Overview of NASA GRC Research on Damping of Jet Engine Blades

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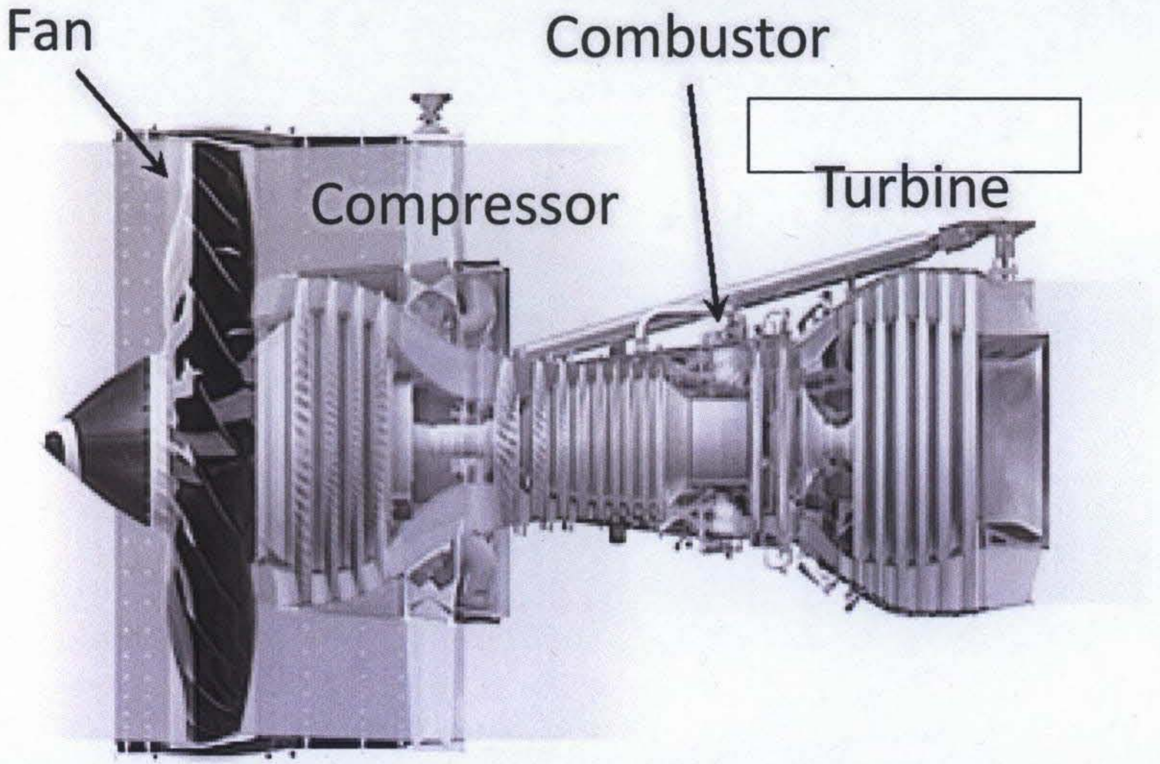
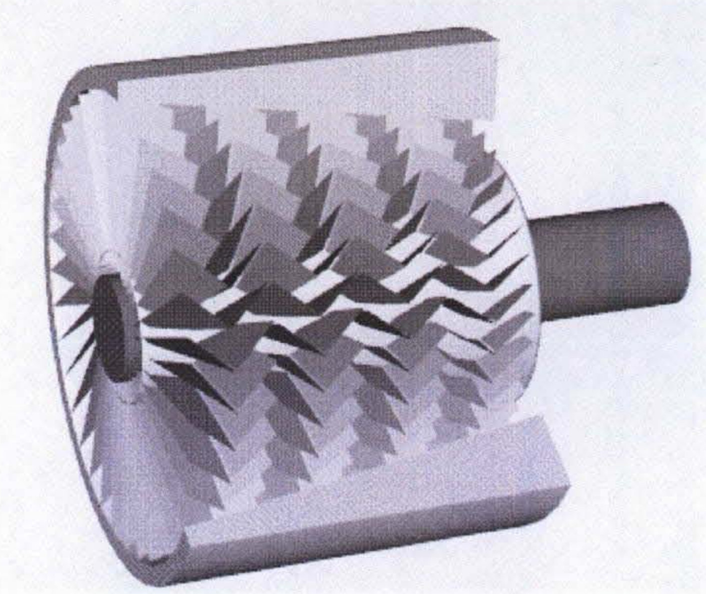
Aircraft Engine



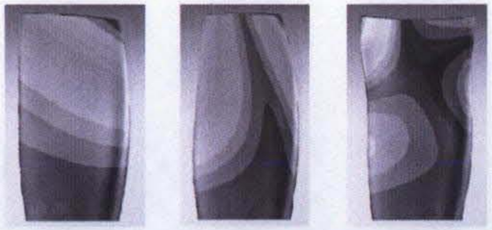
GE90 Turbofan Engine

http://www.geaviation.com/education/theatre/ge90/

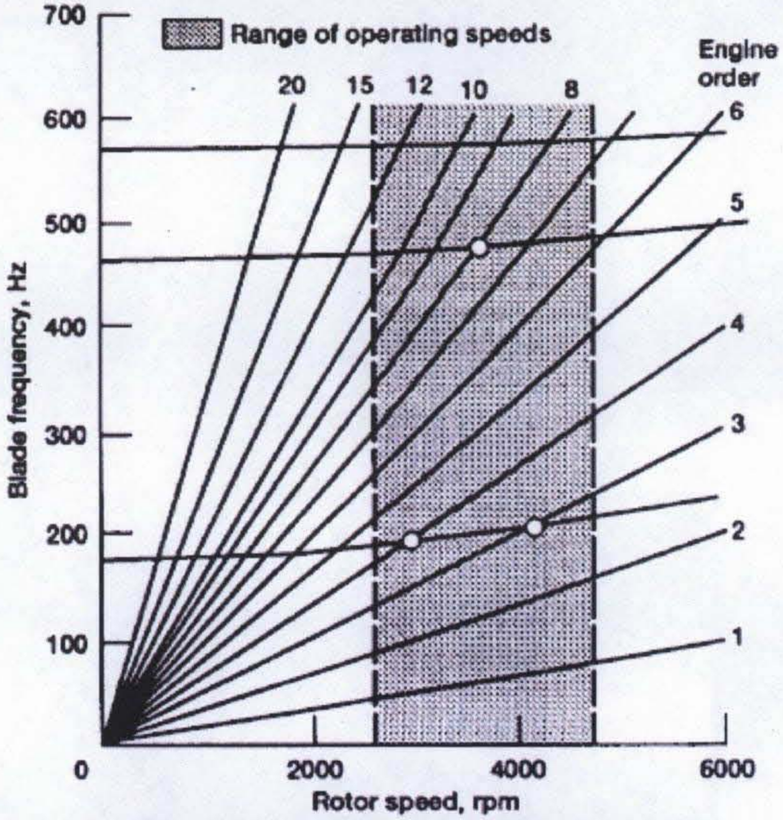
Engine Blade Forced Vibration



www.grc.nasa.gov/WWW/K-12/airplane/caxial.html



Blade Vibration Modes

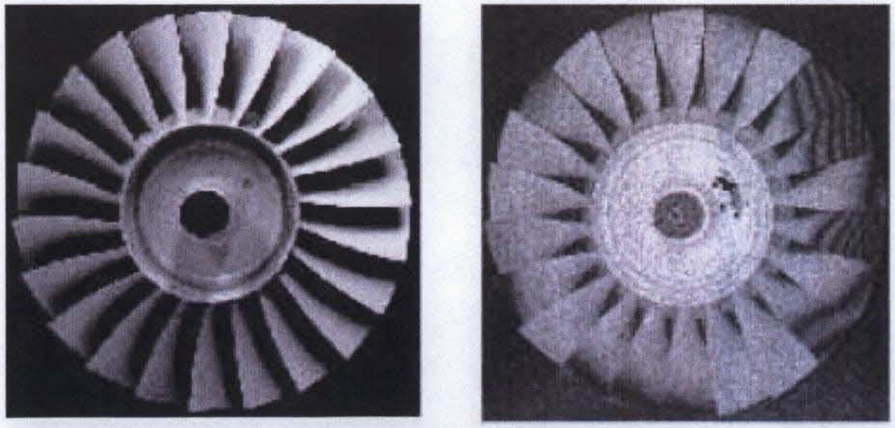


(b) Campbell diagram for rotor blade showing possible forced-response condition from resonance (denoted by circles).

Reddy et. al. 1993 NASA TP-3406
"A review of recent aeroelastic analysis methods for propulsion at NASA Lewis Research Center"

Mistuning

- Blades are manufactured with slight differences
  - Problem → Localized vibration
  - Solutions
    - Increased damping
    - Increased coupling among blades and disk

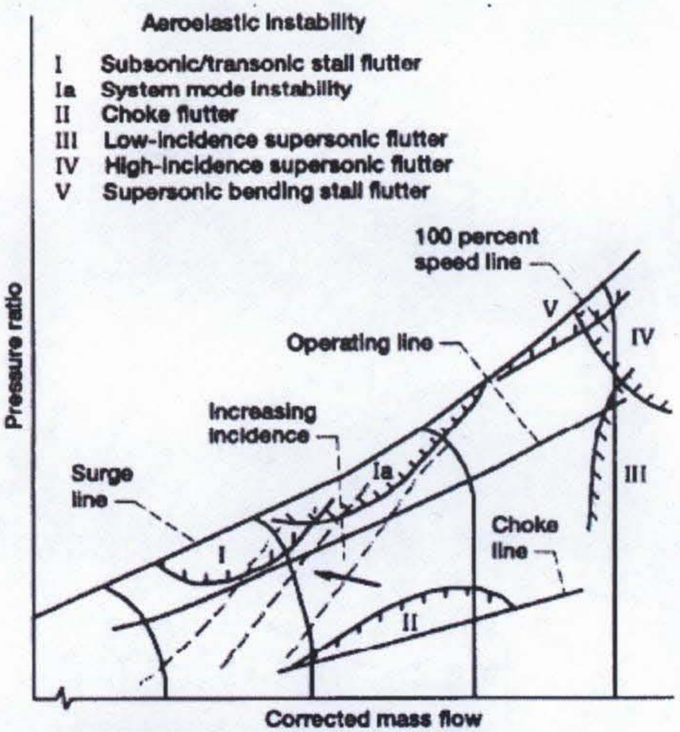


Response levels higher than predicted

"Advanced vibration analysis tools and new strategies developed for robust engine rotor development"
2005 Research and Technology Report – NASA Glenn Research Center
Castanier & Pierre, U. of Michigan – Min, NASA

Flutter

- Flutter
  - Self-excited oscillation
  - Airflow/blade interaction → instability
  - Increasing damping can reduce the risk of flutter

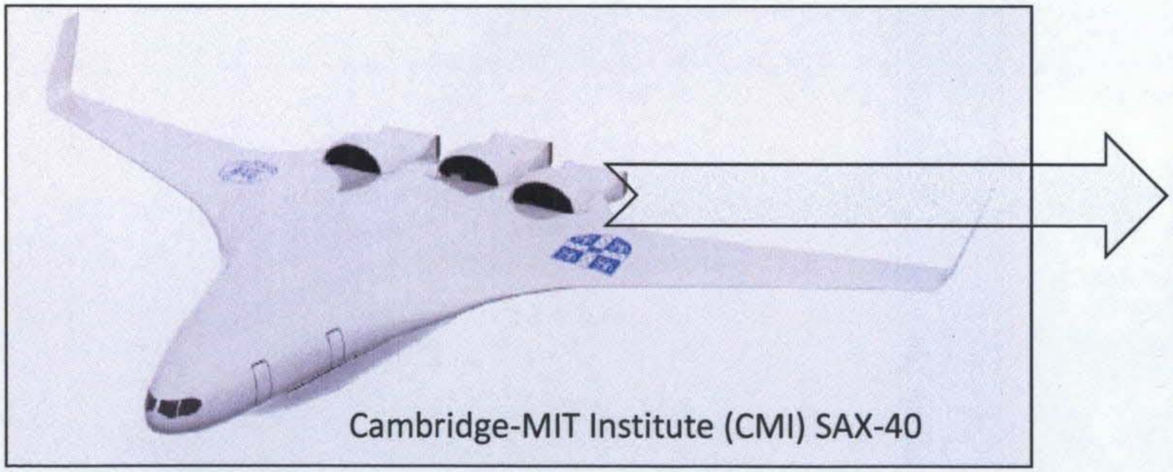


(a) Map showing principal types of flutter and regions of occurrence (ref. 4).

