Overview of NASA GRC Research on Damping of Jet Engine Blades

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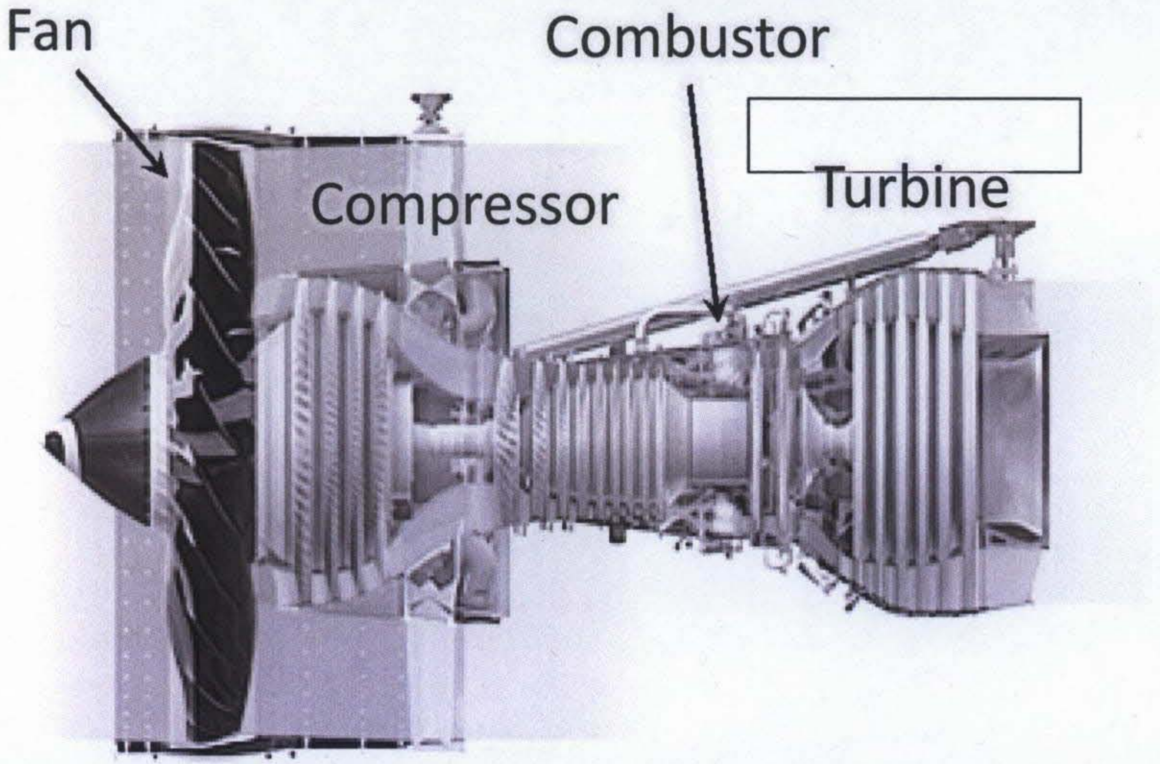
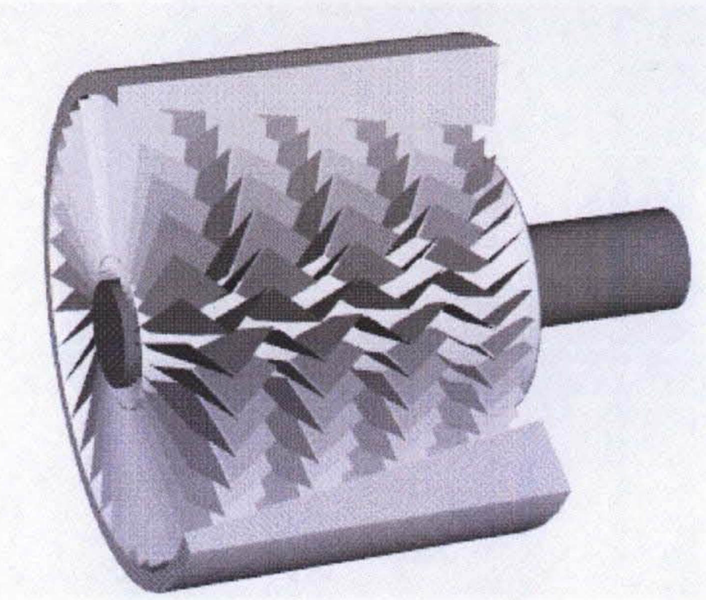
Aircraft Engine



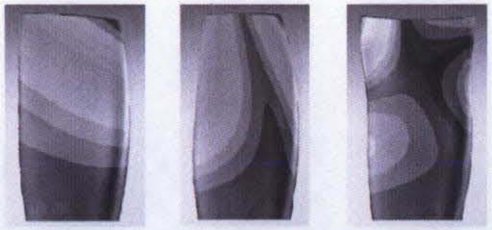
GE90 Turbofan Engine

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

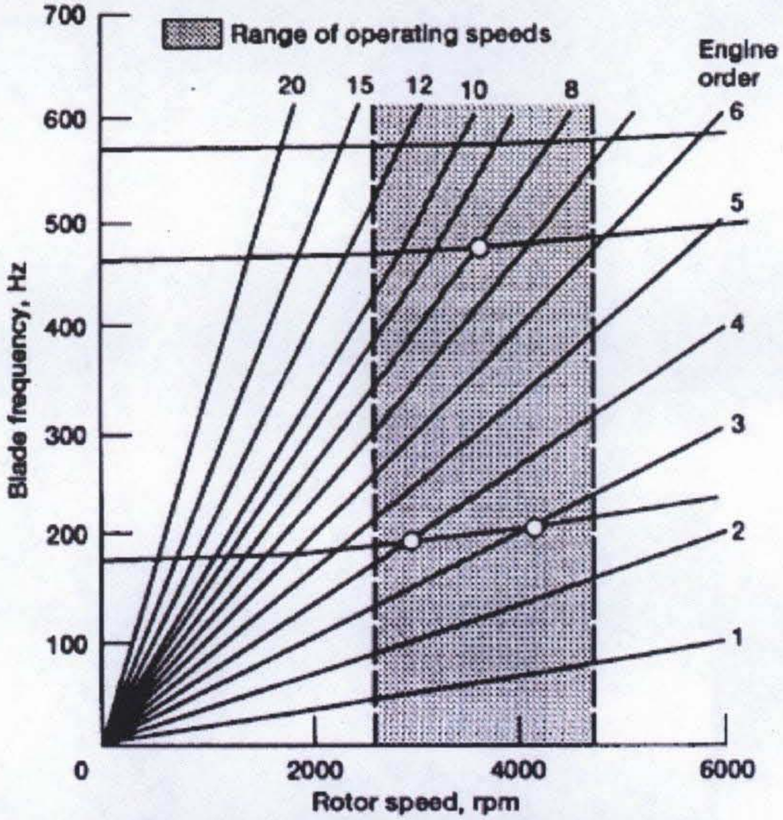
Engine Blade Forced Vibration



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



Blade Vibration Modes

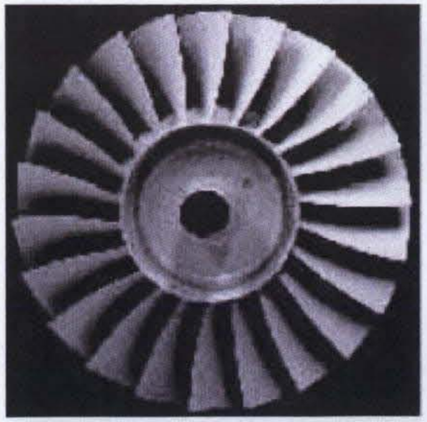


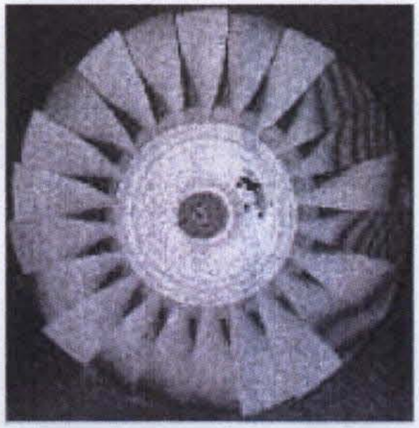
(b) Campbell diagram for rotor blade showing possible forced-response condition from resonance (denoted by circles).

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



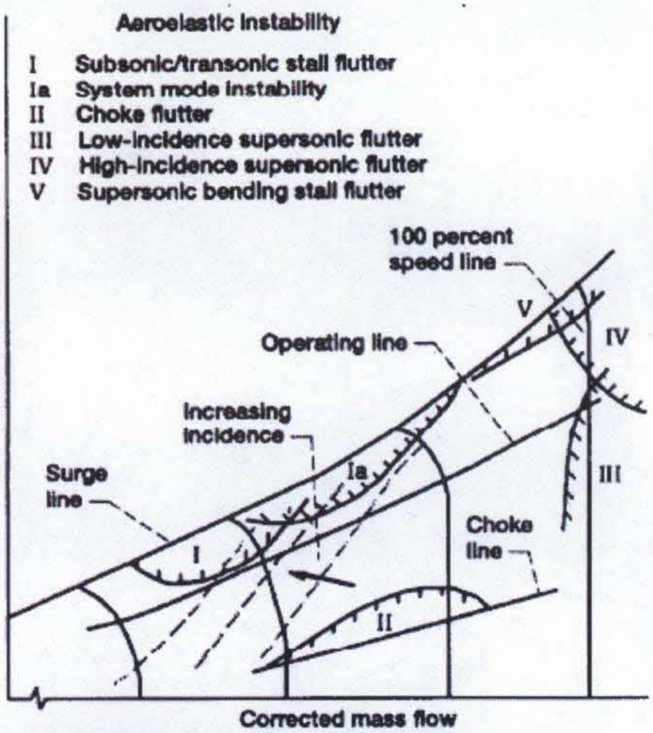


Response levels higher than predicted

"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

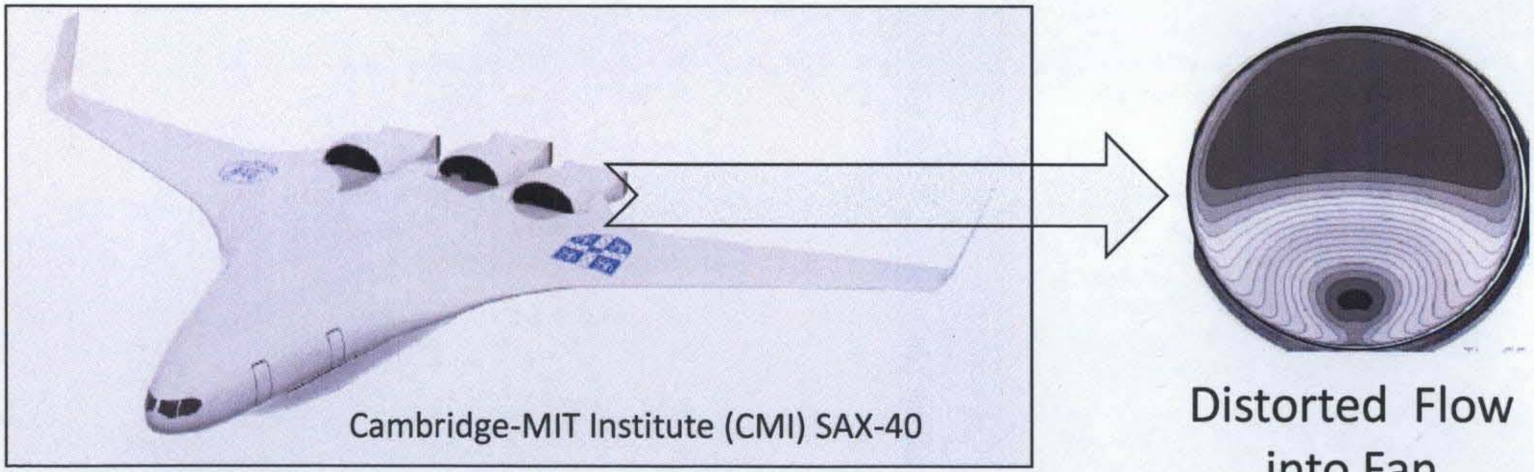


(a) Map showing principal types of flutter and regions of occurrence (ref. 4).

