Damping and Vibration Mitigation: Critical Issues

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Vibration Mitigation: Classification

- Damping Materials
- Damping Devices
- Isolation methods
  - (stiffness controlled)

- Active Control
- Semi Active Control
- Passive Control
- Electronic Damping

Here we focus on issues related to material properties, and some sense of multifunctionality

Issues Remaining in Current State of the Art

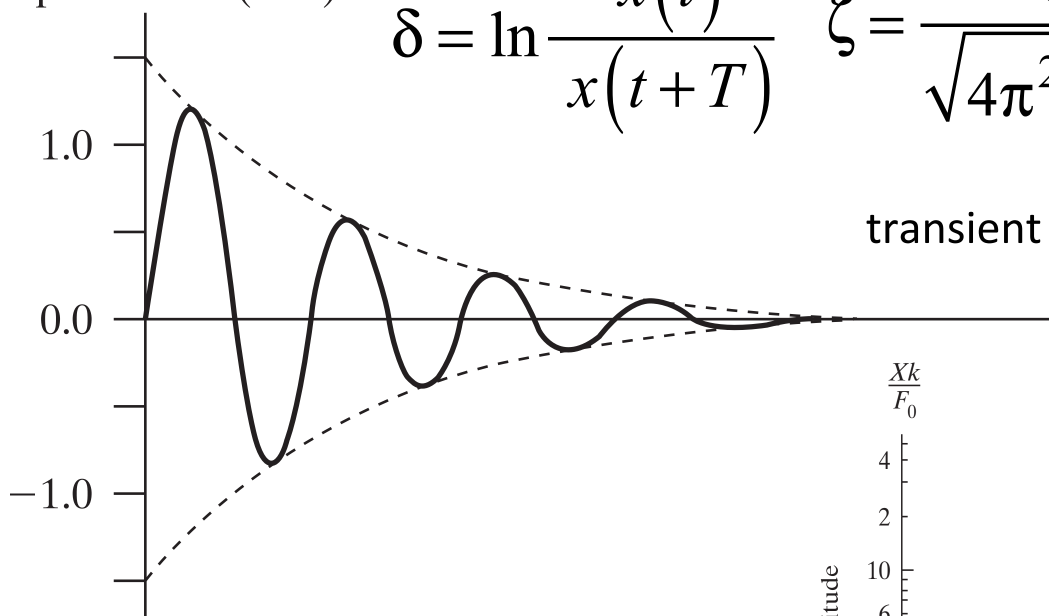
- Damping materials typically have
  - Strong temperature dependence
  - Strong frequency dependence
  - Damping is often an add on solution rather than built in, increasing volume and mass
  - Modeling friction is a continued problem introducing nonlinearity even for small deflections
- Models of damping are difficult because of lack of first principles

10^4 Papers on in 2012 alone

Why so many papers?

- Mass and stiffness, or density and elastic modulus can be measured statically
- Damping is a dynamic quantity and can only be measured by examining a dynamic response
- In many cases, intrinsic damping is small, making it even more difficult to measure
- There is no first principle, such as Hooke's law that stands up to experimental validation, from which to model damping (deformation and rate dependent)