Reddy et. al. 1993 NASA TP-3406
"A review of recent aeroelastic analysis methods for propulsion at NASA Lewis Research Center"

Future Aircraft

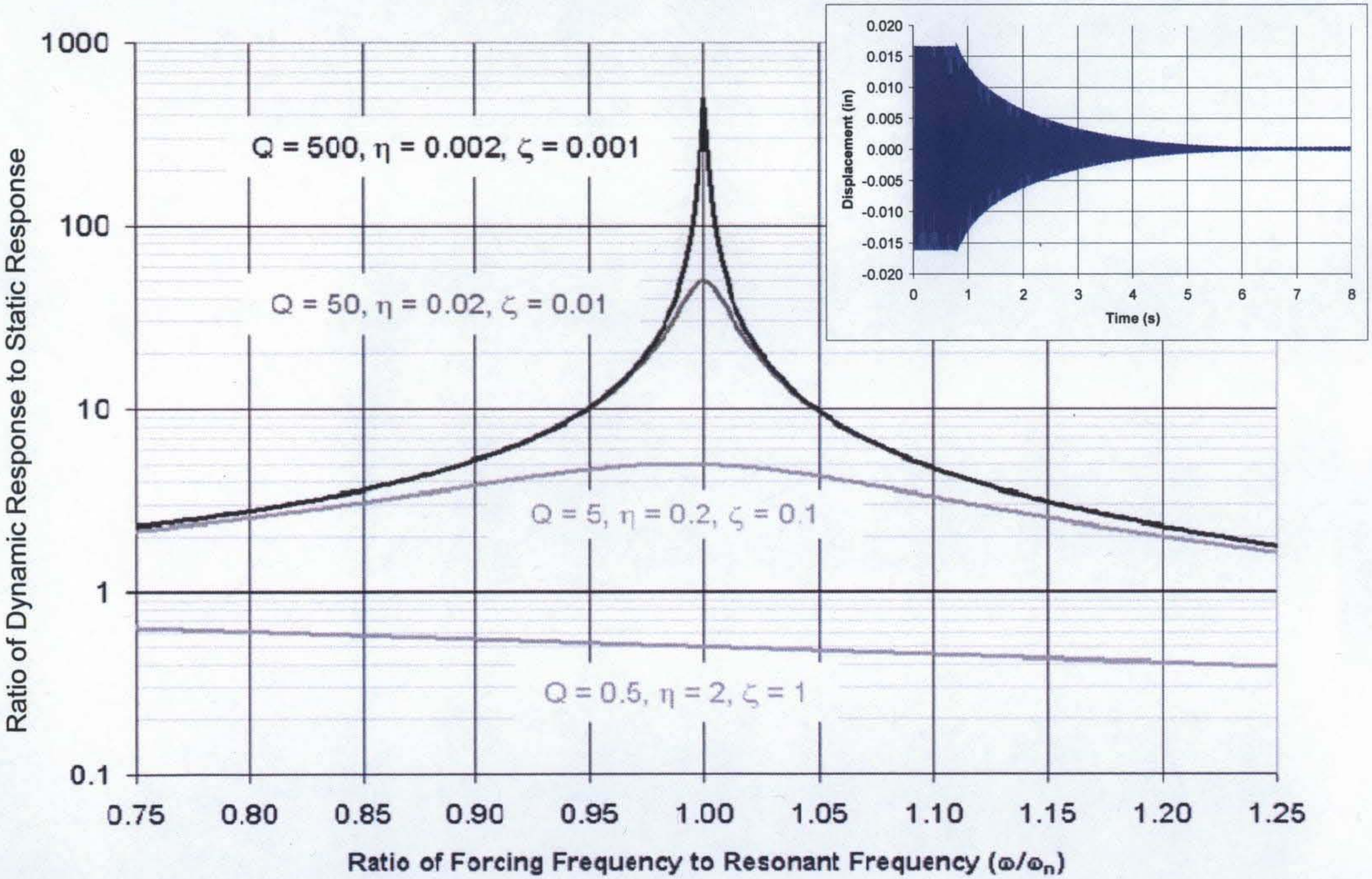
- Embedded engines
  - Benefits:
    - Decreased noise
    - Improved efficiency
    - Possibility of short takeoff and landing
  - Problem: Non-uniform flow into engine – blade excitation



Cambridge-MIT Institute (CMI) SAX-40

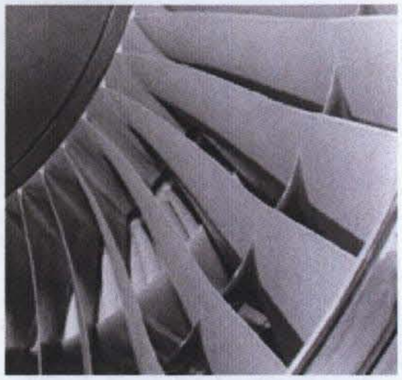
Distorted Flow into Fan

Solution – Damping

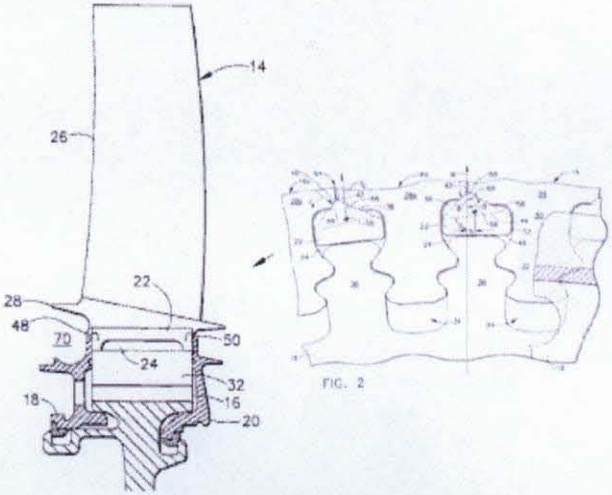


Engine Blade Damping

- Sources of damping*
  - Material damping
    - ~0.02%
    - Very low for metals, higher for composites
  - Aerodynamic damping
    - 0.1% - 1%
  - Structural/mechanical damping
    - Friction at the blade root
    - Friction at shrouds
    - Platform damping
    - Added damping treatments
    - 0.5% - 3%
- Newer blade designs
  - Integrally bladed disks (blisks) – no friction at blade/hub attachment
  - Highly-loaded blades – higher efficiency



Pratt & Whitney
Shrouded Fan Blade

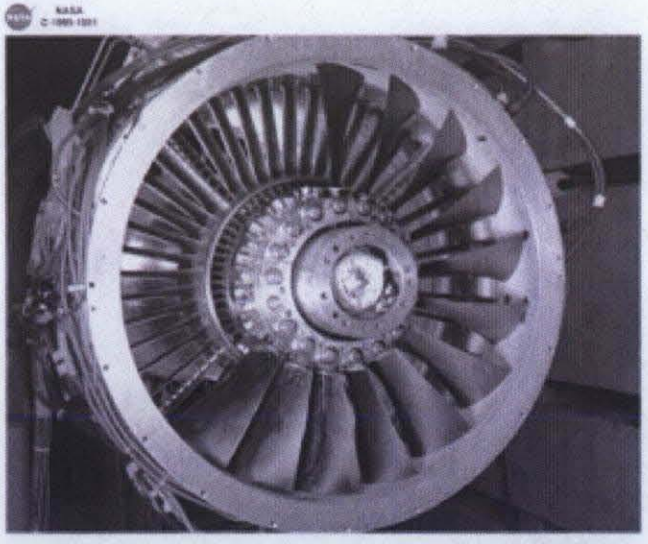


GE Platform Damper
Patent 5,478,207

* Y. El-Aini, R. deLaneuville, A. Stoner, V. Capece, "High Cycle Fatigue of Turbomachinery Components – an Industry Perspective," AIAA-1997-3365.

NASA Damping Research

- **Turbomachinery blade damping research at NASA Glenn**
  - *Impact damping*
  - *Viscoelastic damping of composite blades (with UC San Diego)*
  - *Plasma-sprayed damping coatings*
  - *High-temperature shape memory alloys*
  - *Piezoelectric materials – passive damping and active control*

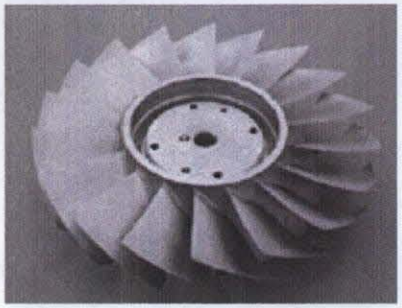


Composite Fan Blades – Tested with Viscoelastic Damping

Aircraft Engine Blade Environment

Typical Target Application – lower-temperature:

- *Titanium alloy fan or cold-side compressor blade*
- *Composite fan blade*

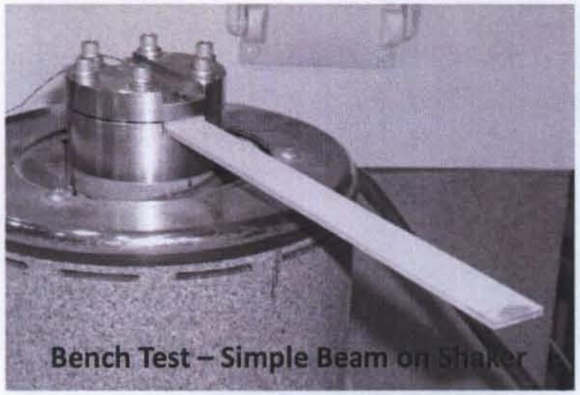


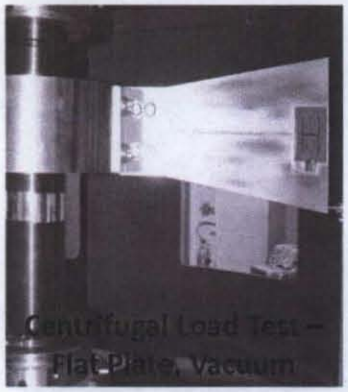
Temperature	*-40 to 300°C*
Vibratory strain amplitude	*up to 10^{-3}*
Mean strain (from centrifugal loading)	*zero to 10^{-3}*
Frequency	*100 to 10,000 Hz*
Typical blade loss factor	*10^{-3} or lower*
Target blade loss factor	*10^{-2}*

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

Analysis and Testing Procedure

- **Analysis** – Simple reduced order models, structural finite element models, aeroelasticity models (fluid/structure interaction)
- **Testing** – Bench testing, testing in simulated engine environments
- **Test Articles** – simple beam, flat plate, twisted plate, blade