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

Future Aircraft

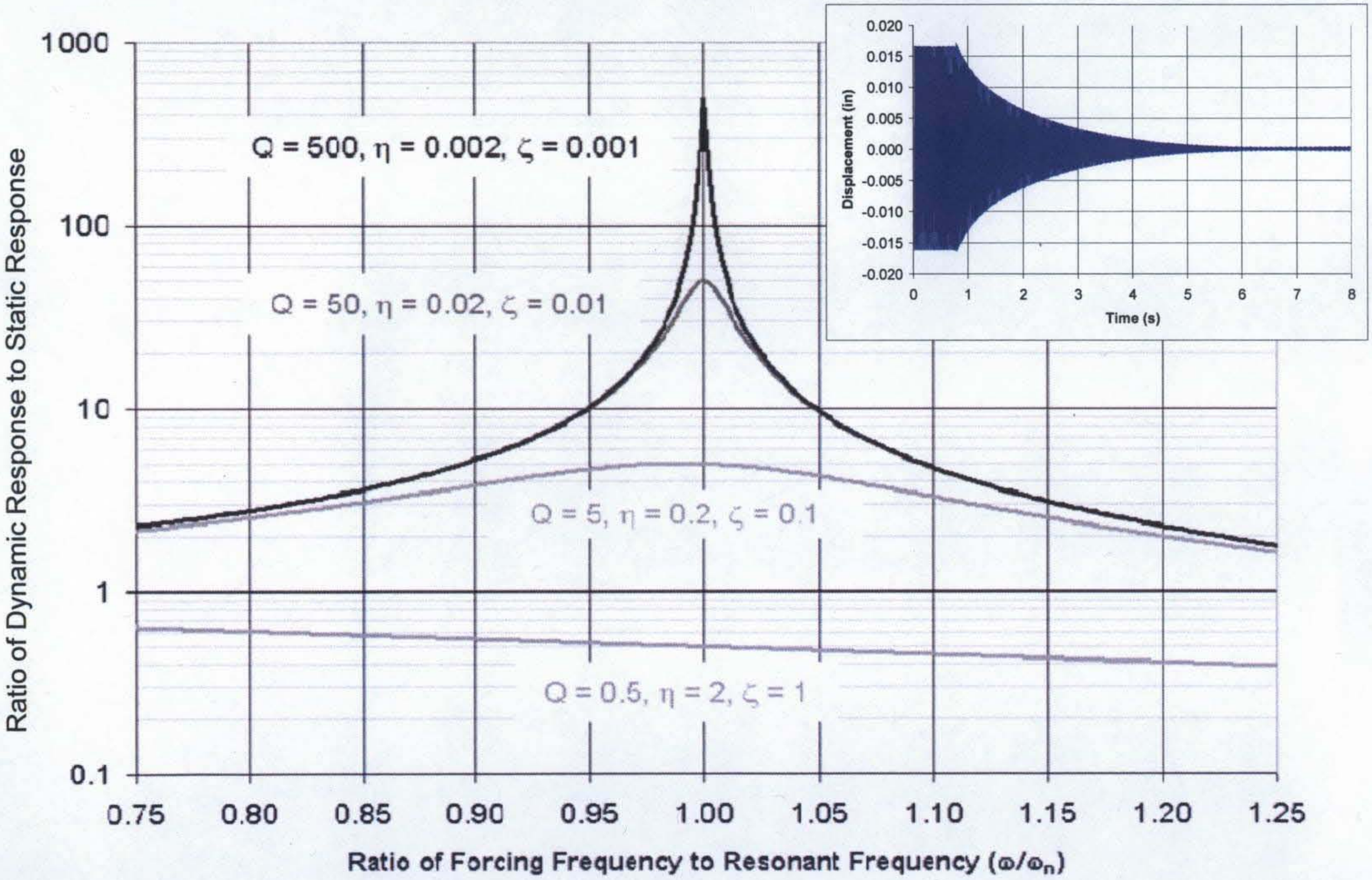
- Embedded engines
  - Benefits:
    - Decreased noise
    - Improved efficiency
    - Possibility of short takeoff and landing
  - Problem: Non-uniform flow into engine – blade excitation



Cambridge-MIT Institute (CMI) SAX-40

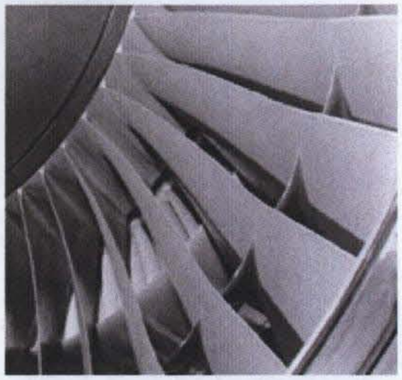
Distorted Flow into Fan

Solution – Damping

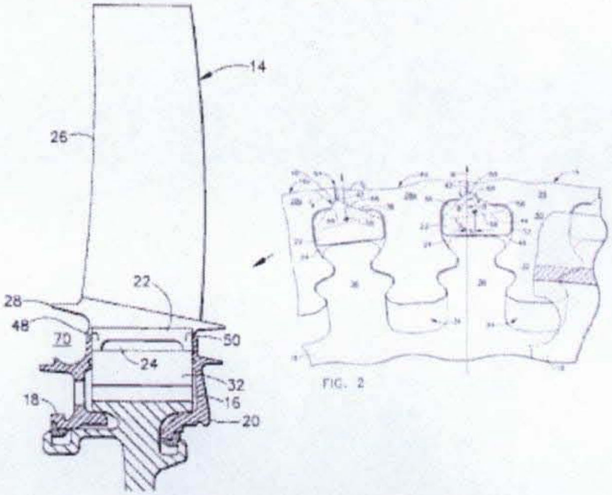


Engine Blade Damping

- 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



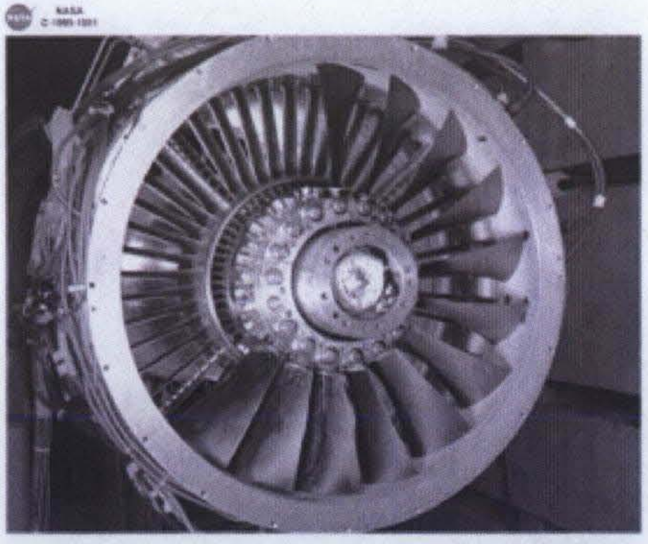
GE Platform Damper

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.

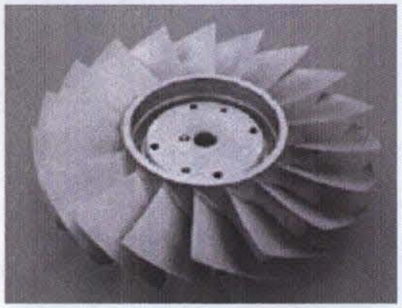
NASA Damping Research

- **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:

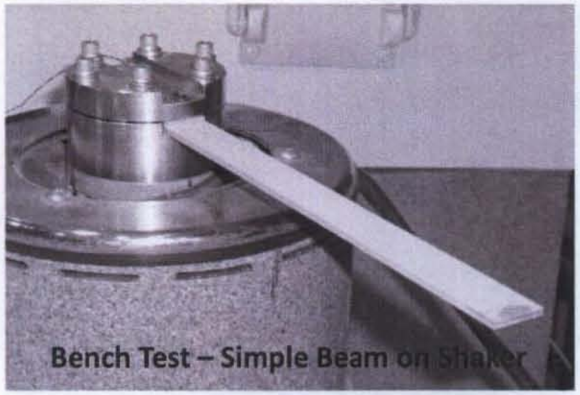
- *Titanium alloy fan or cold-side compressor blade*
- *Composite fan blade*

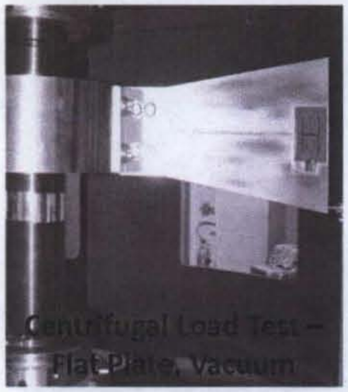
Temperature	*-40 to 300°C*
Vibratory strain amplitude	*up to 10^{-3}*
Mean strain (from centrifugal loading)	*zero to 10^{-3}*
Frequency	*100 to 10,000 Hz*
Typical blade loss factor	*10^{-3} or lower*
Target blade loss factor	*10^{-2}*