Review of Some Basic Concepts

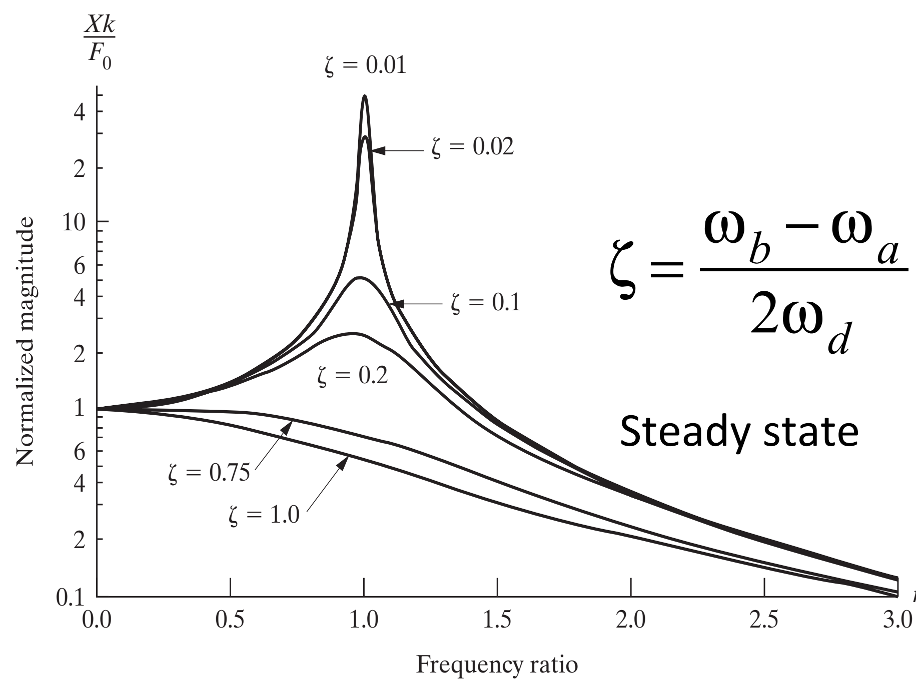


$$\delta = \ln \frac{x(t)}{x(t+T)} \qquad \zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}}$$

transient

$$\eta = 2\zeta$$

But only at resonance!



$$\zeta = \frac{\omega_b - \omega_a}{2\omega_d}$$

Steady state

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The Problem between Structural Models and Material Modeling

- Structural models look like this

$$\frac{\partial^2}{\partial t^2} w(x,t) + \frac{EI}{\rho A} \frac{\partial^4}{\partial x^4} w(x,t) + \frac{C_d I}{\rho A} \frac{\partial^5}{\partial x^4 \partial t} w(x,t) + \frac{C_1}{\rho A} \frac{\partial}{\partial t} w(x,t) = 0$$

- Which emits *many* modes of vibration
- Experimental coupon measurements give loss factors for each mode and a modulus, interpreted as modal damping ratios and frequencies: $\zeta_n, \ \omega_n$

Measured at coupon level → EI

Determined analytically → β_n^4

Measured from structural response → ω_n^2, ζ_n

$$\omega_n^2 = \frac{EI}{\rho A}\beta_n^4 \quad \text{agrees with expermental data}$$

$$2\zeta_n\omega_n = \left[\frac{C_d I}{\rho A}\beta_n^4 + \frac{C_1}{\rho A}\right], \quad \text{however:}$$

Estimates of the coefficients C_1 and C_d based on modes are not consistent

1-2	0.0724	0.7092 x10[6]
1-3	0.2402	0.2699
1-4	0.6053	0.0873
1-5	0.6157	0.0856
1-6	1.3901	0.0323
1-7	1.6867	0.0221
1-8	1.8039	0.0199
1-9	1.7561	0.0205

Yet, if we estimate these damping coefficients using structural measurements only, instead of coupon measurements, we can identify consistent values of C_d and C_1 across different experiments and hardware

This situation gets worse if we use a hysteretic model

Constitutive Model

$$\sigma(t) = E_0\varepsilon(\tau) + \int_0^t g(t-\tau)\frac{d\varepsilon(\tau)}{d\tau}d\tau \Rightarrow$$

Structural Model

$$\rho A\frac{\partial^2}{\partial t^2}w(x,t) + \frac{\partial^2}{\partial x^2}\left[EIw_{xx}(x,t) - \int_{-r}^{0} g(s)w_{xx}(x,t+s)ds\right] = 0$$