Bench Test – Simple Beam on Shaker

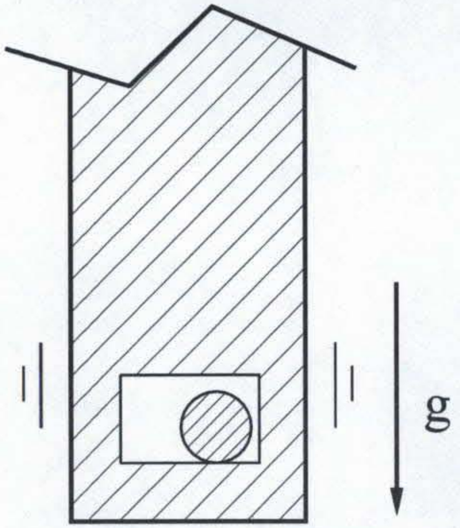

Centrifugal Load Test – Flat Plate, Vacuum


High-temperature Test – Flat Plate


Composite Fan Blade

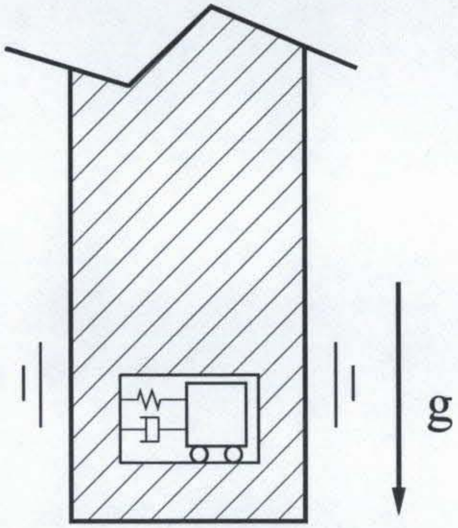

Wind tunnel te

Self-Tuning Impact Damper



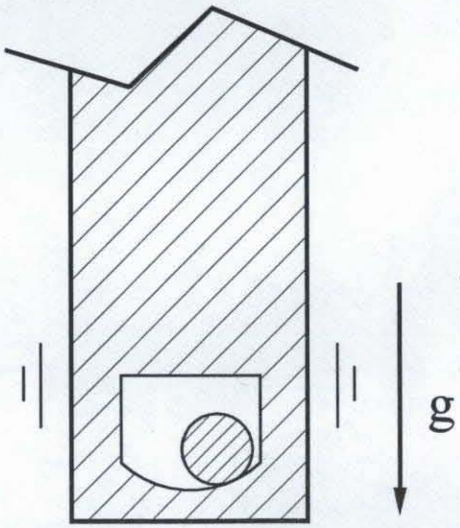
Impact Damper

- Displacement-dependent (nonlinear)
- Immobilized at high-g's



Tuned-Mass Damper

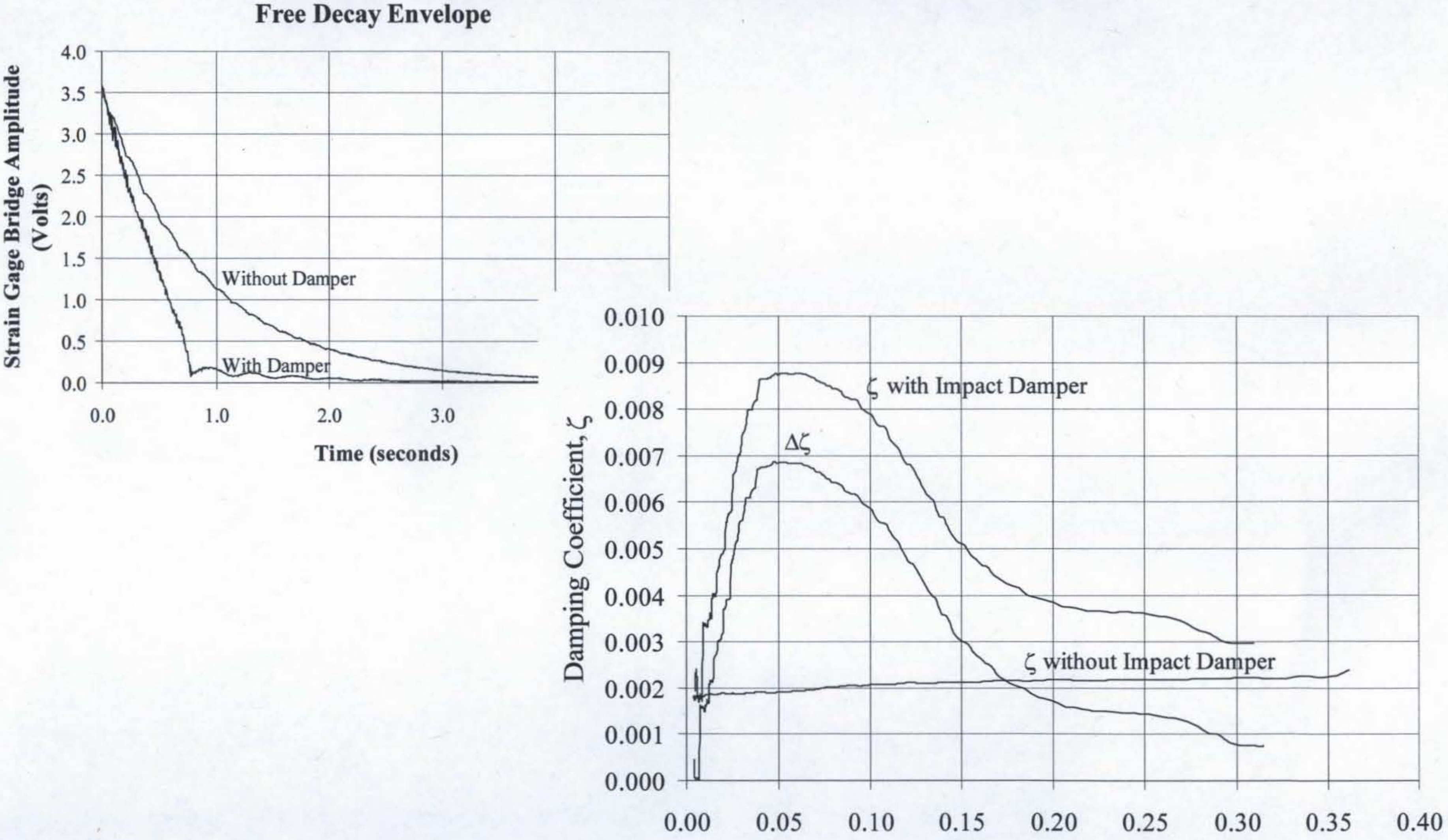
- Frequency-dependent
- Damping at tuning frequency
- Displacements may be too large for blade cavity



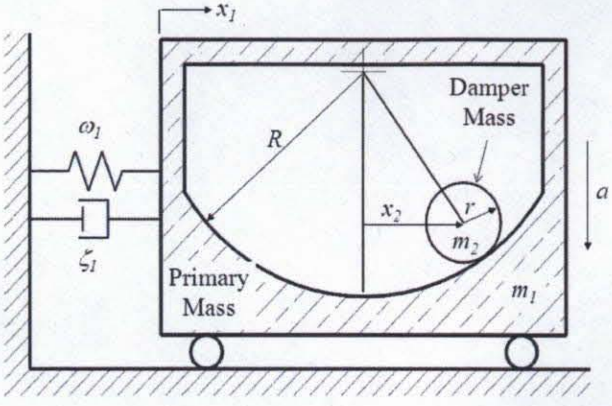
Tuned Impact Damper

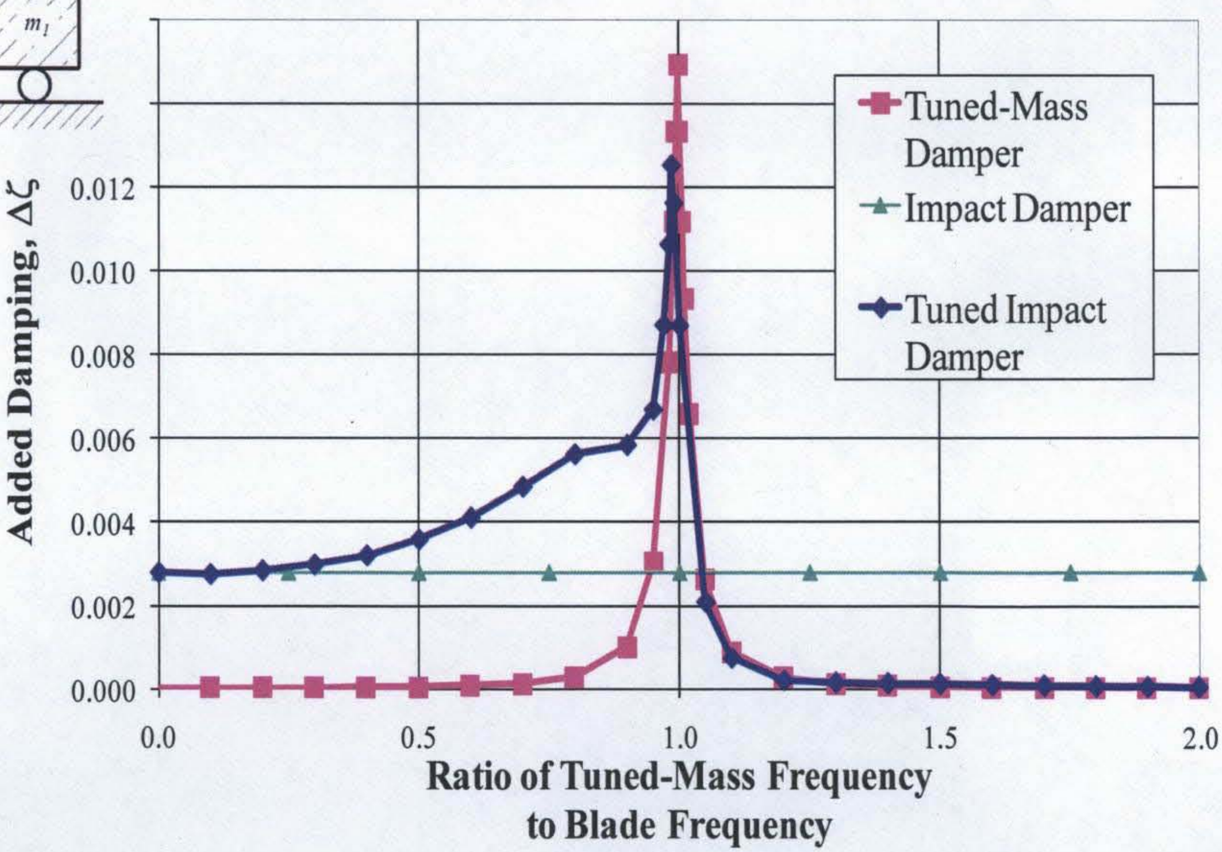
- Frequency- and displacement-dependent (nonlinear)
- Performs better at high-g's