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

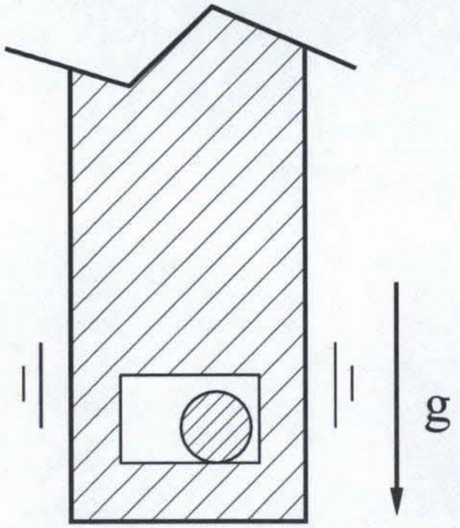

Centrifugal Load Test – Flat Plate, Vacuum


High-temperature Test – Flat Plate


Composite Fan Blade

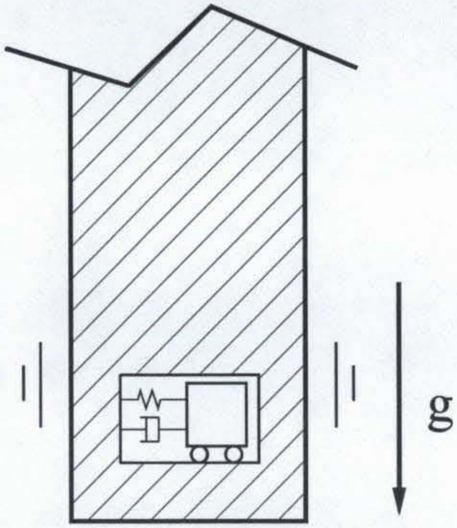

Wind tunnel te

Self-Tuning Impact Damper



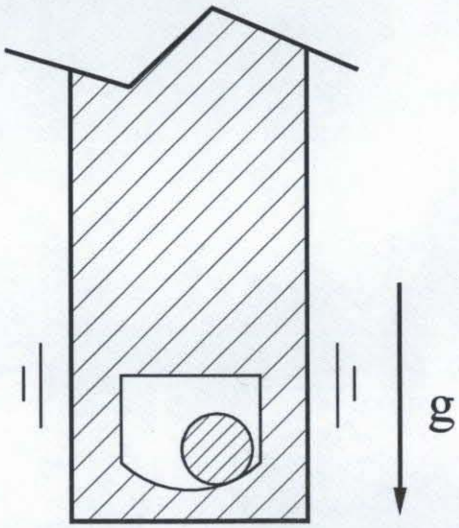
Impact Damper

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



Tuned-Mass Damper

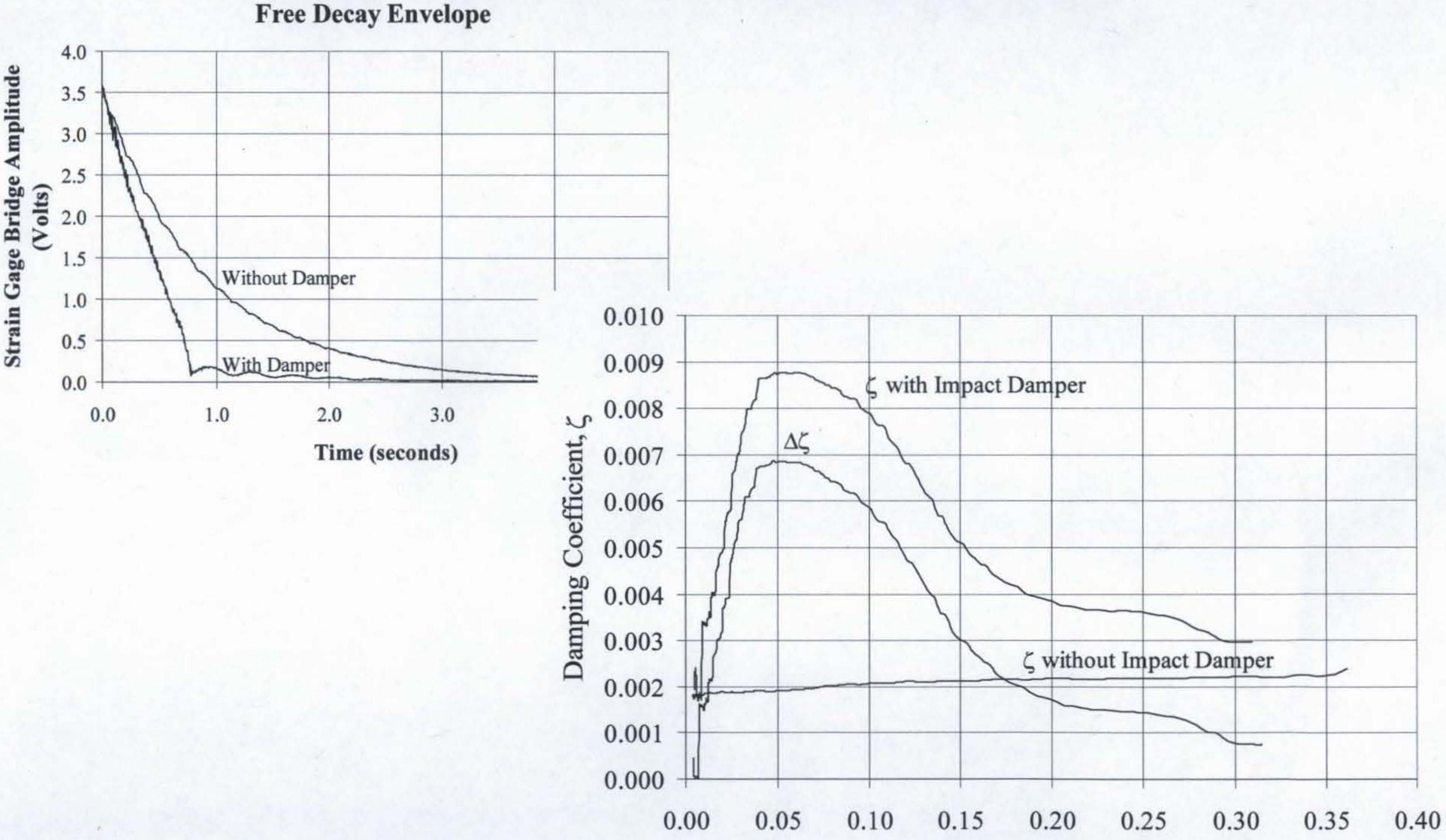
- Frequency-dependent
- Damping at tuning frequency
- Displacements may be too large for blade cavity



