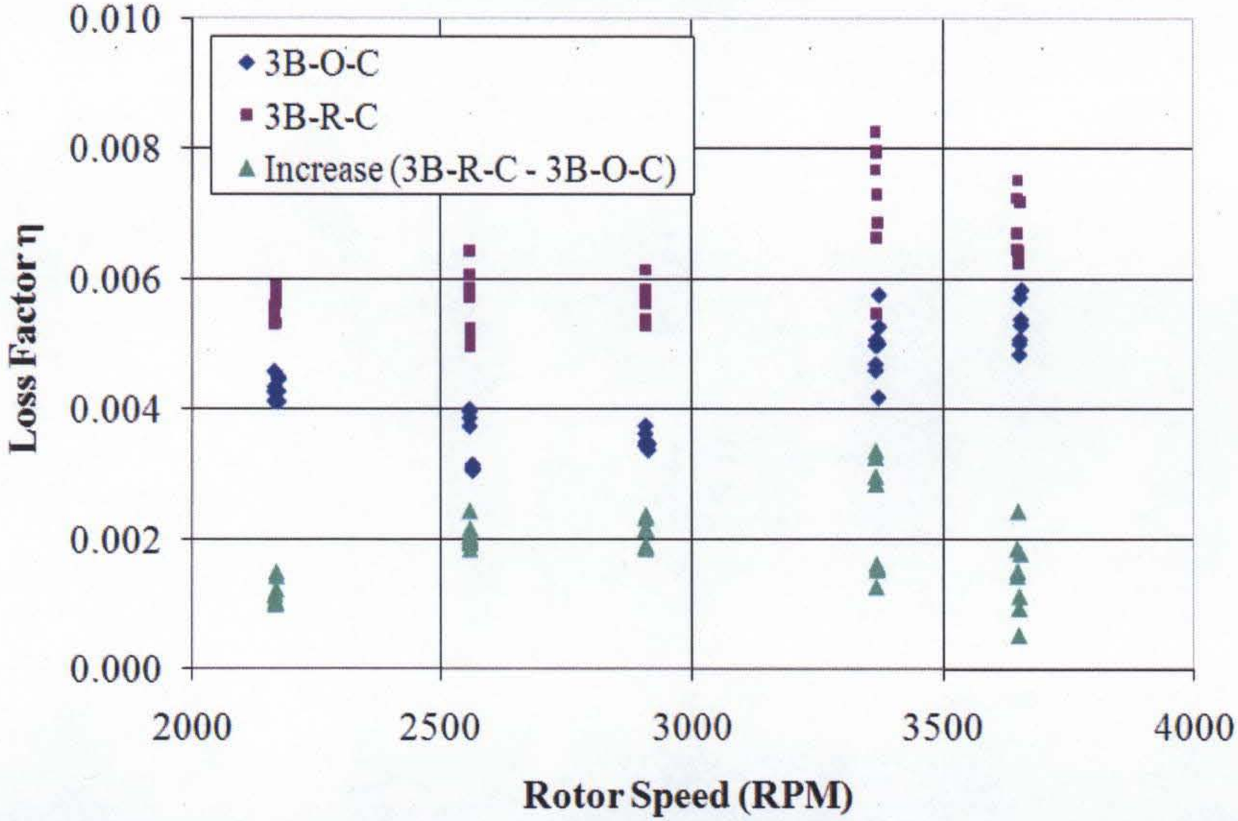
3B-O-C – OPEN CIRCUIT 3B RESONANCE FREQUENCIES



Frequency shift of 683 Hz at 0 rpm (shaker) to 792 Hz at 4000 rpm (spin rig)
$\Delta f \sim 110$ Hz

SPIN TEST RESULTS

3B-O-C & 3B-R-C – OPEN CIRCUIT AND R-CIRCUIT RESULTS



Spin test: $\Delta\eta = 0.0018$ *(average based on tip displacement)*
Shaker test: $\Delta\eta = 0.0025$ *(based on tip velocity)*

SHAKER & SPIN TEST RESULTS

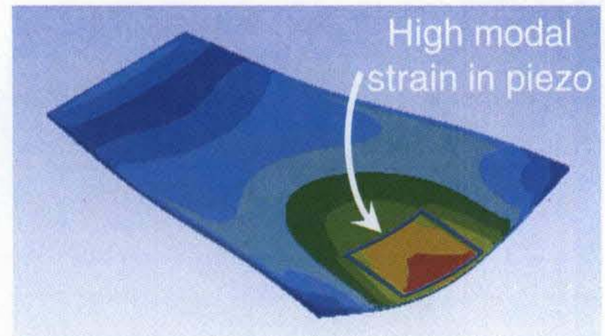
	Shaker Test			Spin Test		
Configuration	**3B Frequency (Hz)**	**3B Loss Factor η**	**3B Loss Factor Increase Δη**	**3B Frequency (Hz)**	**3B Loss Factor η**	**3B Loss Factor Increase Δη**
3B-O-S Open Circuit	684.4	0.0047	---	758-792	Min 0.0031 Max 0.0058 Avg 0.0043	---
3B-S-S Short Circuit	682.0	0.0044	-0.0003	---	---	---
3B-R-S R-Circuit	683.7	0.0072	0.0025	760-791	Min 0.0050 Max 0.0083 Avg 0.0061	Min 0.0005 Max 0.0034 Avg 0.0018
3B-RL-S RL-Circuit	681.2	0.0206	0.0159	*FY09*	*FY09*	*FY09*

SUMMARY

- **Results – damping with purely passive piezoelectric circuit**
  - Shaker test (0 rpm) – achieved desired damping with RL-circuit
  - Spin test R-circuit – similar damping to shaker test R-circuit
  - Spin test RL-circuit – will be required to achieve desired damping level (to be performed in near future)
- **Goals**
  - **Centrifugal loading**
    - FEM model – piezoelectric strain well below max allowable
    - Surface-mounted patch and wiring maintained integrity under centrifugal loading up to 4000 rpm
  - **Target modes**
    - Able to damp mode with high resonant stress levels toward the blade tip (e.g. third bending mode)
  - **Shunt circuit implementation**
    - Passive circuit required no external power source
    - Small circuit size – resistor very small, but target frequency will need to be higher (e.g. 5 kHz) for reasonable-sized inductor
    - Circuit maintained integrity under centrifugal loading
    - Based on reduced order modeling, the RL-circuit should be able to damp the 3B mode over the 0-4000 rpm speed range. Needs to be verified experimentally.

FUTURE WORK

- **RL-circuit spin test**
  - Perform test with L = 0.69 H for both plates
  - Inductor housing has been fabricated, will be located below the lower magnetic bearing
- **Tapered plate spin test**
  - Plate with tapered shape to drive the 2-stripe (chordwise bending mode) below the 1 kHz excitation bandwidth
  - True tip mode – very low stress at the base
- **High-temperature piezoelectric damping**
  - Oven facility built to test plates with new materials being developed at NASA GRC
  - Measure damping as a function of temperature and compare with material properties
- **Realistic implementation**
  - Metal blades – piezo material recessed or internal to blade
  - Composite blades – piezo material between plies, or piezo fibers
  - Circuit size and location



Tapered plate
Two-stripe modal strain

ACKNOWLEDGMENTS

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