Self-Tuning Impact Damper

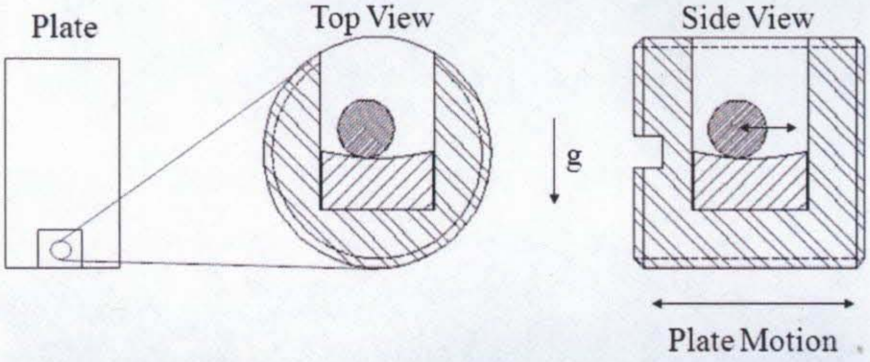


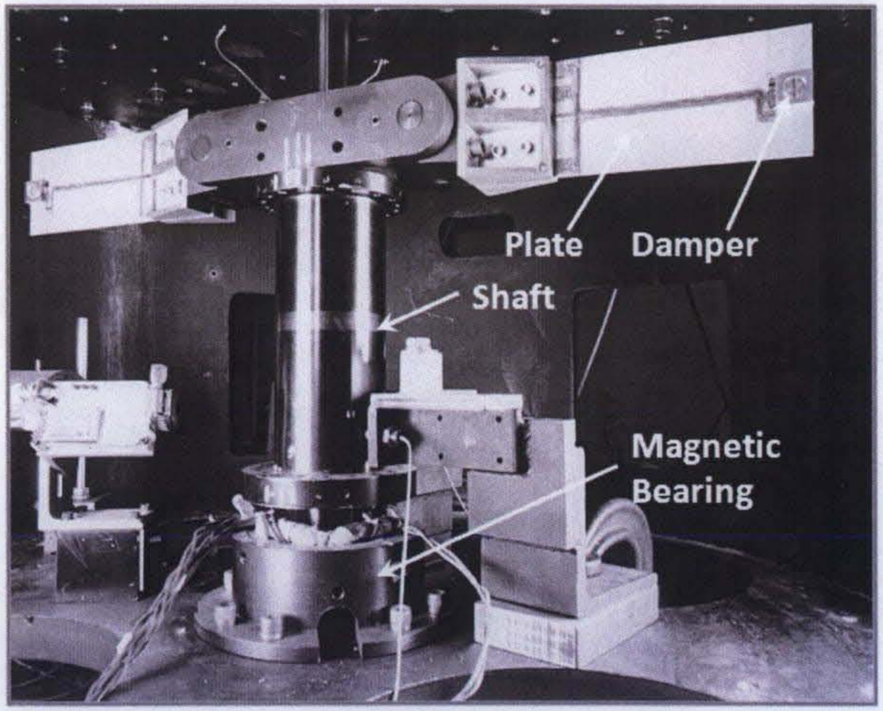
Self-Tuning Impact Damper

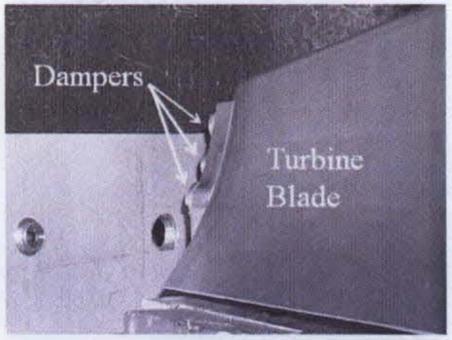



Tuned-Mass Damper vs Tuned Impact Damper

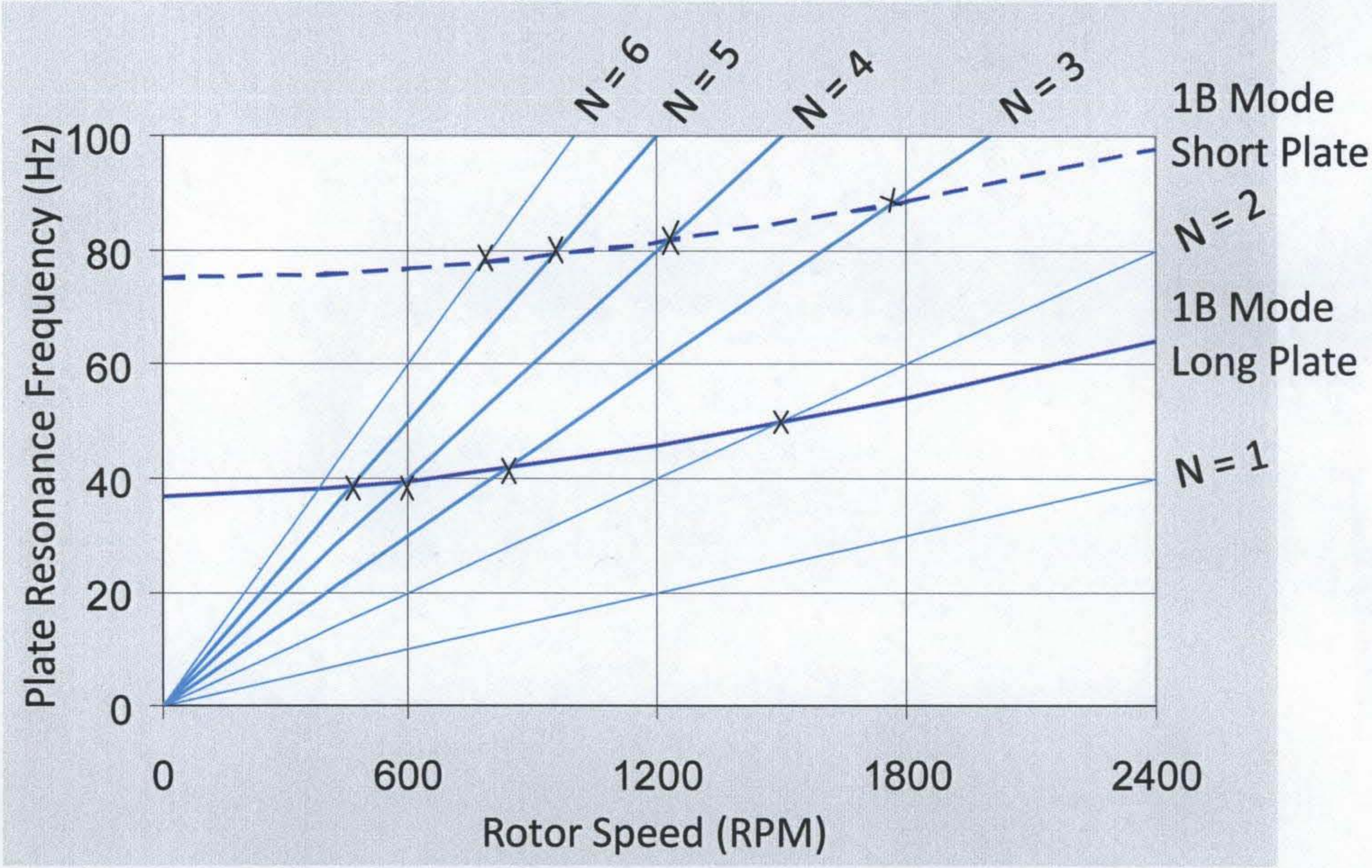
Self-Tuning Impact Damper



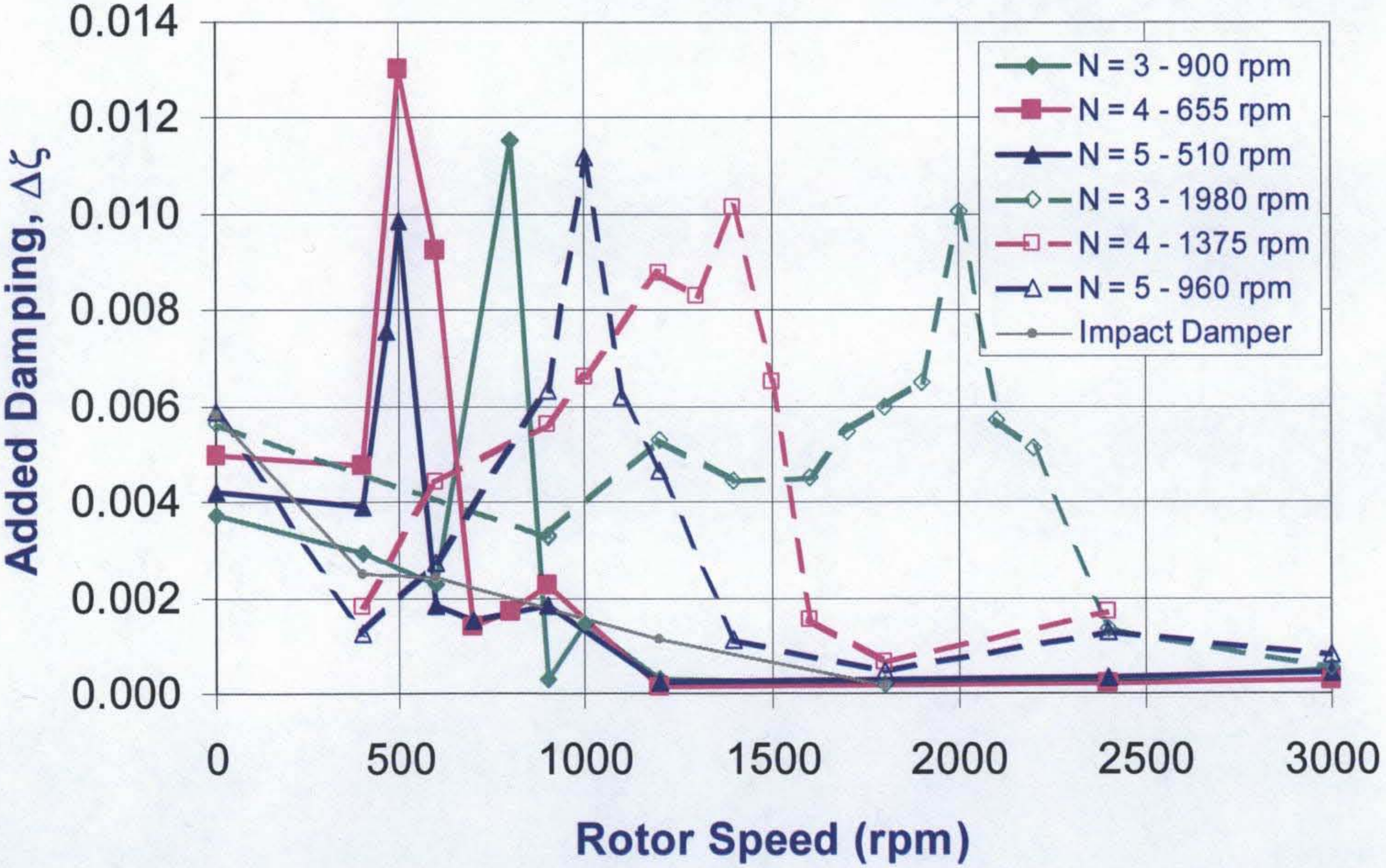




Self-Tuning Impact Damper

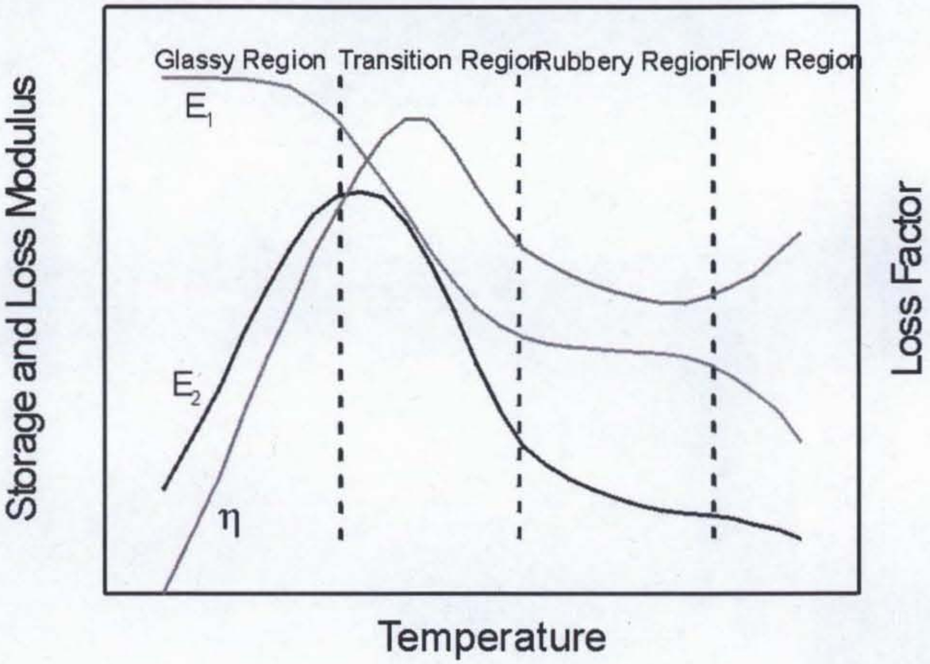


Self-Tuning Impact Damper



Viscoelastic Damping

- Complex Modulus
  - $E = E_1 + i\,E_2 = E_1(1 + i\,\eta)$
  - E_1 – Storage Modulus
  - E_2 – Loss Modulus
  - η – Loss Factor
  - ***Properties dependent on frequency and temperature***
- Material Behavior
  - Glassy region – polymer chains highly ordered – higher stiffness
  - Transition region – high damping
  - Rubbery region – lower stiffness, lower damping
- Energy Dissipation
  - Through ***shear stress***
  - Constrained layer treatment

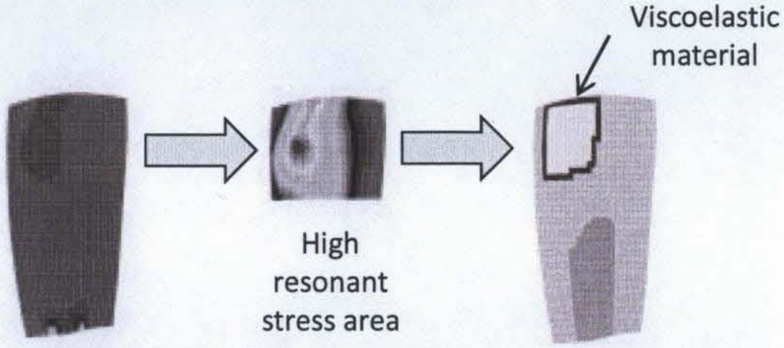


Roush-Anatrol

Viscoelastic Damping

Composite Fan Blade

Kosmatka, Appuhn, Mehmed
AIAA Paper 2002-1511
"Design and Testing of Integrally Damped First-Stage Composite Fan Blades"



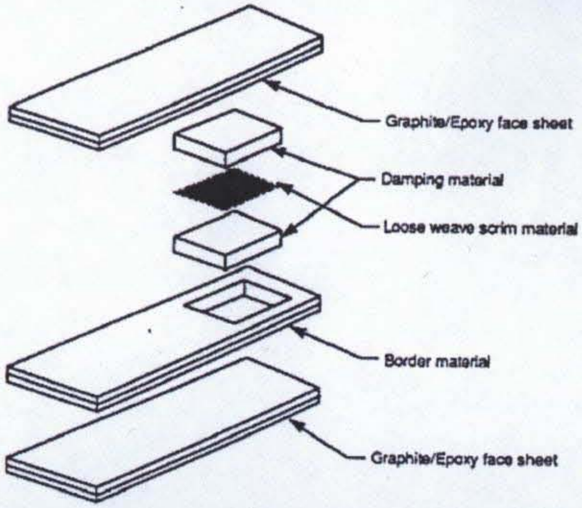


Fig. 3 Blade components

Kosmatka, Lapid, Mehmed – AIAA Paper 96-1598
"Passive vibration control of advanced composite turbo-fan blades using integral damping materials"

- Collaboration between NASA GRC and John Kosmatka – UC San Diego
  - Place viscoelastic material within pocket between graphite/epoxy plies
  - Locate visco in area of high modal shear stress
  - ➢ Successful demonstration in dynamic spin testing at NASA Glenn

Viscoelastic Damping

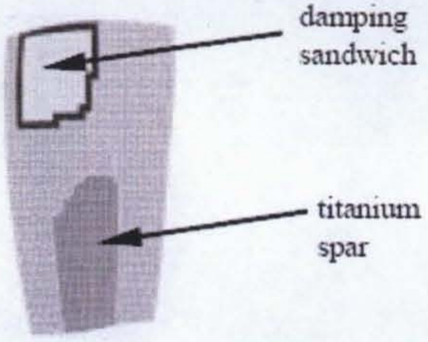


Fig. 6 Patch definition for optimum damping of first chord-wise mode (1581 Hz).

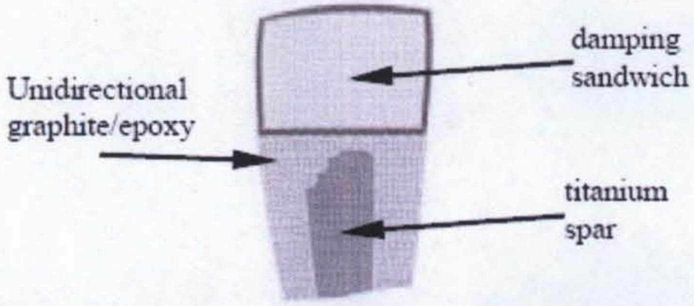


Fig. 5 Patch definition for maximum damping of first chord-wise mode (1581 Hz).