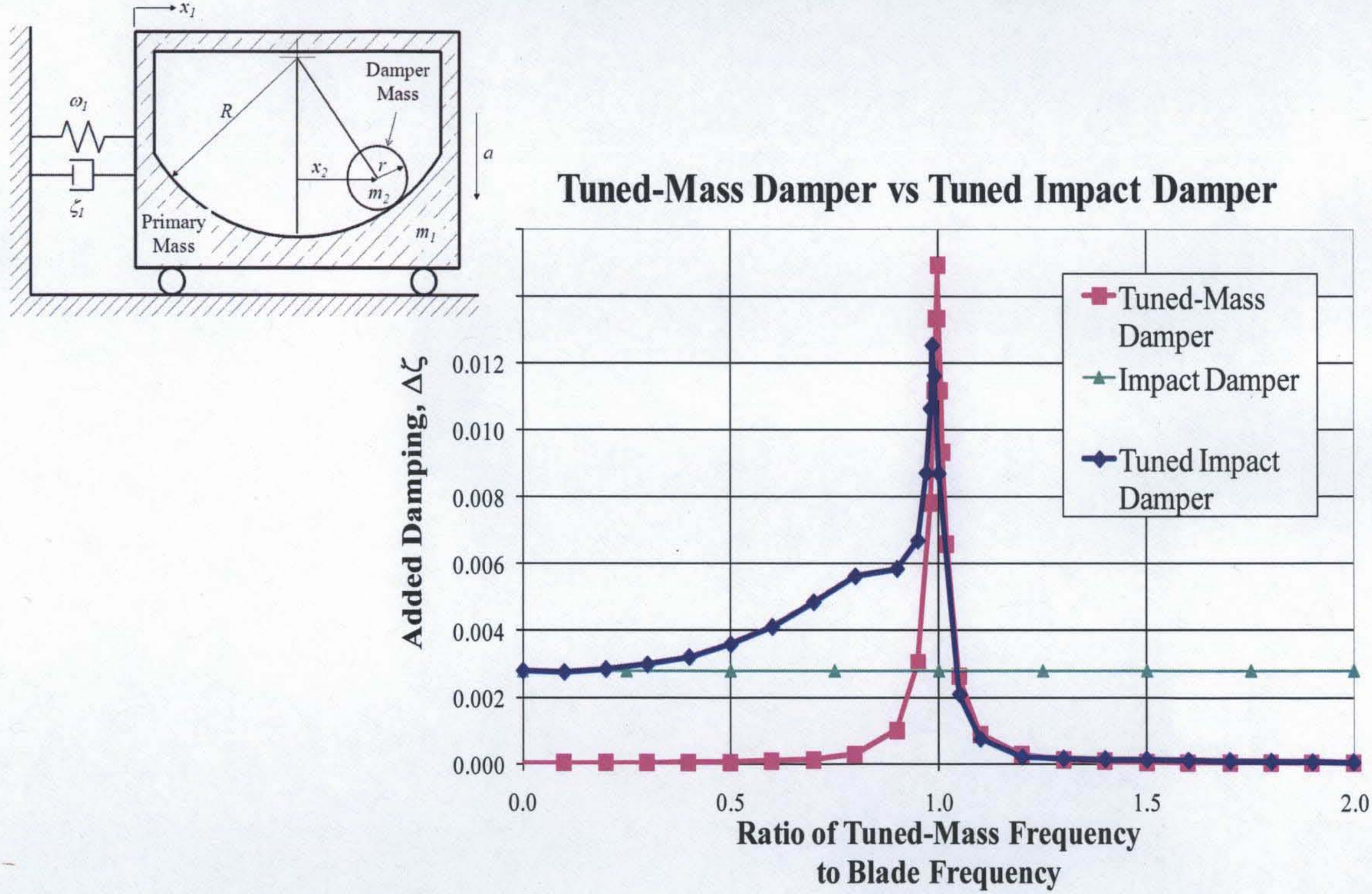
Tuned Impact Damper

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

Self-Tuning Impact Damper

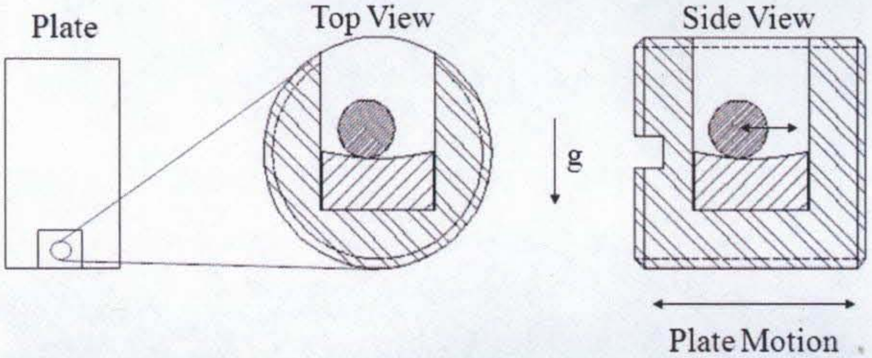


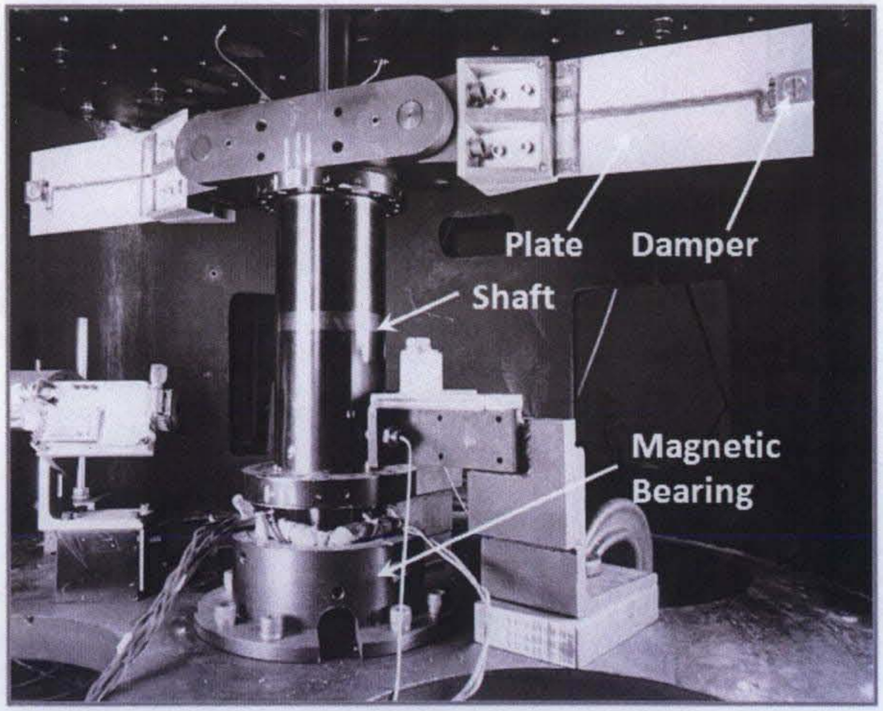
Self-Tuning Impact Damper

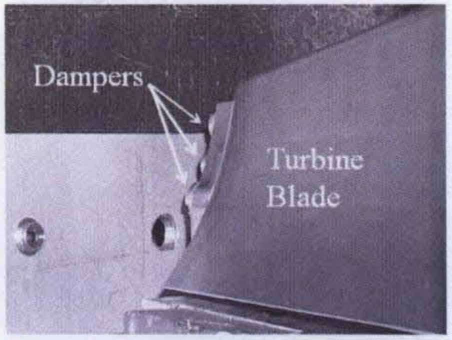


Tuned-Mass Damper vs Tuned Impact Damper

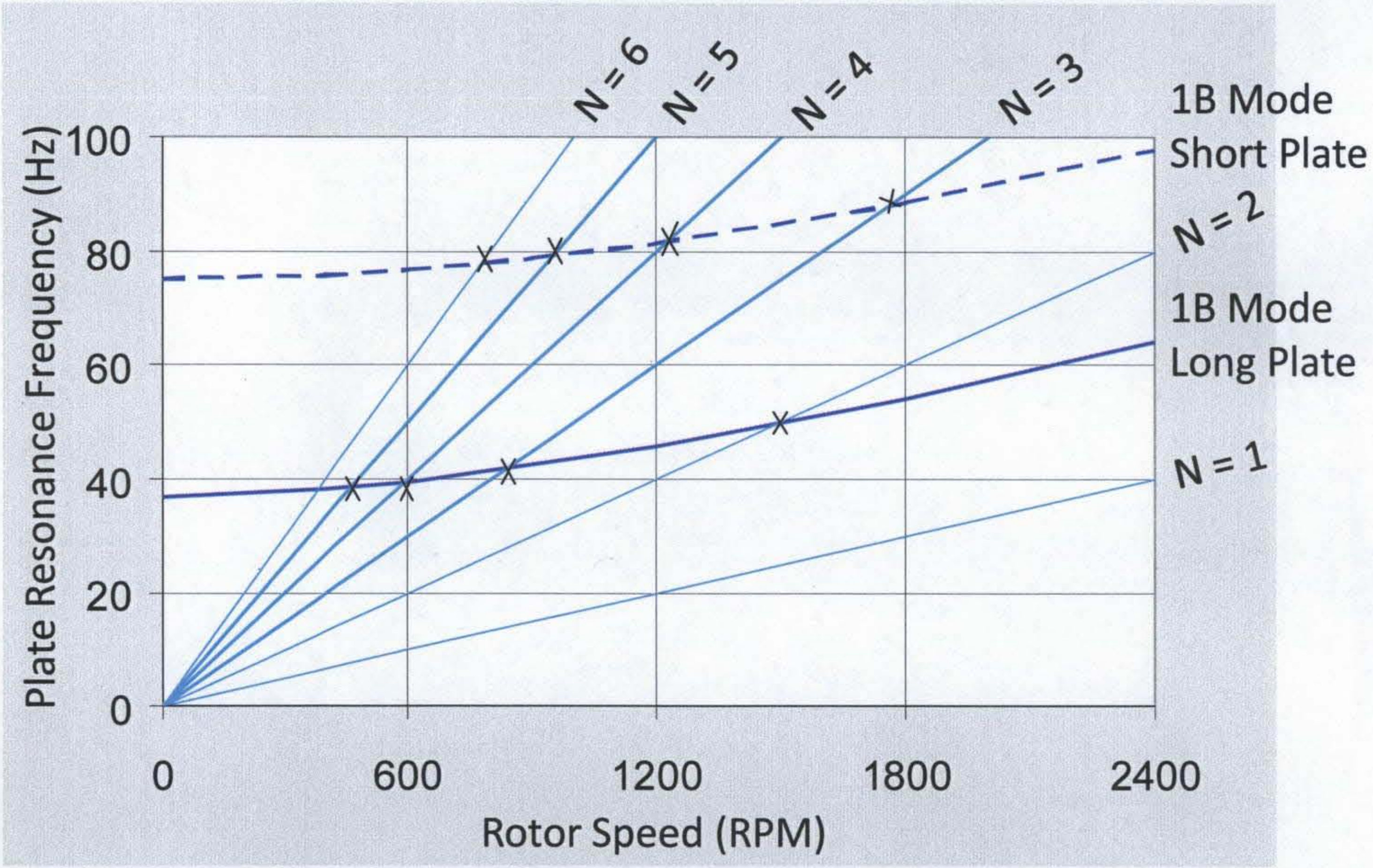
Self-Tuning Impact Damper



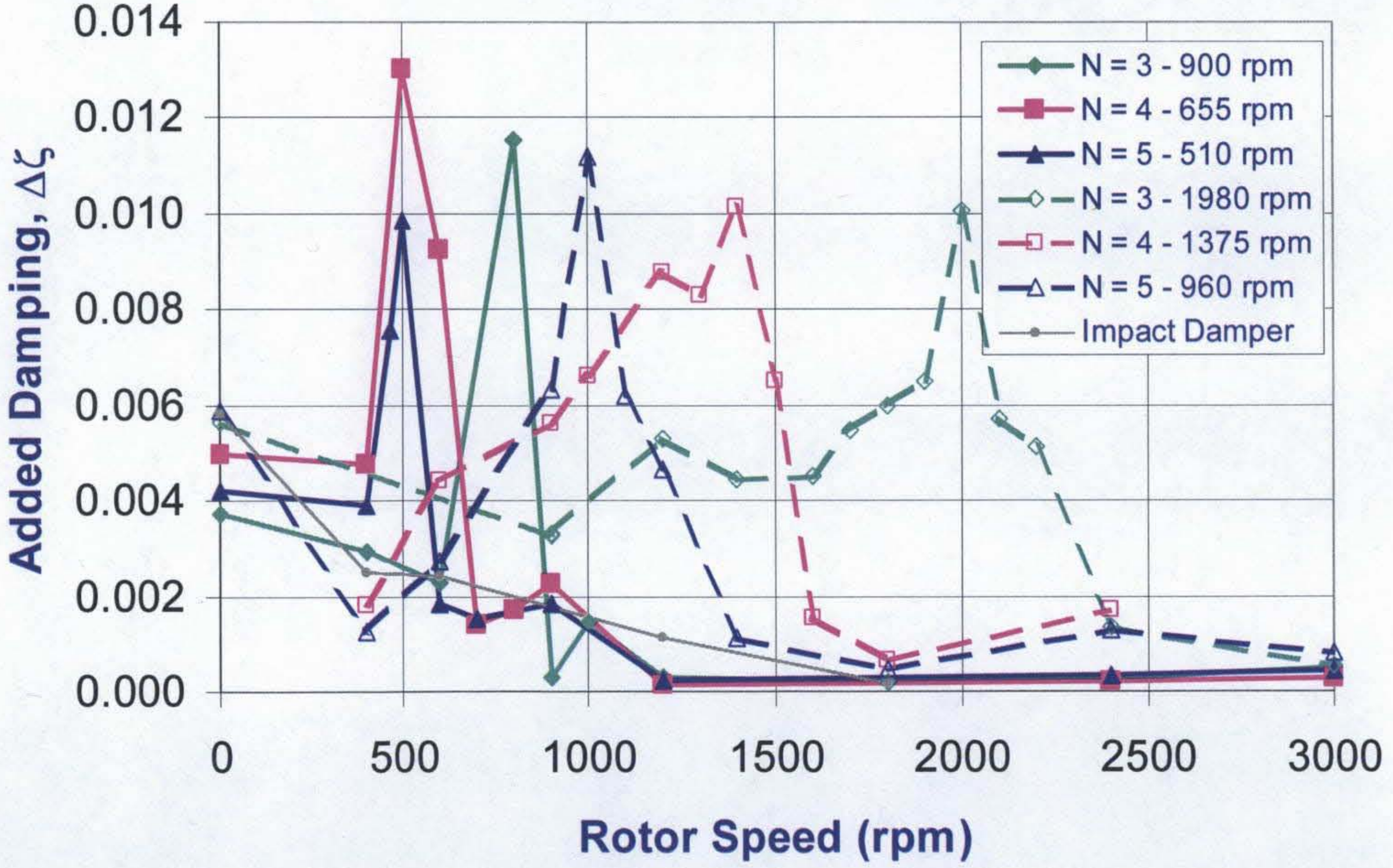




Self-Tuning Impact Damper

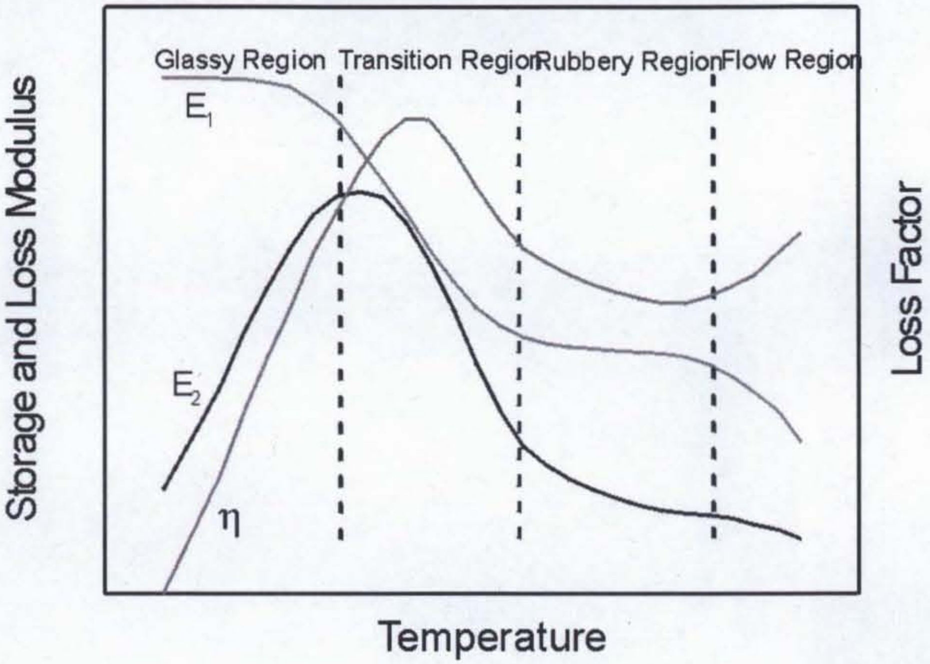


Self-Tuning Impact Damper



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

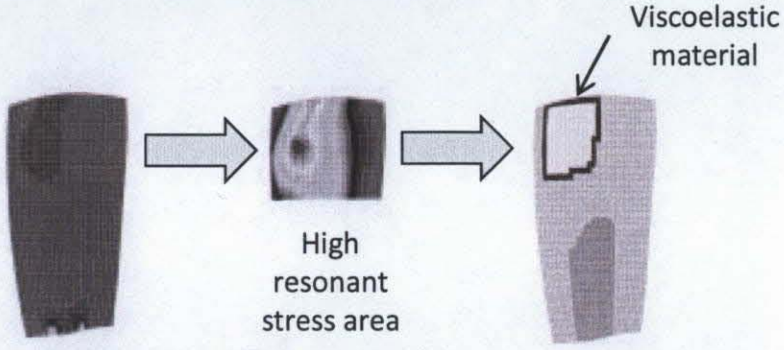


Roush-Anatrol

Viscoelastic Damping

Composite Fan Blade

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



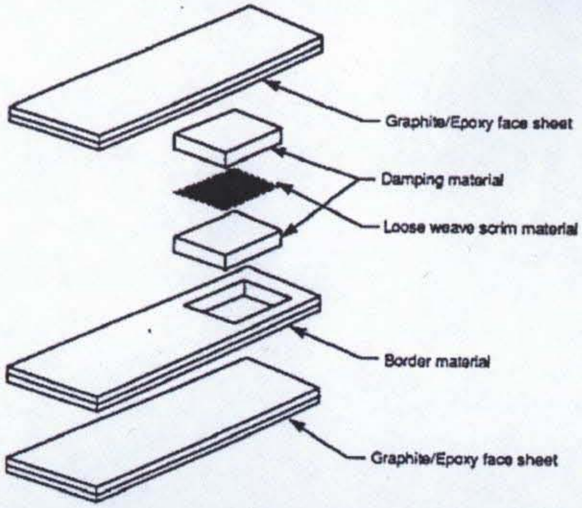


Fig. 3 Blade components

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

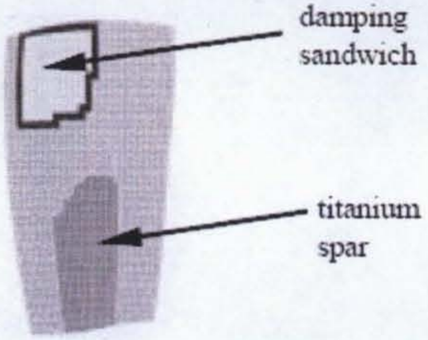


Fig. 6 Patch definition for optimum damping of first chord-wise mode (1581 Hz).

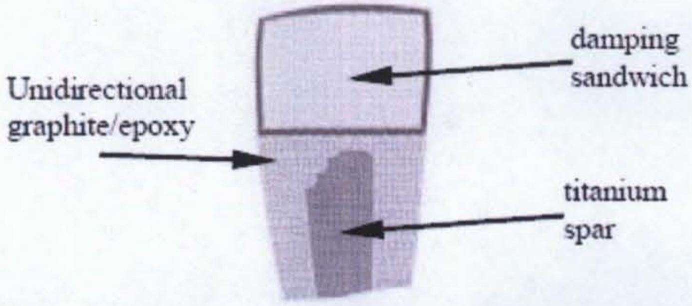


Fig. 5 Patch definition for maximum damping of first chord-wise mode (1581 Hz).