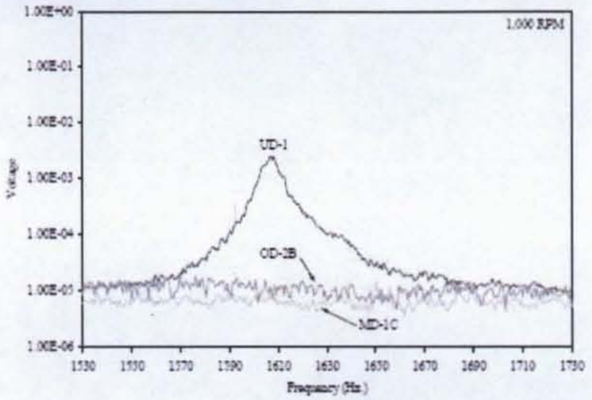


Fig 20 Power Spectrum Comparison for the 1st Chordwise Mode at 1.000 RPM

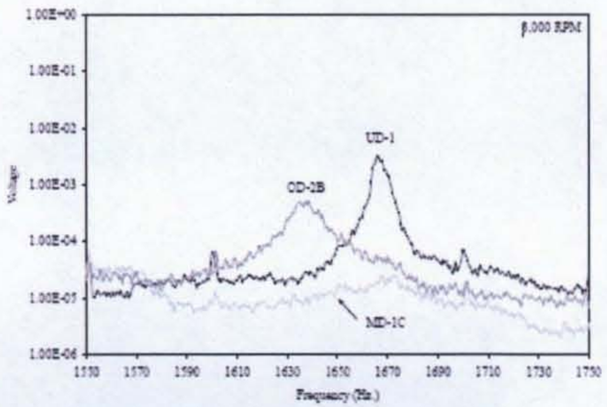


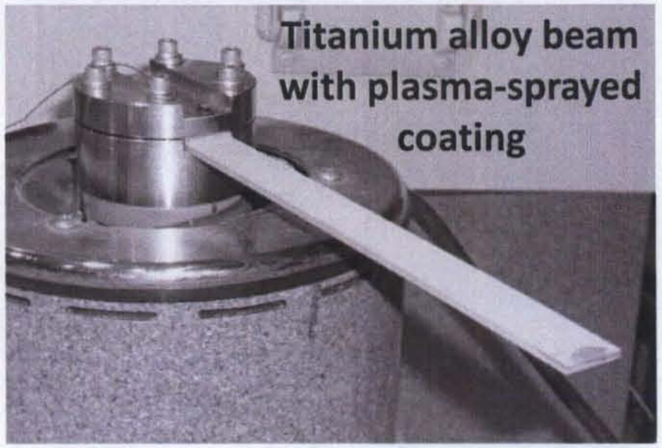
Fig 21 Power Spectrum Comparison for the 1st Chordwise Mode at 3.000 RPM

Kosmatka, Appuhn, Mehmed - AIAA Paper 2002-1511
"Design and Testing of Integrally Damped First-Stage
Composite Fan Blades"

Damping Surface Treatment

Examples:

- Viscoelastic surface treatment
- Plasma-sprayed damping coating
- Surface-mounted high-damping shape memory alloy
- Surface-mounted shunted piezoelectric patch


Titanium alloy beam with plasma-sprayed coating

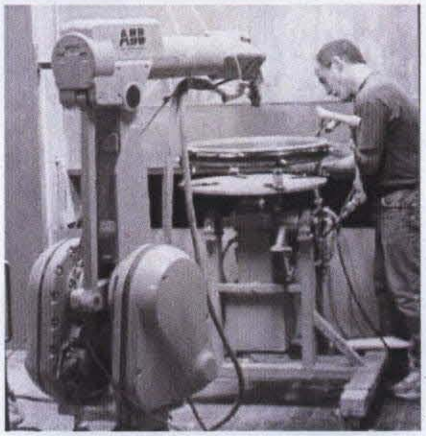
Oberst beam – thin layer of damping material on beam surface

- Very thin layer:

$$\eta_{beam+damping} \approx 3\eta_{damping}\left(\frac{E_{damping}}{E_{beam}}\right)\left(\frac{t_{damping}}{t_{beam}}\right)$$

Plasma-Sprayed Damping Coatings

- Typical coatings currently in use
  - Thermal-barrier coating
    - Allow higher-temperature airflow while insulating metallic blades
  - Environmental-barrier coating
    - Erosion-resistance, durability
  - Added benefit → damping
- Damping mechanism
  - Low temperature (compressor application) – friction between "splats" of coating material – strain level dependent
  - High temperature (turbine application) – elevated damping corresponds with decrease in Young's modulus of the coating – temperature-dependent

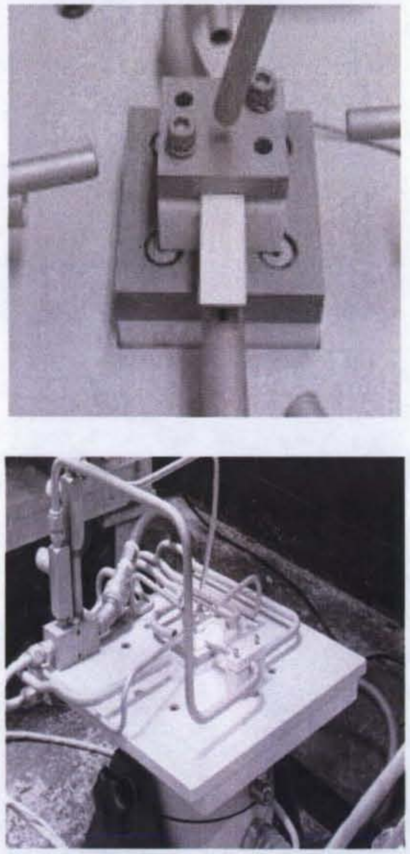


Plasma Spray Torch

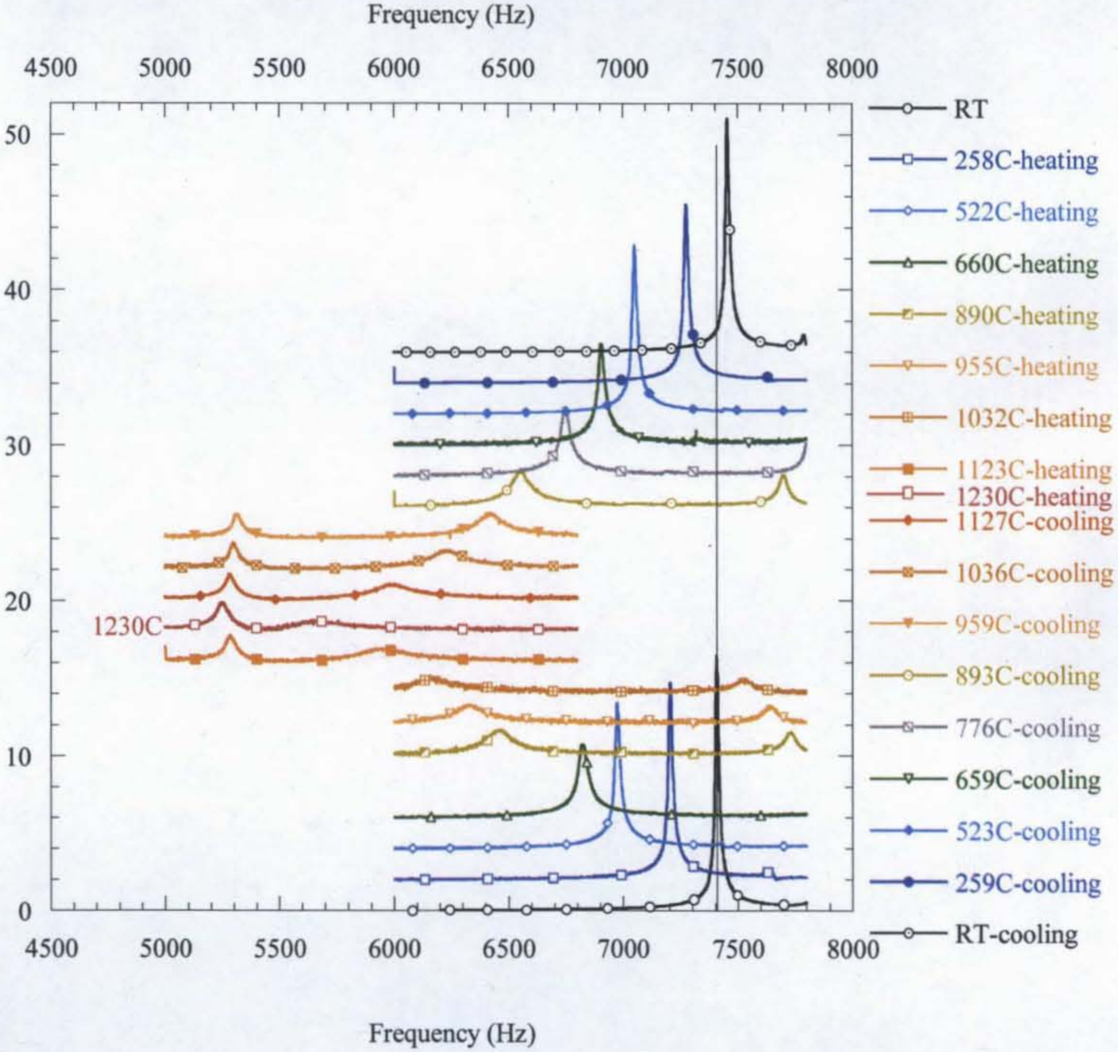
Plasma-Sprayed Coating used for Damping Test

Plasma-Sprayed Damping Coatings

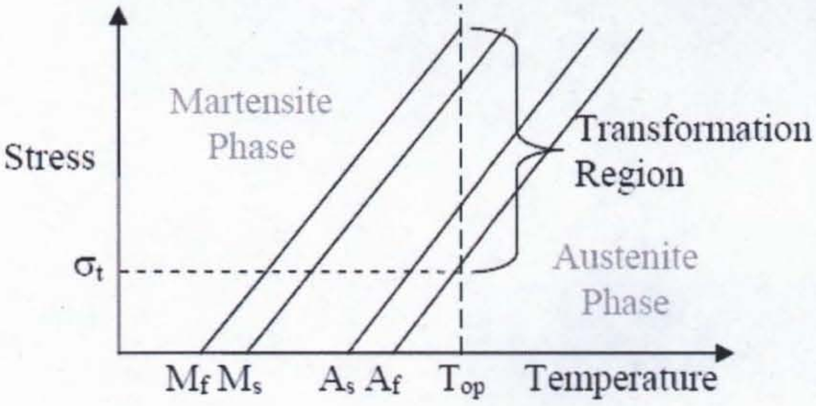
High-temp application

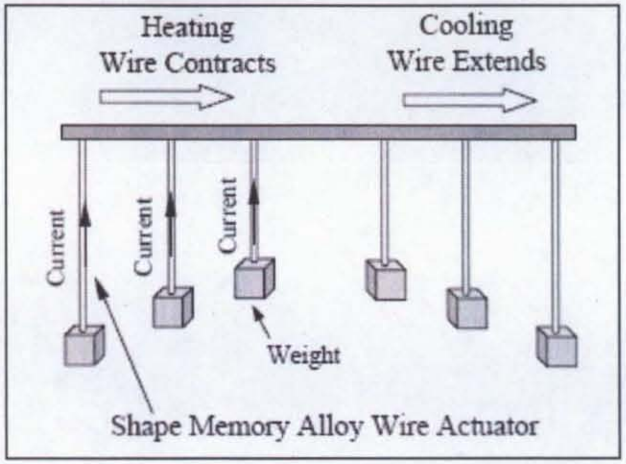


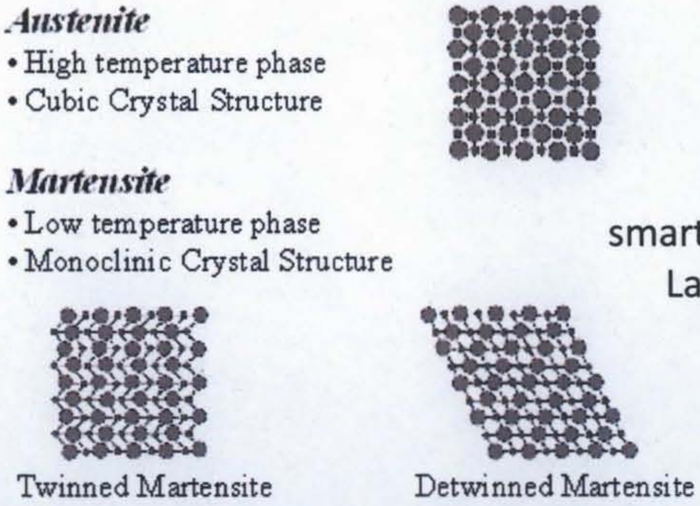
Zhu, Miller, Duffy, Ghosh – 2009
"High Temperature Damping Behavior of Plasma-Sprayed Thermal Barrier and Protective Coatings"
The 33rd International Conference on Advanced Ceramics & Composites



Shape Memory Alloys







Austenite
- High temperature phase
- Cubic Crystal Structure

Martensite
- Low temperature phase
- Monoclinic Crystal Structure

Figure 1. Different phases of an SMA.

smart.tamu.edu
Lagoudas

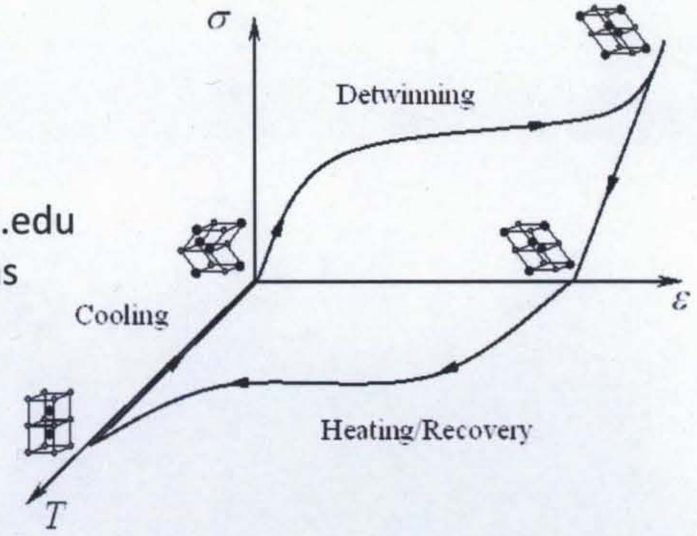
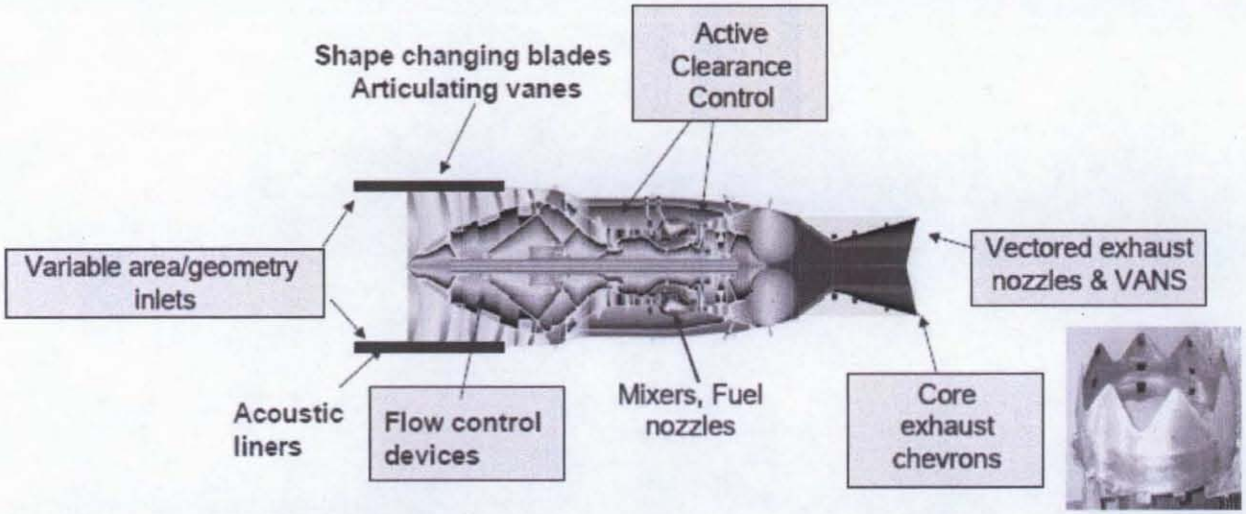


Figure 3. Schematic of a stress-strain-temperature curve showing the shape memory effect.

High-Temperature Shape Memory Alloys

High-Temperature Shape Memory Alloys are an enabling technology to a host of "smart" structures in jet engines



Shape changing blades
Articulating vanes

Active Clearance Control

Variable area/geometry inlets

Vectored exhaust nozzles & VANS

Acoustic liners

Flow control devices

Mixers, Fuel nozzles

Core exhaust chevrons

Advantages of HTSMA

- High force per volume/weight - compact, lightweight
- Solid State - eliminates hydraulics, pneumatics, mechanical systems
  simple, frictionless, quiet, maintenance free
- Passive control - eliminates sensors, electronics
- Can be actively controlled for high-force, precision movements

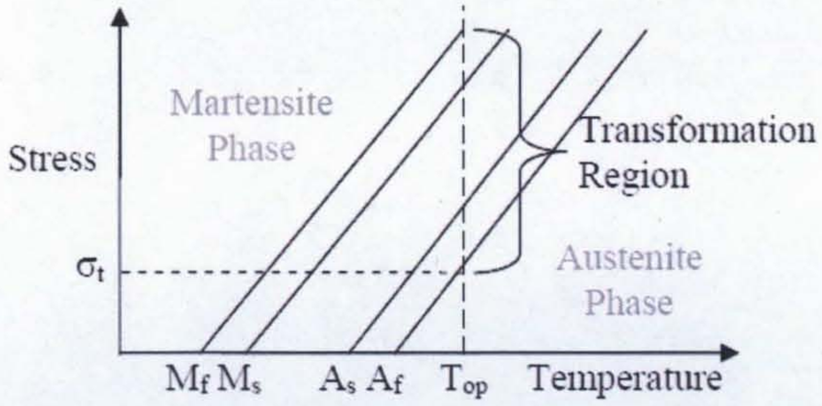
"Characterization of a New Phase and its Effect on the Work Characteristics of a Near-Stoichiometric Ni30 Pt20 Ti50 (at.%) High-Temperature Shape Memory Alloy (HTSMA)", Garg et. al., Presentation at The International Conference on Shape Memory and Superelastic Technologies (SMST) 2008, 21-25 Sep. 2008; Stresa; Italy

High-Temperature Shape Memory Alloys

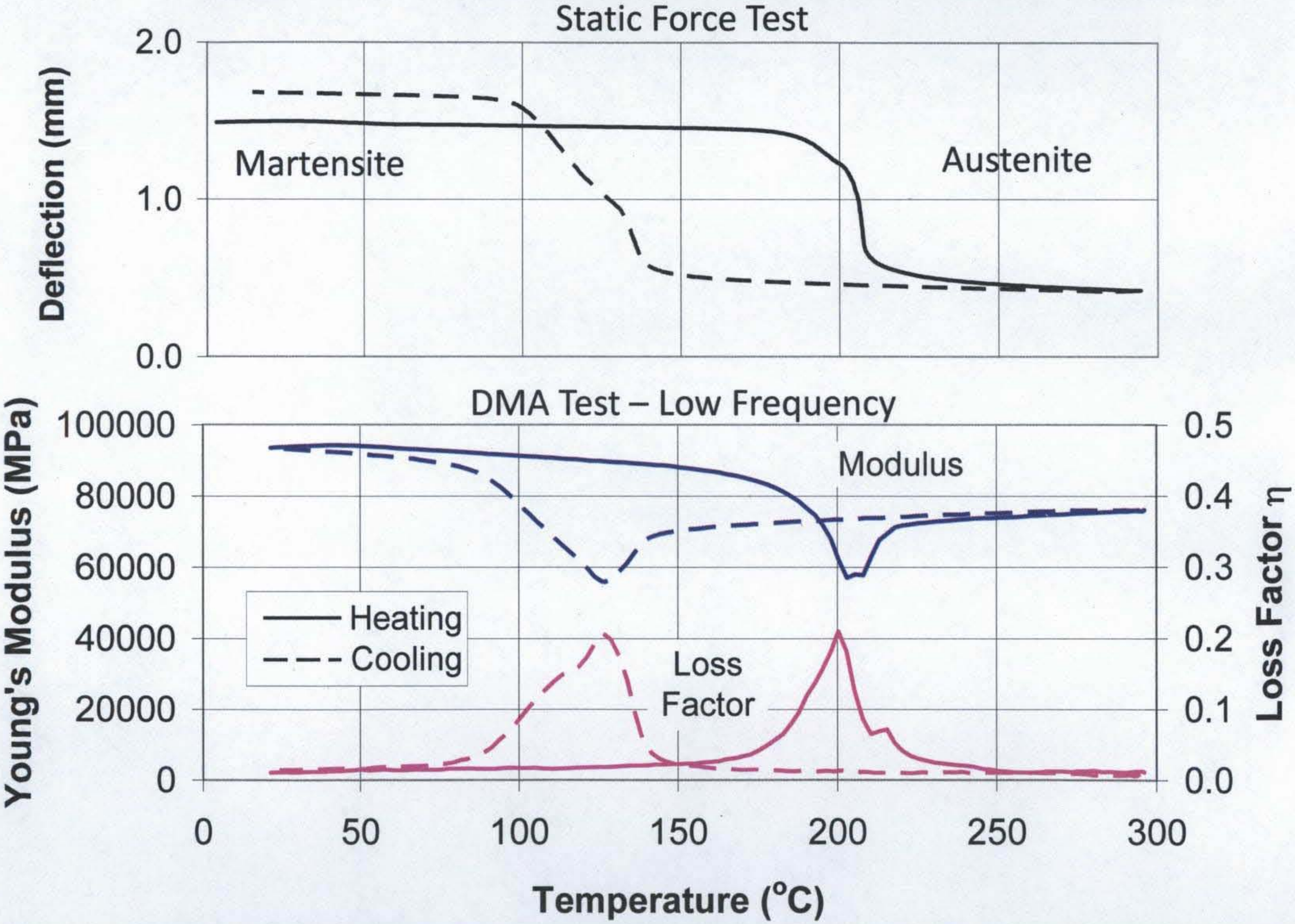
- HTSMAs
  - High temperature and force capability
  - Low frequency applications
- Potential engine applications
  - **Surge control rod for a centrifugal compressor – avoid instability**
    - "Development of a HTSMA-Actuated Surge Control Rod for High-Temperature Turbomachinery Applications" Padula et. al., 15th AIAA/ASME/AHS Adaptive Structures Conference; 23-26 Apr. 2007
  - **Supersonic inlet compression ramp – improve engine efficiency**
    - "Development and Test of an HTSMA Supersonic Inlet Ramp Actuator (Future of SMA)" Quackenbush et. al., Proceedings of the 15th SPIE Smart Structures/NDE Annual International Symposium, vol. 6930, 2008, paper 6930–25.
  - **Active blade tip clearance control – improve engine efficiency**
    - "Progress on Shape Memory Alloy Actuator Development for Active Clearance Control" DeCastro, Melcher, and Noebe, NASA-CP-2006-214383
  - **Adaptive exhaust chevrons – noise reduction**
    - "Benchtop Demonstration of an Adaptive Chevron Completed Using a New High-Temperature Shape-Memory Alloy" Noebe and Padula, NASA GRC 2005 Research and Technology Report

Shape Memory Alloy Damping

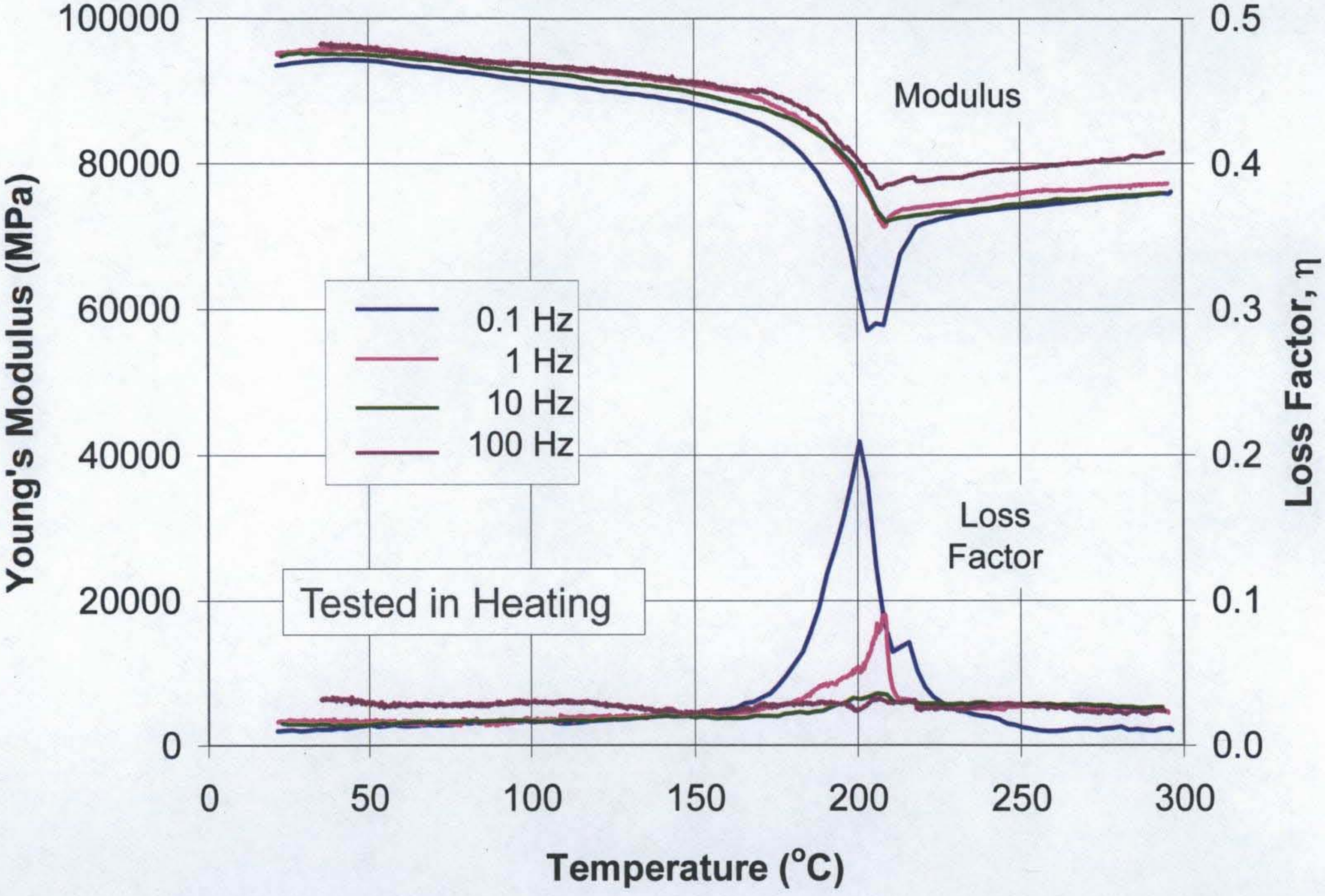
- NiTiHf samples tested for modulus and damping properties
  - Looking for damping in phase-transition region
  - Purely passive damping properties
  - Damping is temperature-dependent
  - Tested using Dynamic Mechanical Analysis (DMA) at 0-300°C and at 0.1-200 Hz



Shape Memory Alloy Damping



Shape Memory Alloy Damping



Piezoelectric Materials

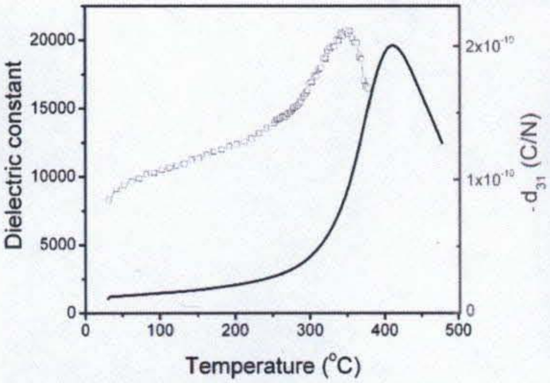
- High-temperature piezoelectric materials
  - Off-the-shelf high-temperature material – Type-II PZT – T_c = 350°C
  - NASA GRC-developed materials – T_c = 430°C
- Potential engine applications
  - **Active combustion control**
    - Mitigate thermo-acoustic instabilities and/or gas flow control to improve efficiency
  - **Synthetic jets for active flow control**
  - **Energy harvesting**

- "High-Temperature Piezoelectric Material Developed" Sayir and Sehirlioglu, NASA GRC 2007 Research and Technology Report
- "Doping of BiScO3 -PbTiO3 Ceramics for Enhanced Properties" Sehirlioglu, Sayir, and Dynys, Materials Science and Technology Meeting ASM/ACERS; 5-9 Oct. 2008; Pittsburgh, PA

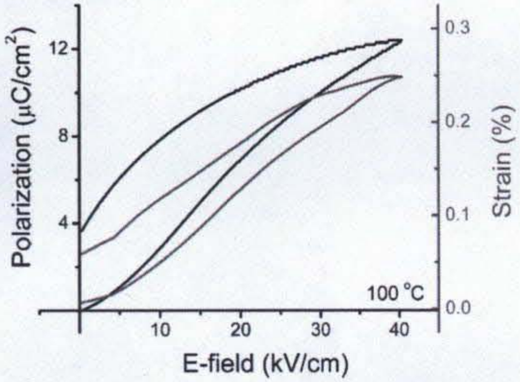
High-Temperature Piezoelectric Material

- **Objective:** Piezoelectric material development for damping system for high temperature turbomachinery blade applications.