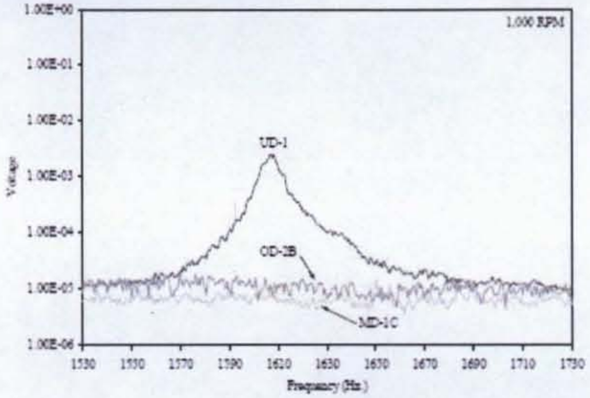


Fig 20 Power Spectrum Comparison for the 1st Chordwise Mode at <u>1.000 RPM</u>

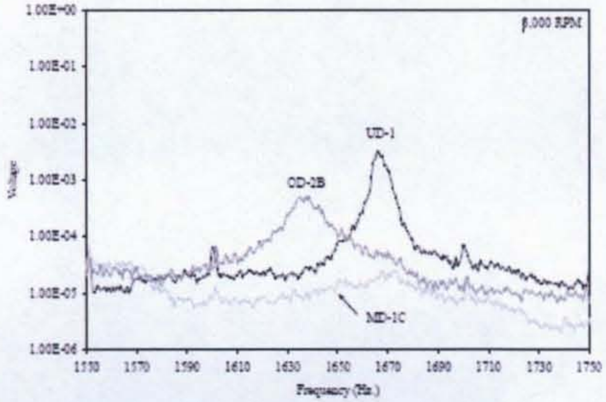


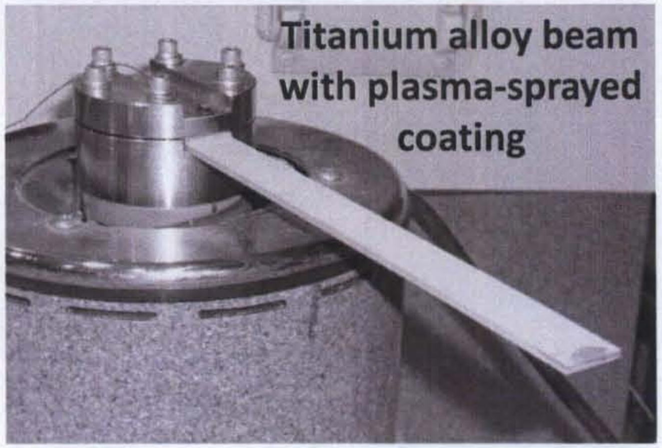
Fig 21 Power Spectrum Comparison for the 1st Chordwise Mode at <u>3.000 RPM</u>

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

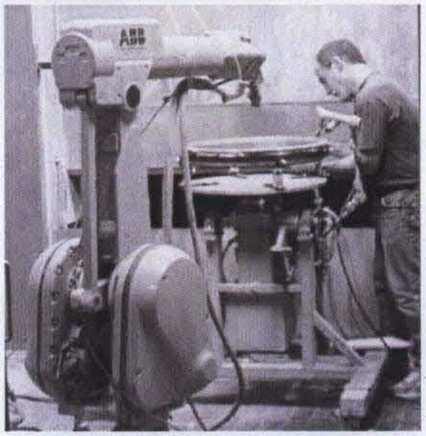
Oberst beam – thin layer of damping material on beam surface

- 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

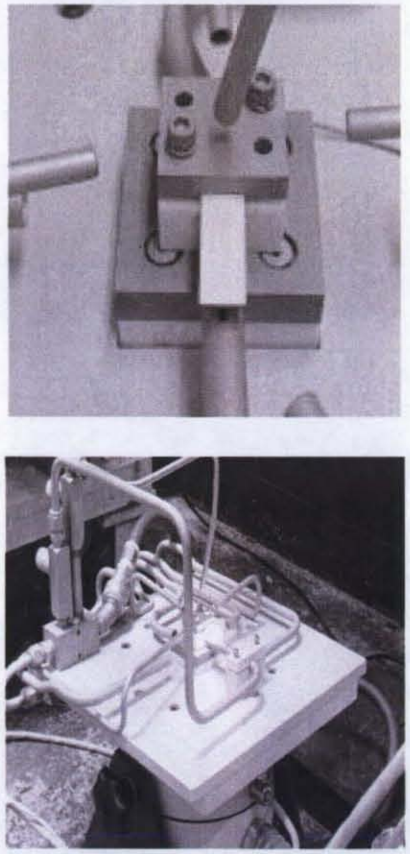


Plasma Spray Torch

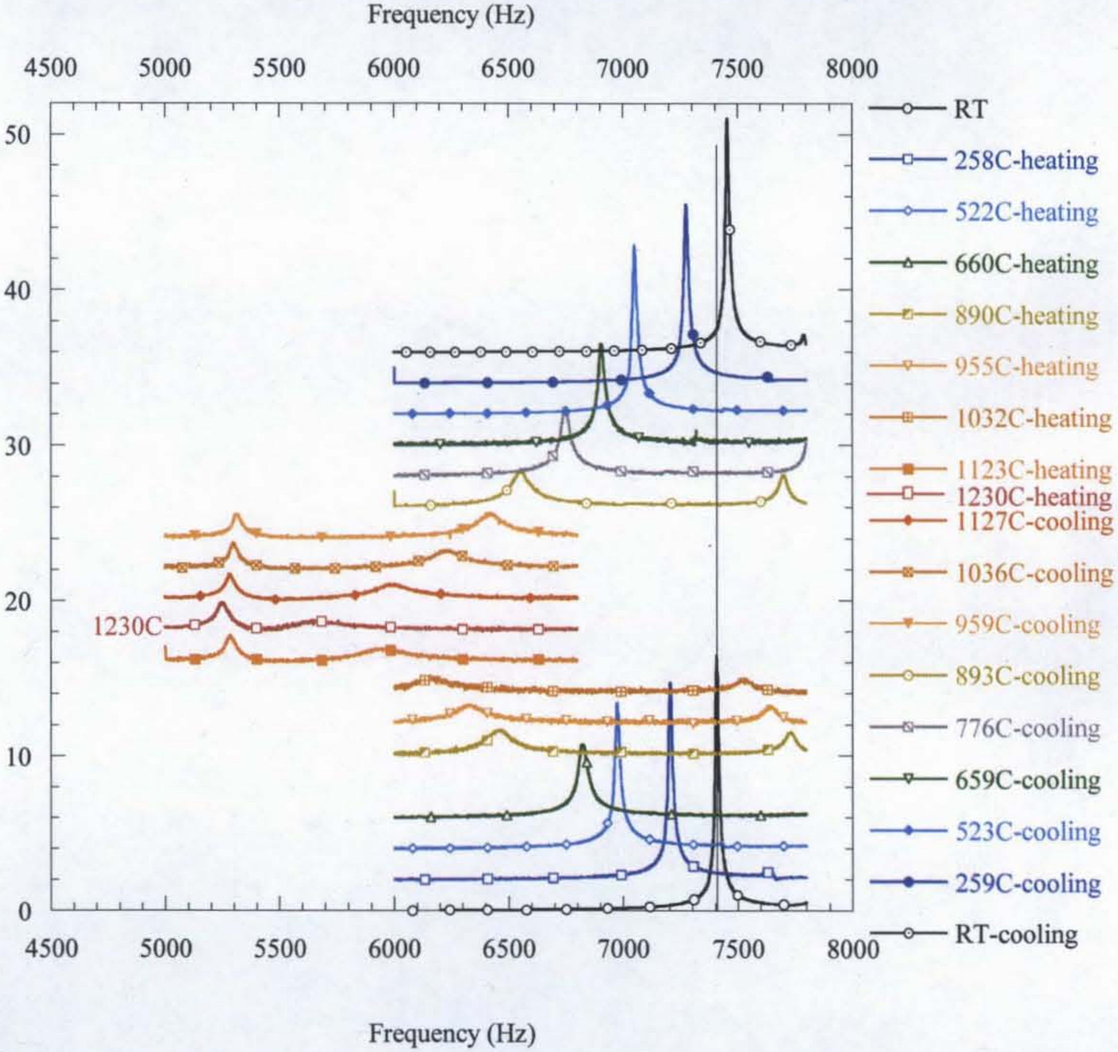
Plasma-Sprayed Coating used for Damping Test

Plasma-Sprayed Damping Coatings

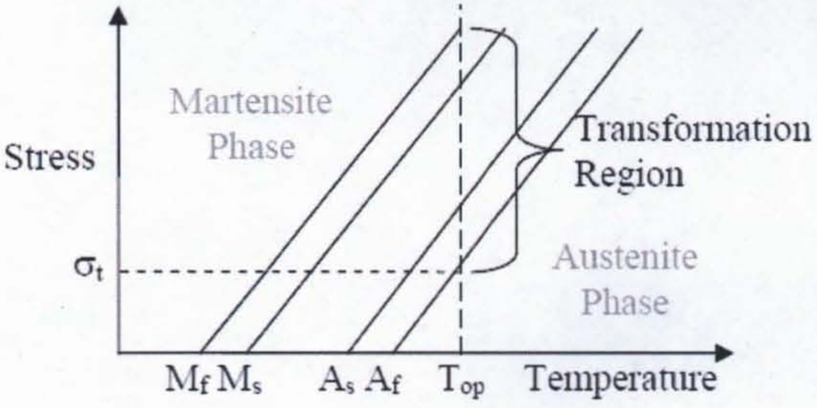
High-temp application

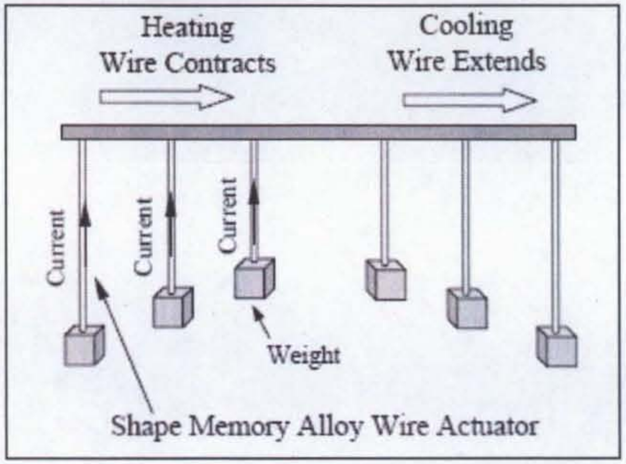


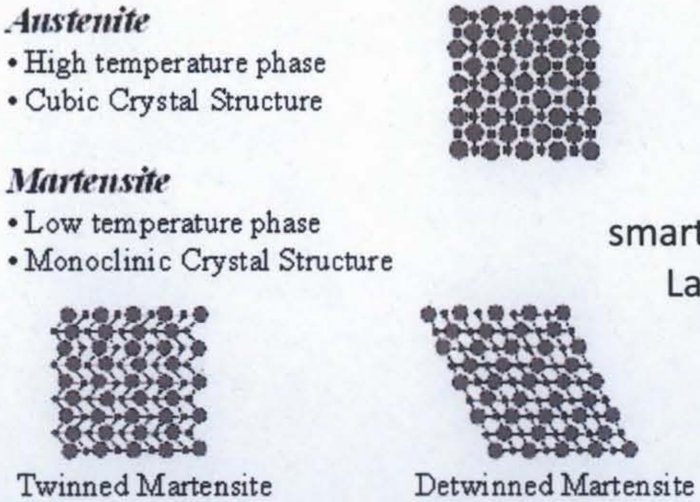
Zhu, Miller, Duffy, Ghosn – 2009
"High Temperature Damping Behavior of Plasma-Sprayed Thermal Barrier and Protective Coatings"
The 33rd International Conference on Advanced Ceramics & Composites



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

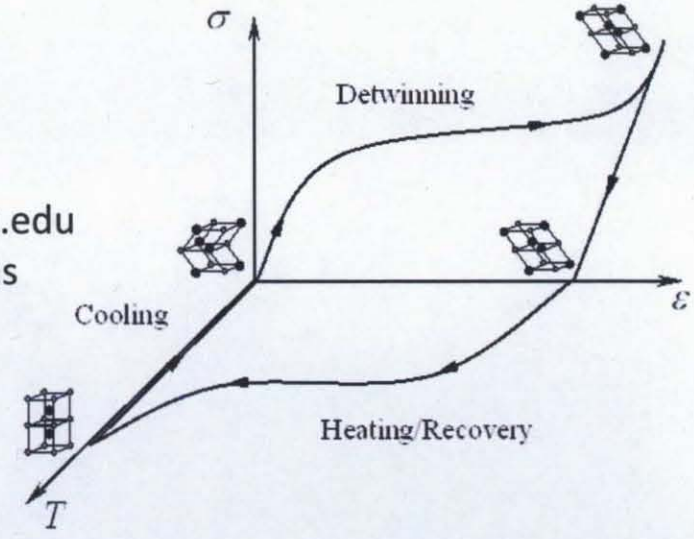
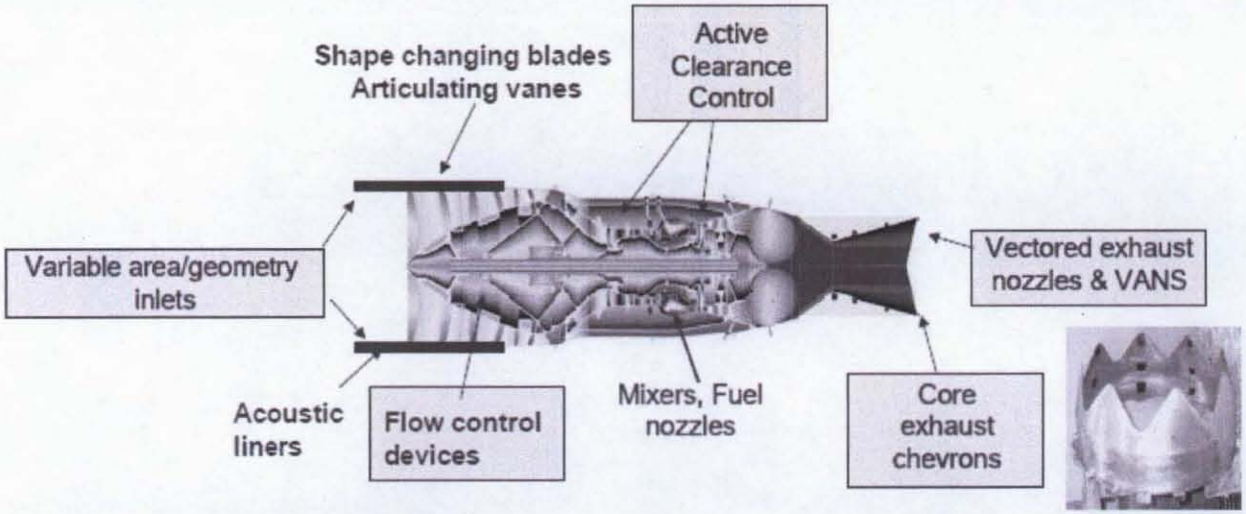


Figure 3. Schematic of a stress-strain-temperature curve showing the shape memory effect.

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

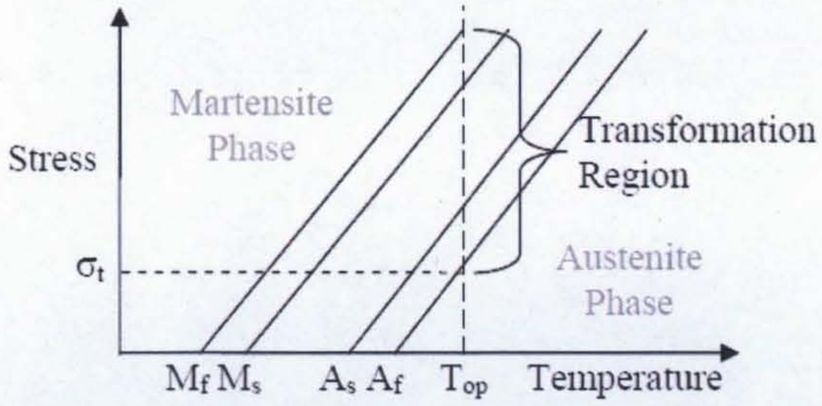
"Characterization of a New Phase and its Effect on the Work Characteristics of a Near-Stoichiometric Ni30 Pt20 Ti50 (at.%) High-Temperature Shape Memory Alloy (HTSMA)", Garg et. al., Presentation at The International Conference on Shape Memory and Superelastic Technologies (SMST) 2008, 21-25 Sep. 2008;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

High-Temperature Shape Memory Alloys

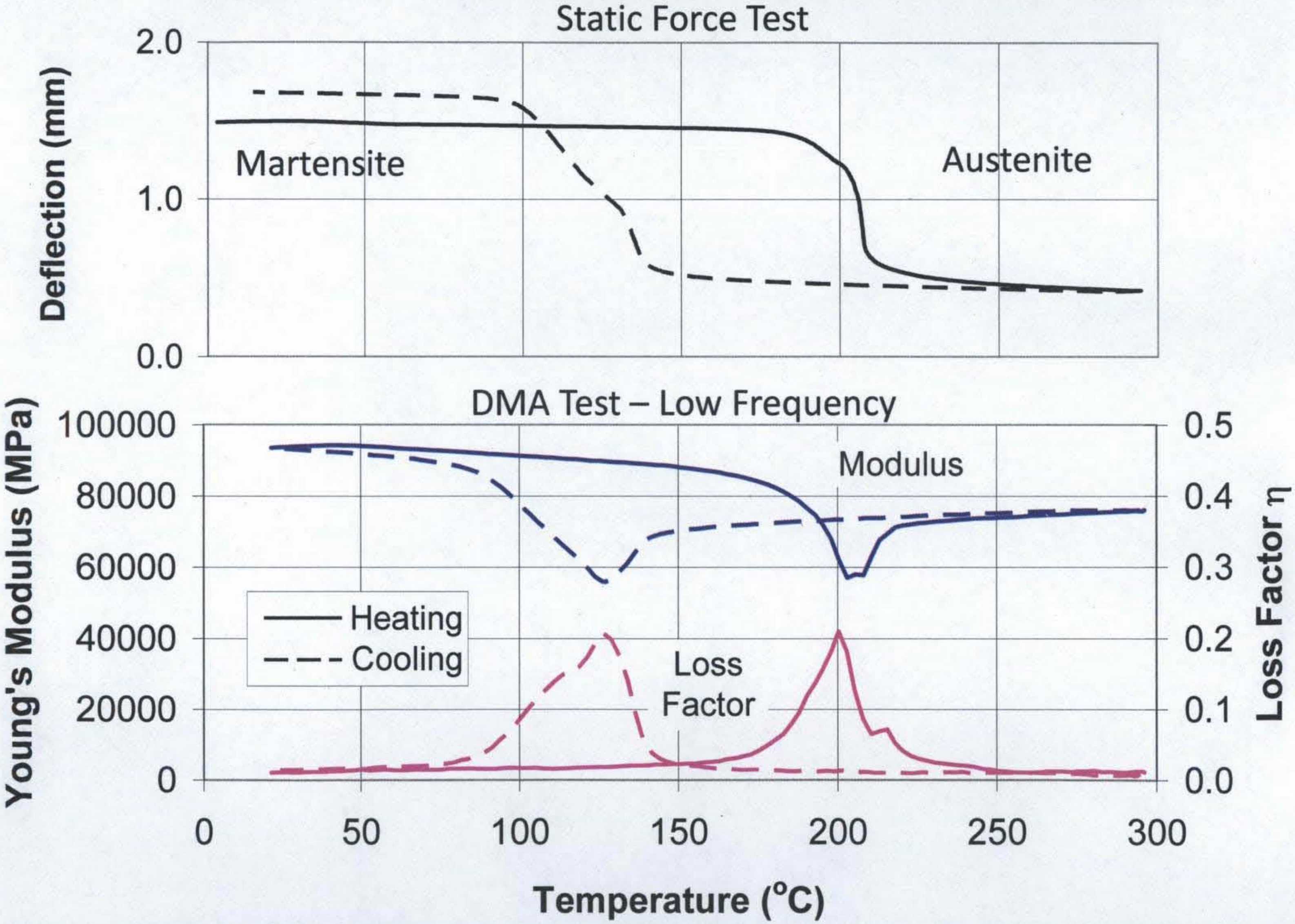
- HTSMAs
  - High temperature and force capability
  - Low frequency applications
- Potential engine applications
  - **Surge control rod for a centrifugal compressor – avoid instability**
    - "Development of a HTSMA-Actuated Surge Control Rod for High-Temperature Turbomachinery Applications" Padula 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

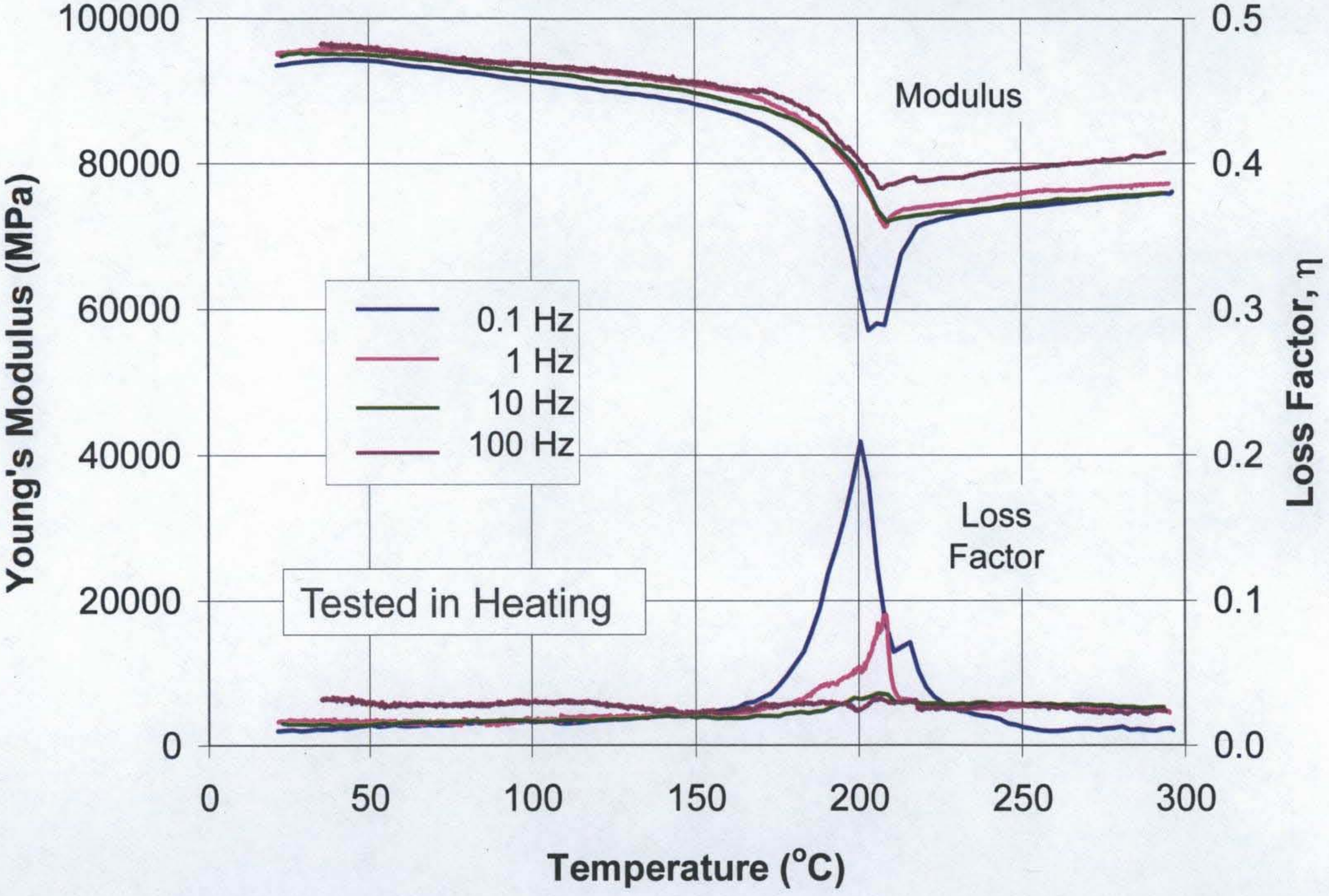
- NiTiHf samples tested for modulus and damping properties
  - Looking for damping in phase-transition region
  - Purely passive damping properties
  - Damping is temperature-dependent
  - Tested using Dynamic Mechanical Analysis (DMA) at 0-300°C and at 0.1-200 Hz



Shape Memory Alloy Damping



Shape Memory Alloy Damping



Piezoelectric Materials

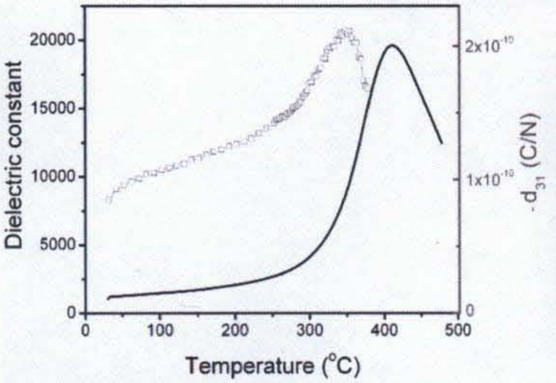
- High-temperature piezoelectric materials
  - Off-the-shelf high-temperature material – Type-II PZT – $T_c = 350^oC$
  - NASA GRC-developed materials – $T_c = 430^oC$
- Potential engine applications
  - **Active combustion control**
    - Mitigate thermo-acoustic instabilities and/or gas flow control 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