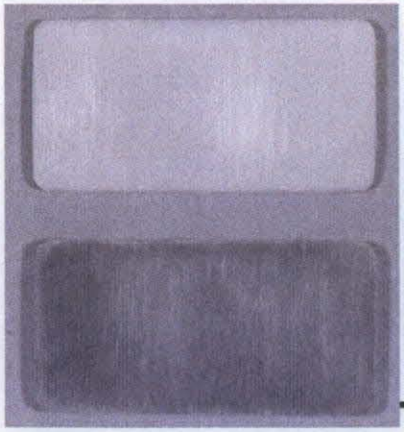
Slip cast patches of GRC-63L composition developed and processed at NASA Glenn Ceramics Branch



✓ Higher operating temperature
✓Higher piezoelectric coefficient
✓ Higher Coercive field
X Lower energy conversion efficiency



Material



Device

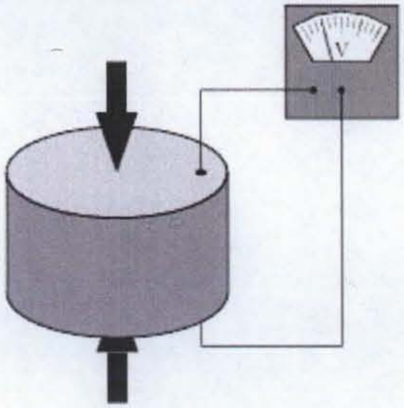
Comparison to the state of the art material

PZT Type II by Piezo Kinetics, Inc	Temperature (°C)		Ferroelectric and Piezoelectric (100 °C)		Electromechanical coupling coefficients	
	Curie	Depoling	E_C (kV/cm)	d_{33} (pC/N)	k_p	k_{31}
GRC-63L	**430**	352	23	625	0.43	0.22
PZT-II	315	280	12	585	0.52	0.28

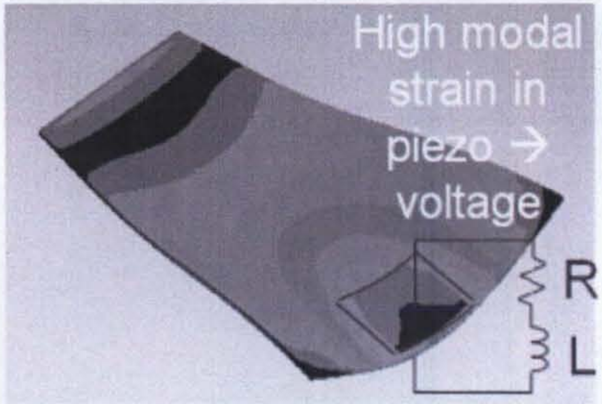
- Points of Contact: Ceramics Branch/ Dr. Alp Sehirlioglu, 216-433-6159, Dr. Ali Sayir, 216-433-6254, Dr. Fred Dynys, 216-433-2404

Piezoelectric Damping

- **Concept:**
  - Piezoelectric material under load produces an electric field
  - Place piezoelectric material in an area of high modal stress in/on the blade
  - **Passive damping technique** – place a shunt circuit across the piezo material to dissipate energy
  - **Active vibration control** – use piezo materials as actuators and sensors with a control system to actively reduce vibration level

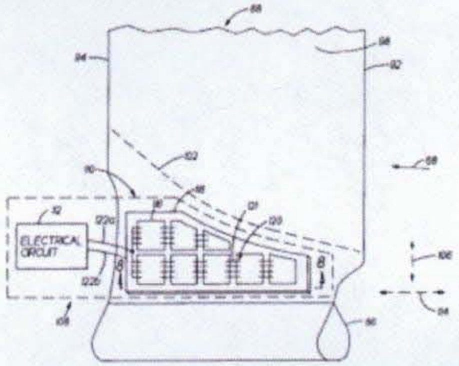


www.wikipedia.org



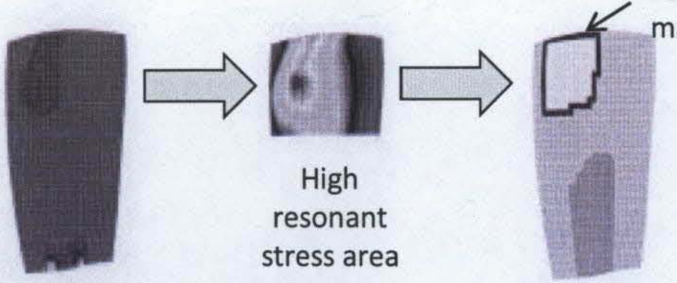
Piezoelectric Damping

- Metal blades
  - Require machining to place piezoelectric material and circuits
  - Possible placement below blade platform
- Composite blades
  - Embed piezoelectric material between plies
  - Weave piezoelectric fibers into the plies – 15-250 micron diameters



Hilbert et. al. Patent 6,299,410

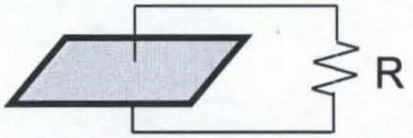
Fibers – Advanced Cerametrics Inc.



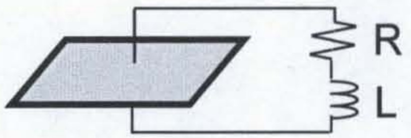
Kosmatka et.al.

Piezoelectric Damping

- **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***



Piezoelectric Damping

Air-Core Inductor

Optimal inductor for 700-800Hz

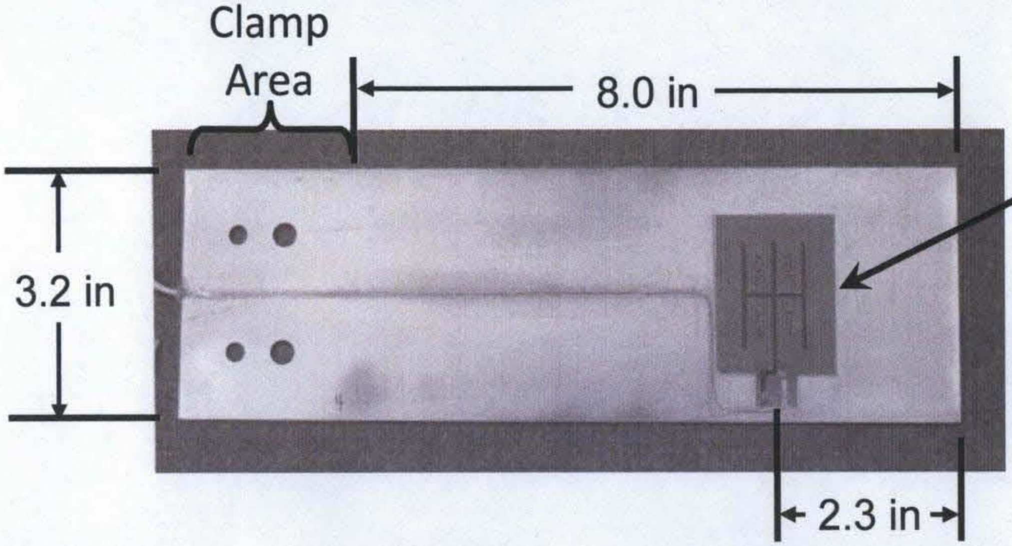
0.69 H wound inductor:

- *34-gauge wire*
- *0.75-inch inner diameter*
- *2.6-inch outer diameter*
- *0.30-inch length*
- *510 W*
- ***Too large for blade application***

Inductor size required for higher frequencies:

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

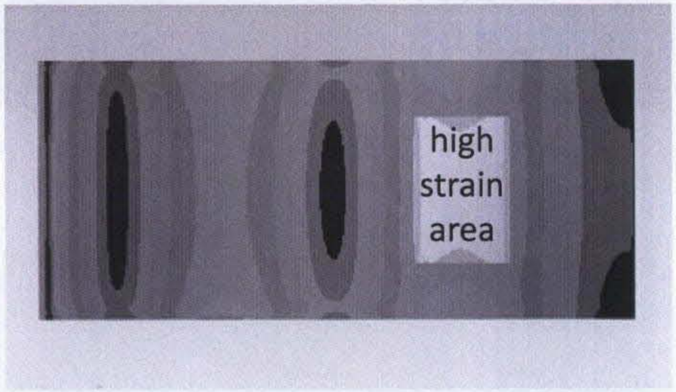
Piezoelectric Damping



Midé qp10w
PZT-5A patch
1.31" x 1.81"
x 0.010" thick

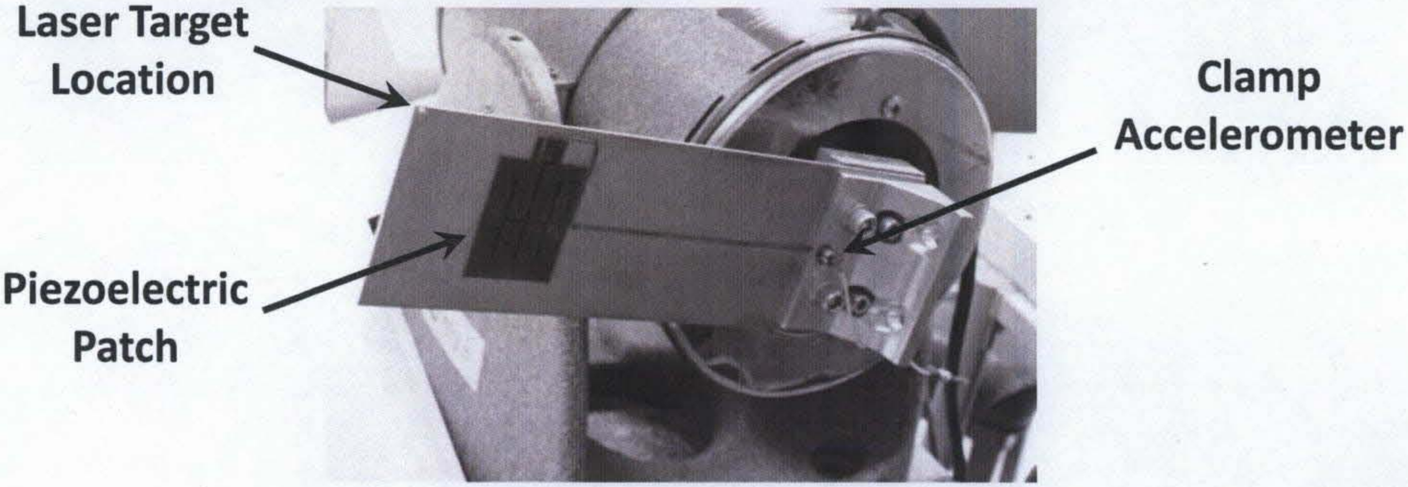
Ti 6Al-4V
0.078" thick plate

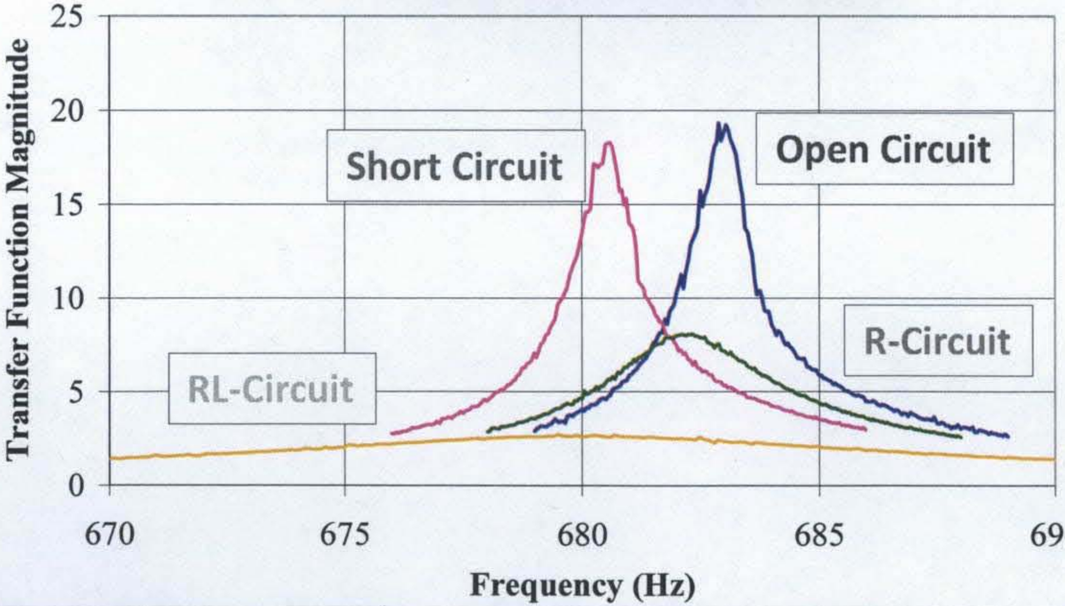
3B Mode – Modal Deformation



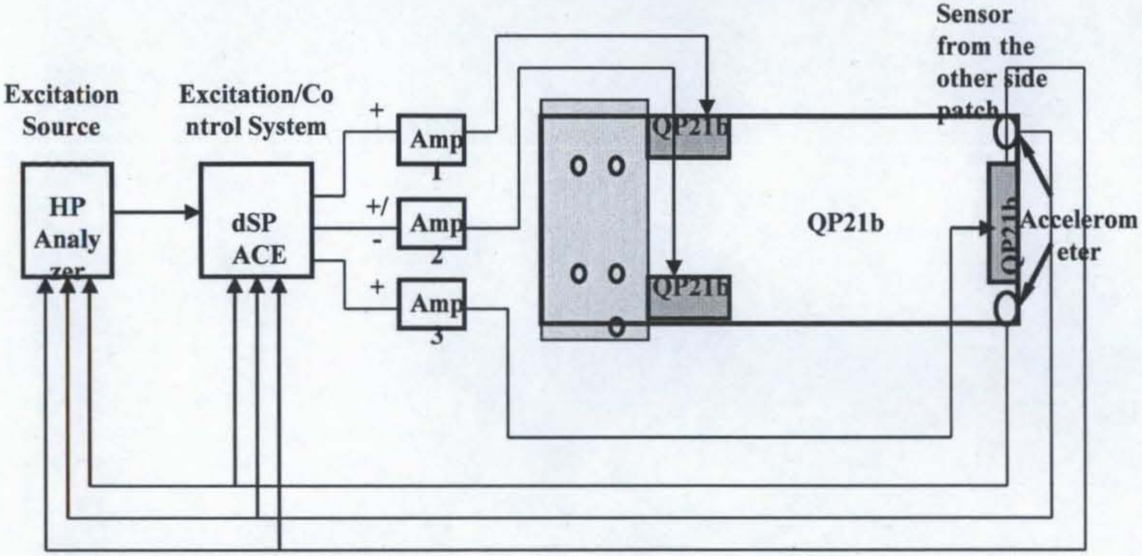
3B Mode – von Mises Modal Strain

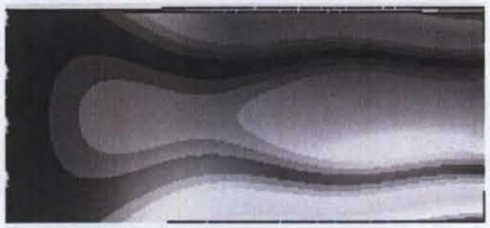
Piezoelectric Damping





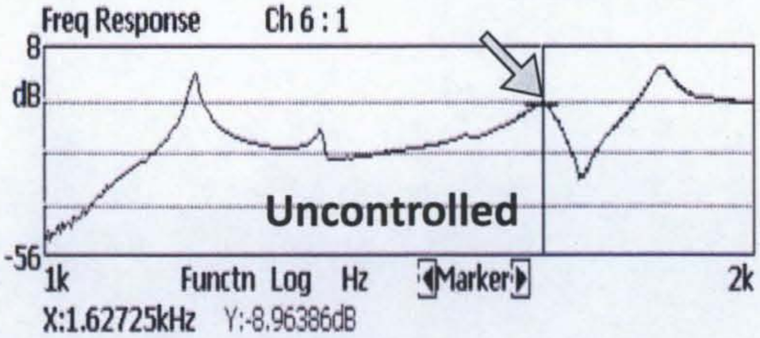
Active Control with Piezoelectrics

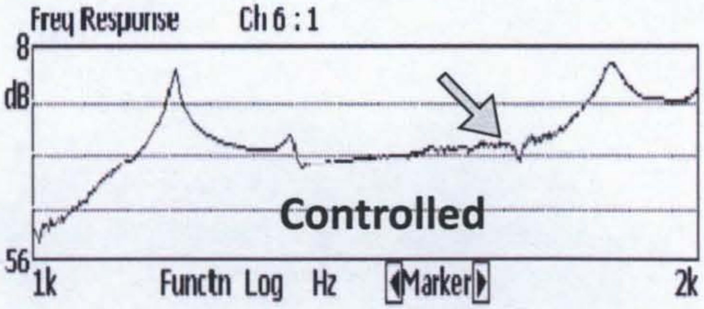




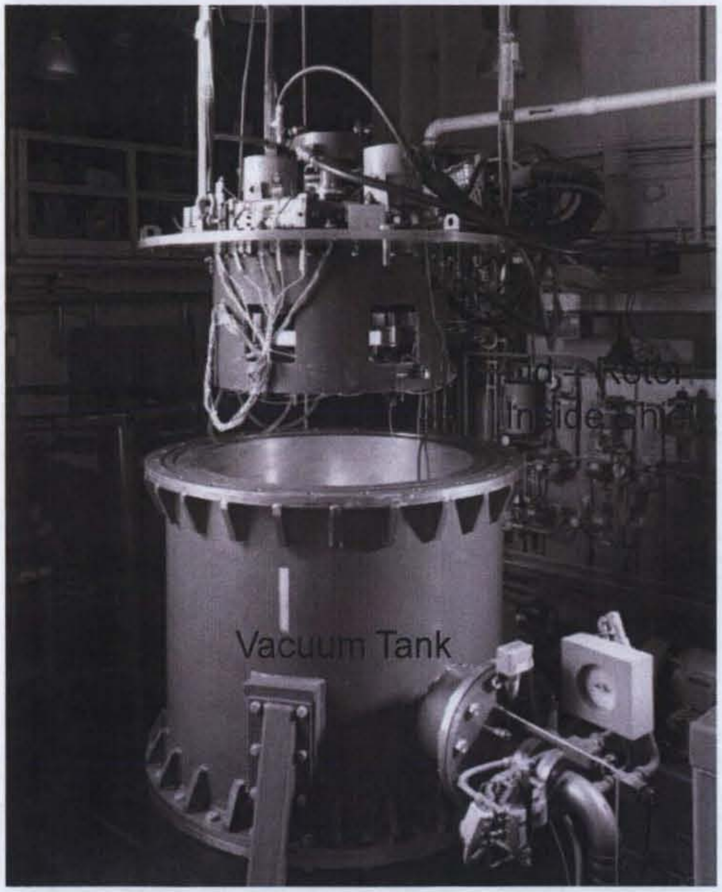
2-Stripe Mode Shape

Ben Choi – NASA GRC

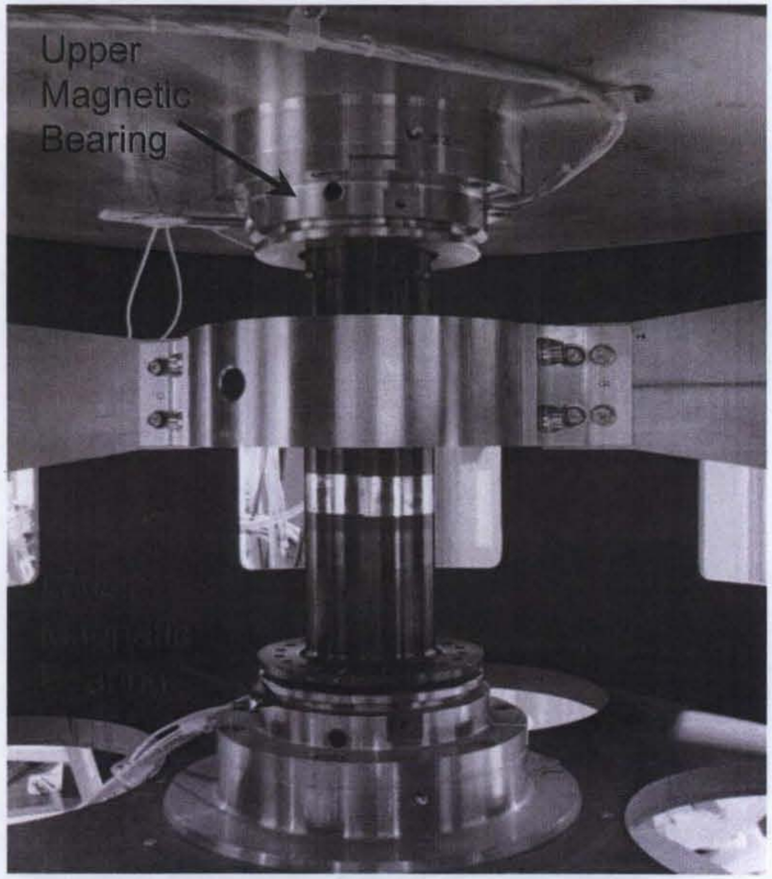




Piezoelectric Damping



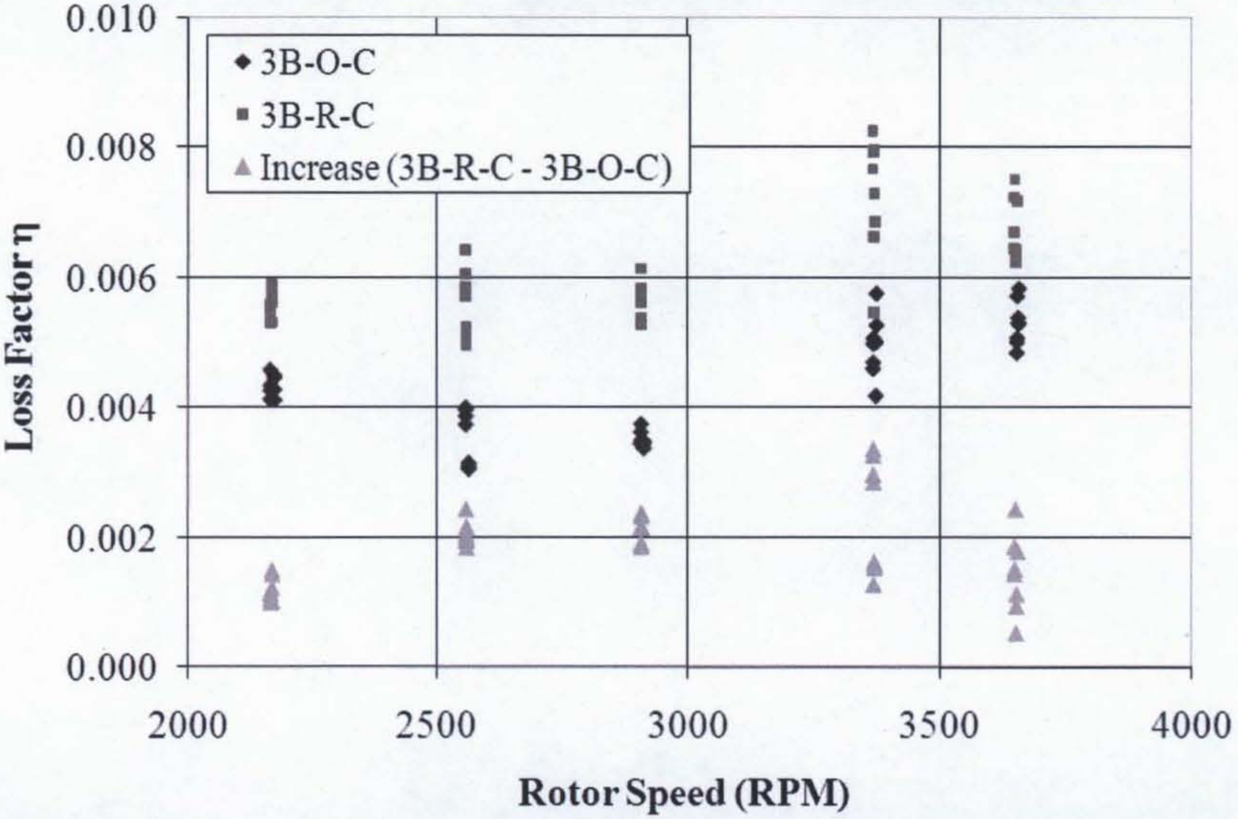
Dynamic Spin Facility



Rotor with Tapered Test Plates

Piezoelectric Damping

R-Circuit vs. Open Circuit Damping in Spin Rig



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

Current Research Plans

- Plasma-sprayed damping coatings
  - Measure modulus and damping of individual coatings
- HTSMA damping
  - SMA materials with less temperature hysteresis
  - SMA materials with phase transitions less frequency-dependent
- Piezoelectric damping
  - Application to metal blades
    - Continue spin testing of passive damping with tuned RL-circuit
    - Begin spin testing of actively controlled plates
  - Application to composite fan blades
    - Embedding piezoelectric materials/patches within composite blades
  - Trade studies
    - Determine potential weight savings for entire engine