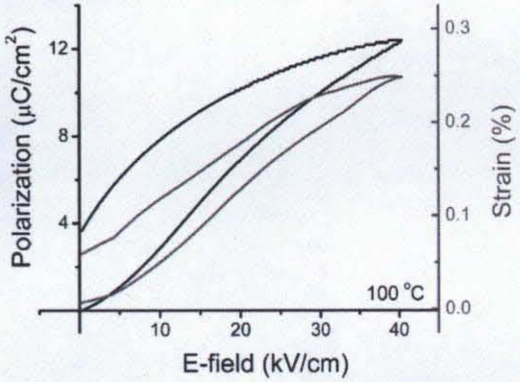
High-Temperature Piezoelectric Material

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

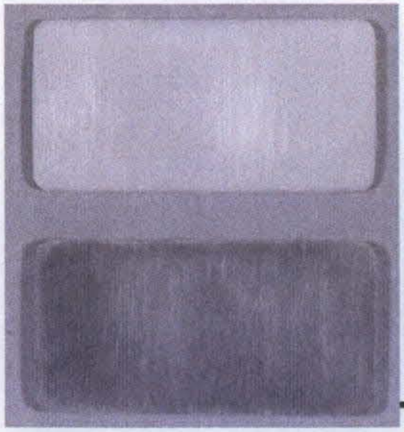
Slip cast patches of GRC-63L composition developed and processed at NASA Glenn Ceramics Branch



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



Material



Comparison to the state of the art material

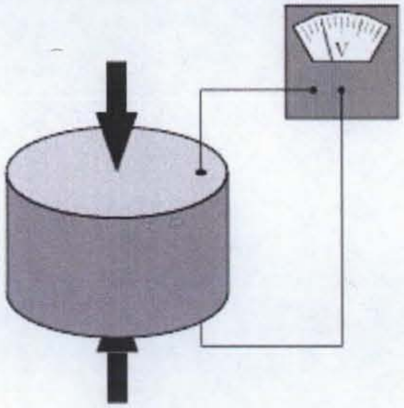
PZT Type II by Piezo Kinetics, Inc	Temperature (°C)		Ferroelectric and Piezoelectric (100 °C)		Electromechanical coupling coefficients	
	Curie	Depoling	E_C (kV/cm)	d_{33} (pC/N)	k_p	k_{31}
GRC-63L	**430**	352	23	625	0.43	0.22
PZT-II	315	280	12	585	0.52	0.28

Device

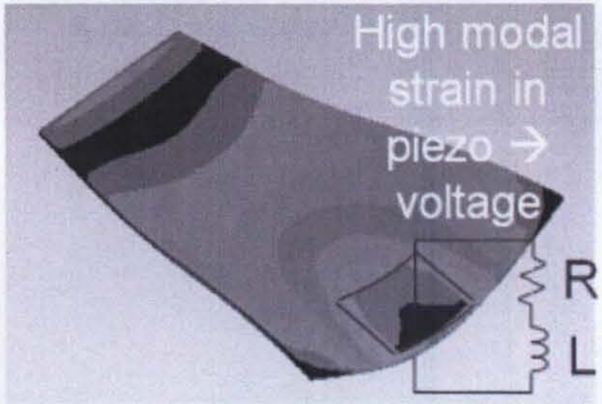
•Points of Contact: Ceramics Branch/ Dr. Alp Sehirlioglu, 216-433-6159, Dr. Ali Sayir, 216-433-6254, Dr. Fred Dynys, 216-433-2404

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

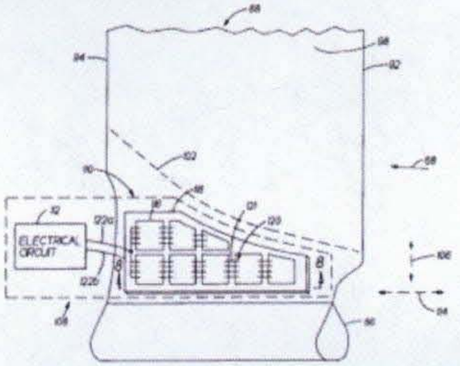


www.wikipedia.org



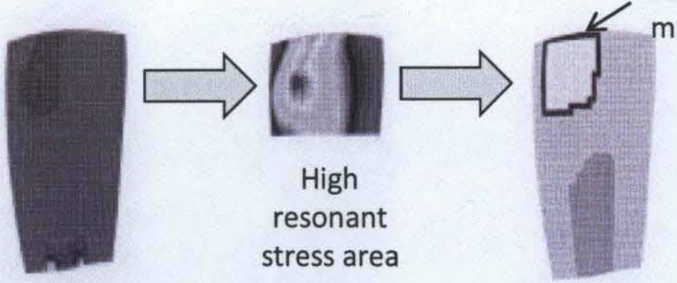
Piezoelectric Damping

- 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

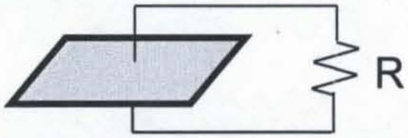
Fibers – Advanced Cerametrics Inc.



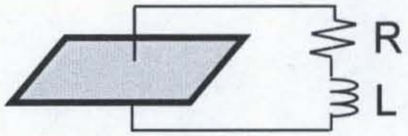
Kosmatka et.al.

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

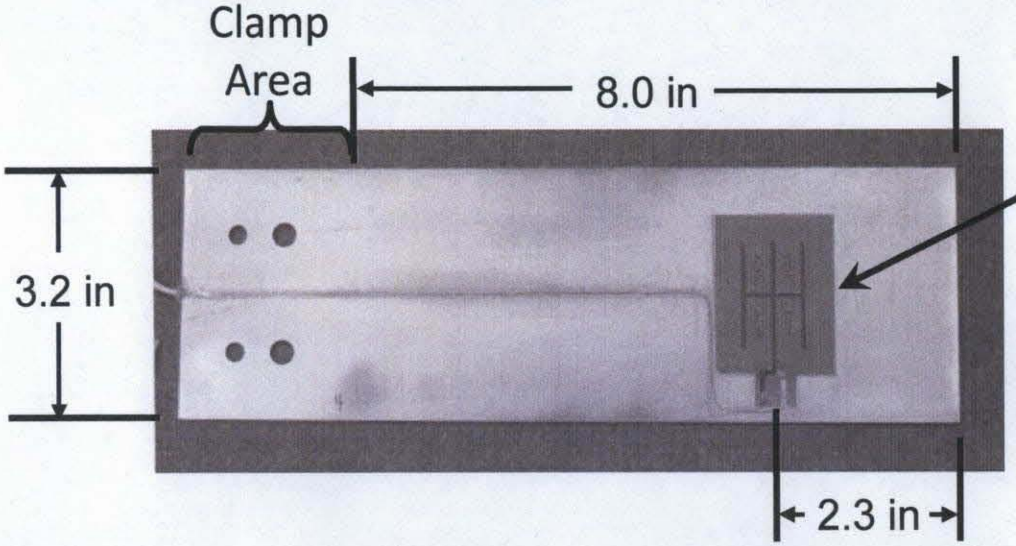
0.69 H wound inductor:

- *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*

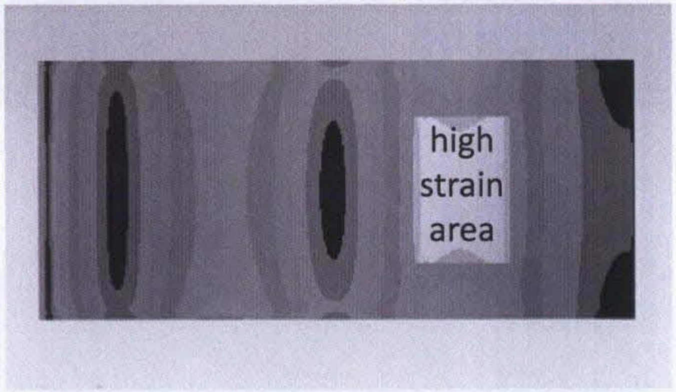
Piezoelectric Damping



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

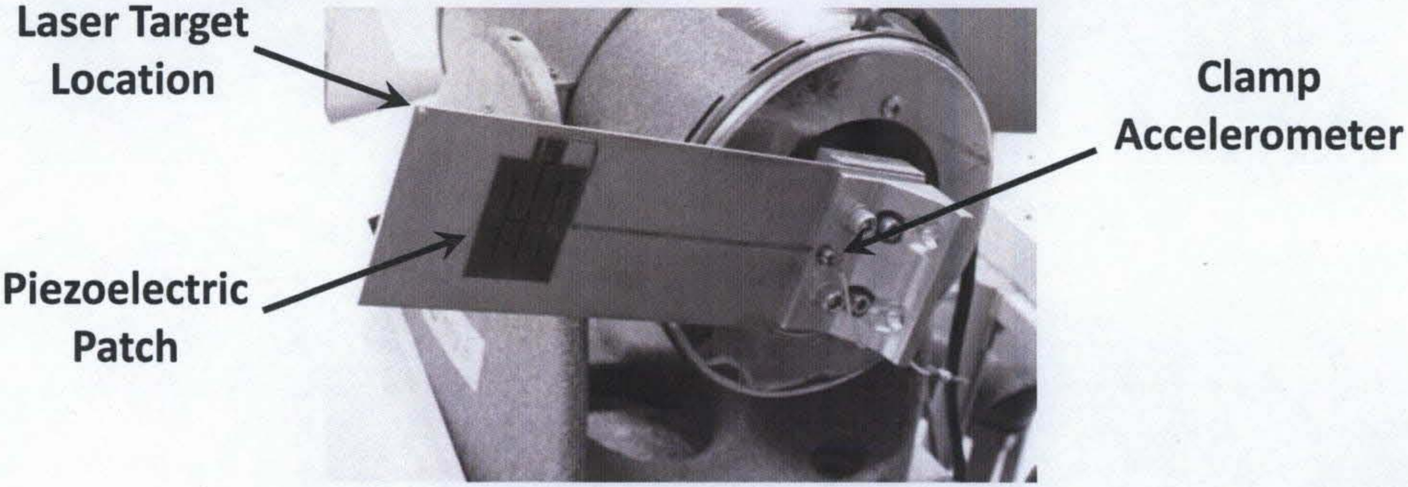
Ti 6Al-4V
0.078" thick plate

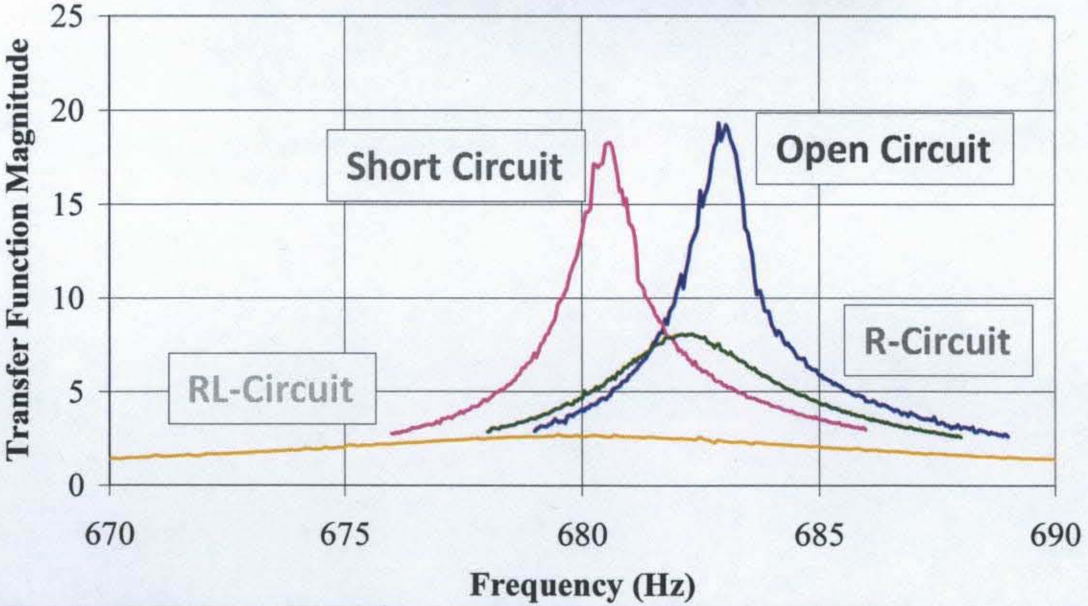
3B Mode – Modal Deformation



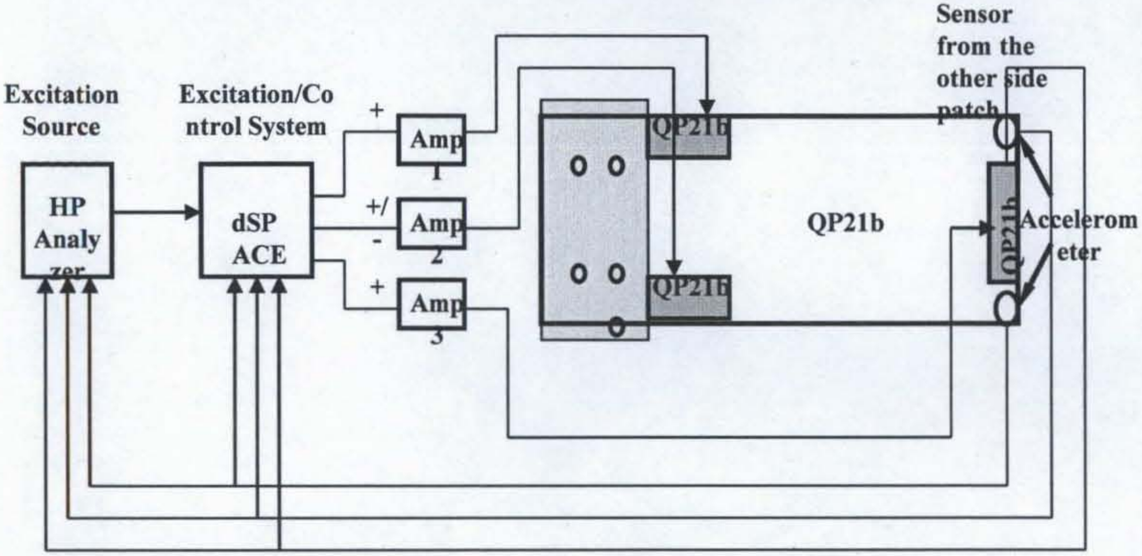
3B Mode – von Mises Modal Strain

Piezoelectric Damping





Active Control with Piezoelectrics



Excitation Source

Excitation/Control System

HP Analyzer

dSP ACE

Amp 1

Amp 2

Amp 3

+

+/-

+

QP21b

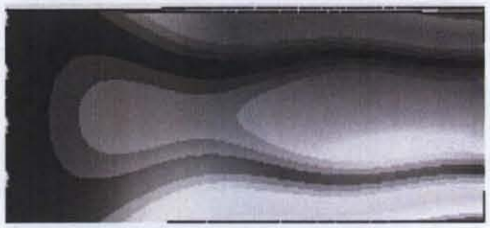
QP21b

QP21b

QP21b

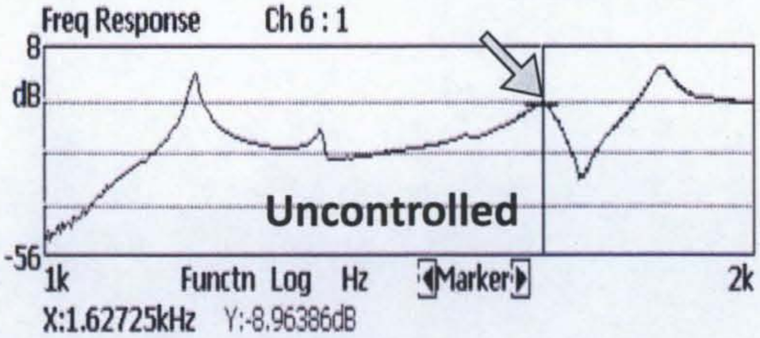
Sensor from the other side patch

Accelerometer

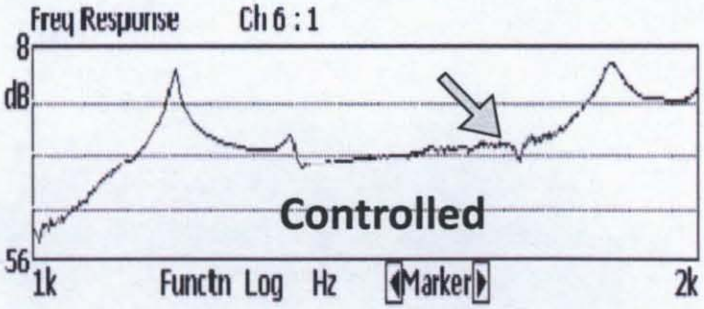


2-Stripe Mode Shape

Ben Choi – NASA GRC

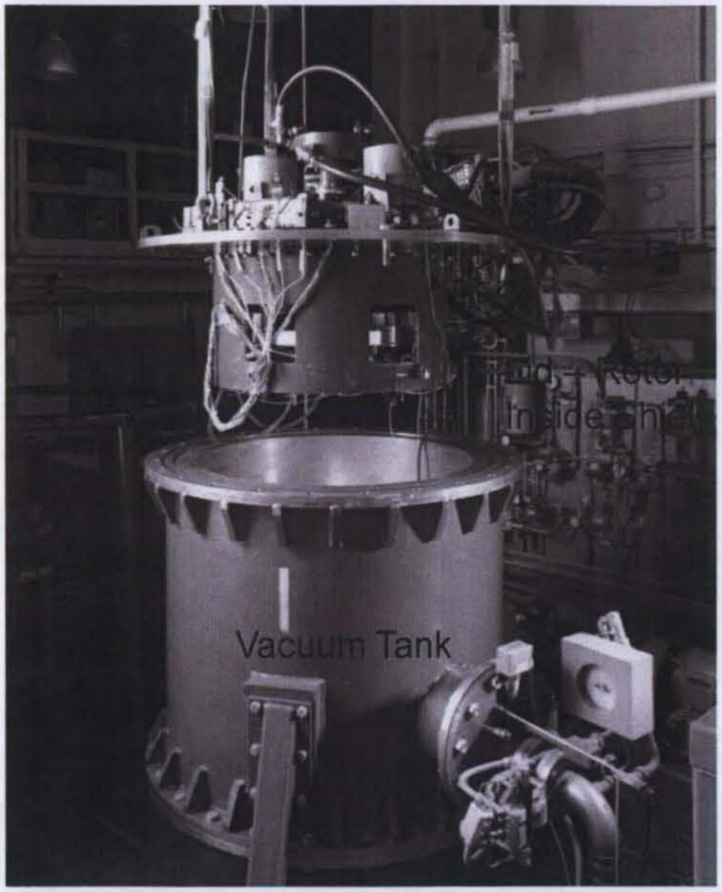


Uncontrolled

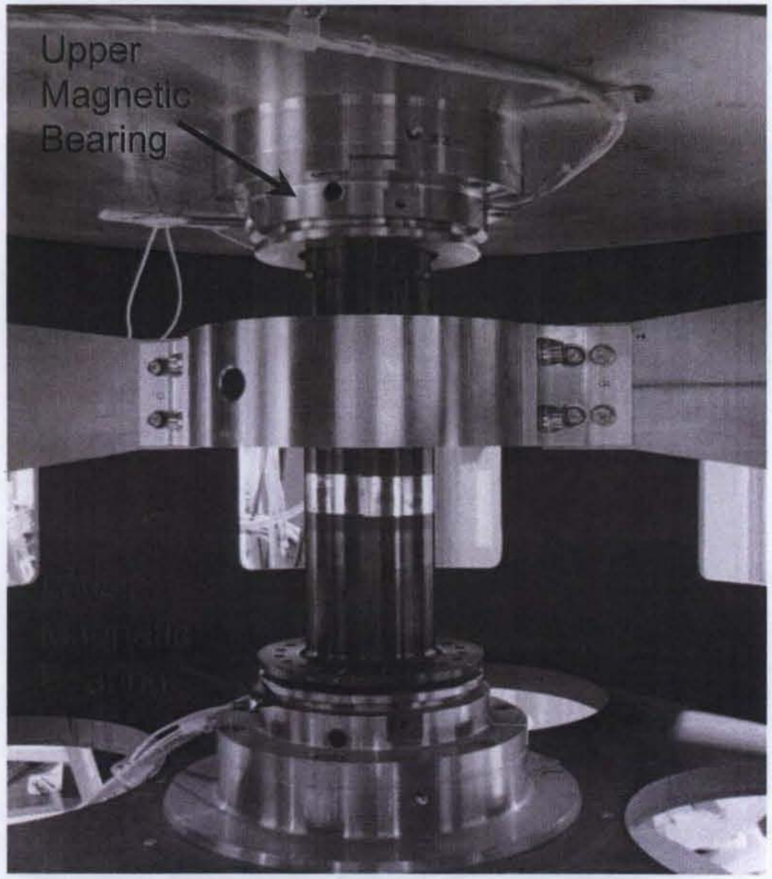


Controlled

Piezoelectric Damping

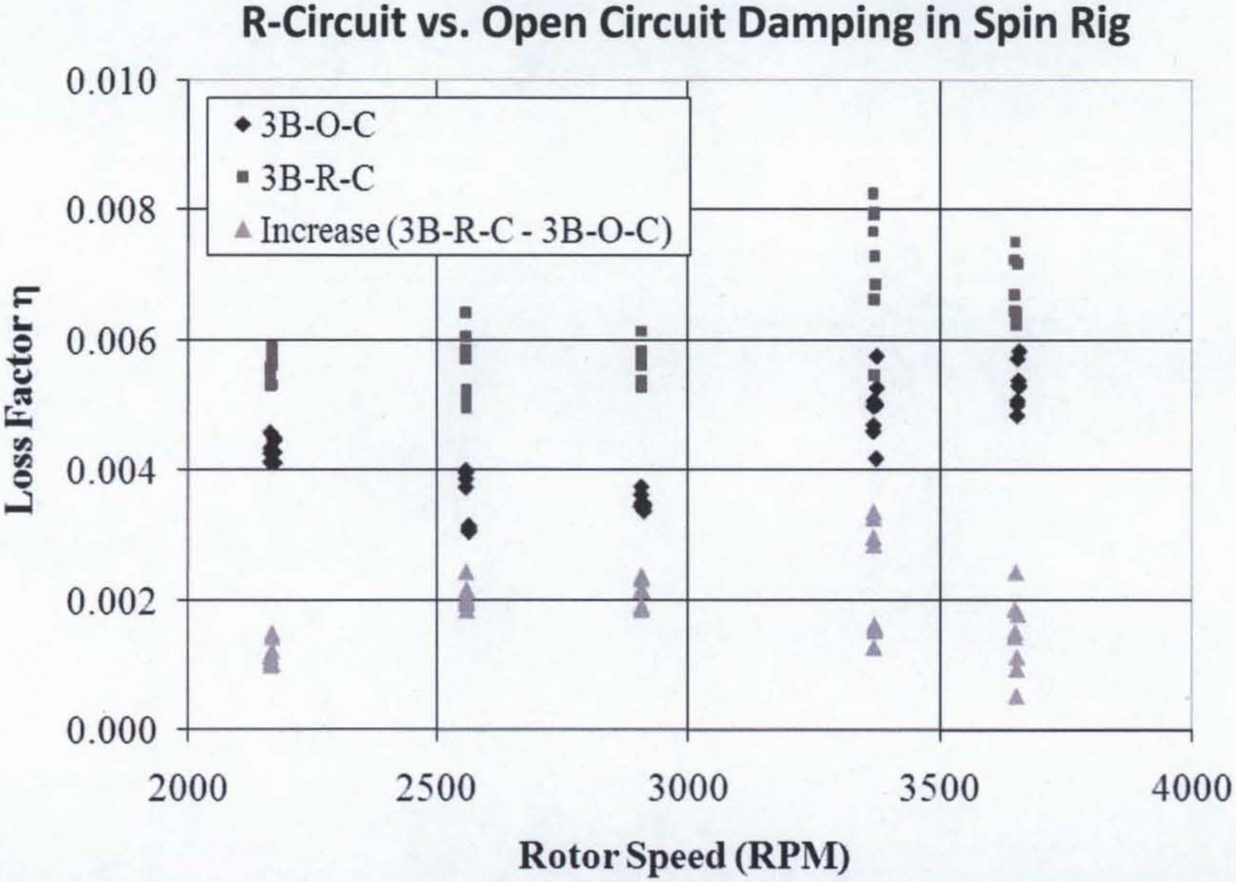


Dynamic Spin Facility



Rotor with Tapered Test Plates

Piezoelectric Damping



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