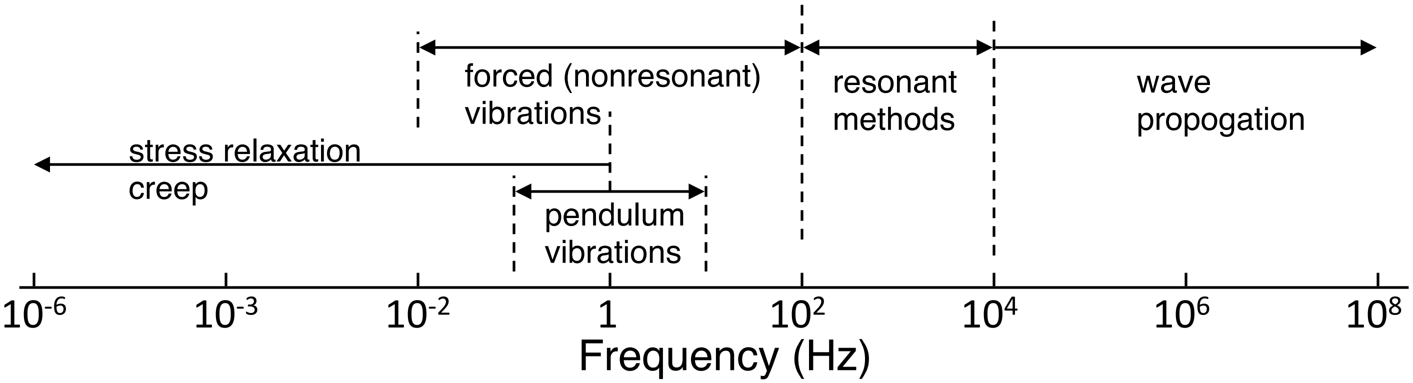
Experimental Model

$$E' = E[1+\eta(\omega)j]$$

$$\eta = \frac{E''}{E'} = \frac{\text{loss modulus}}{\text{storage modulus}}$$

Overview of Characterization of Damping Properties

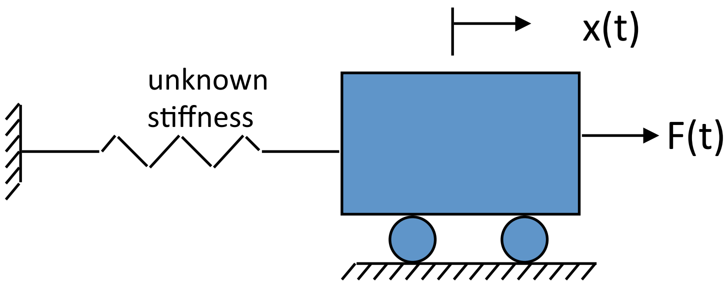
- Different approaches for different frequency ranges



ref. Ward, *Mechanical Propertis of Solid Polimers*, Figure 6.1

- Stress relaxation/creep
  - large or small deformations measured over time
- Nonresonant testing
  - displacement due to known force measured directly
- Resonant testing
  - modulus backed out from frequency and damping of a simple structure (cantilever beam)

Complex Stiffness Model for Viscoelastic Behavior



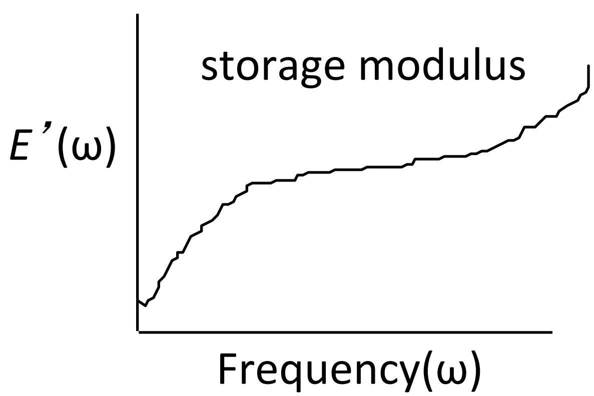
complex stiffness $$k(\omega)=\frac{F(\omega)}{X(\omega)}$$

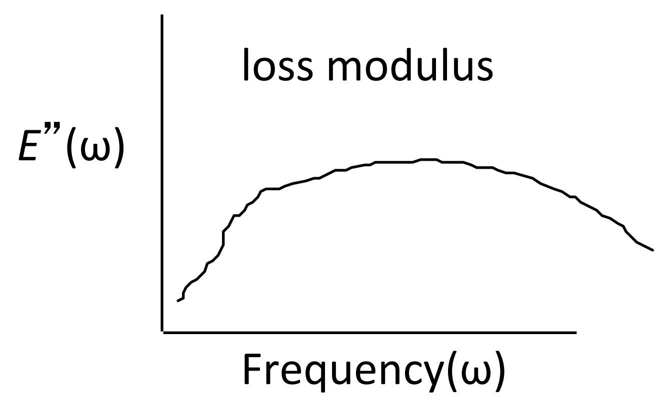
For a viscoelastic behavior the complex modulus becomes:

$$k(\omega)=E(\omega)=E'(\omega)+E''(\omega)i=E'(\omega)\left[1+\eta(\omega)i\right]$$

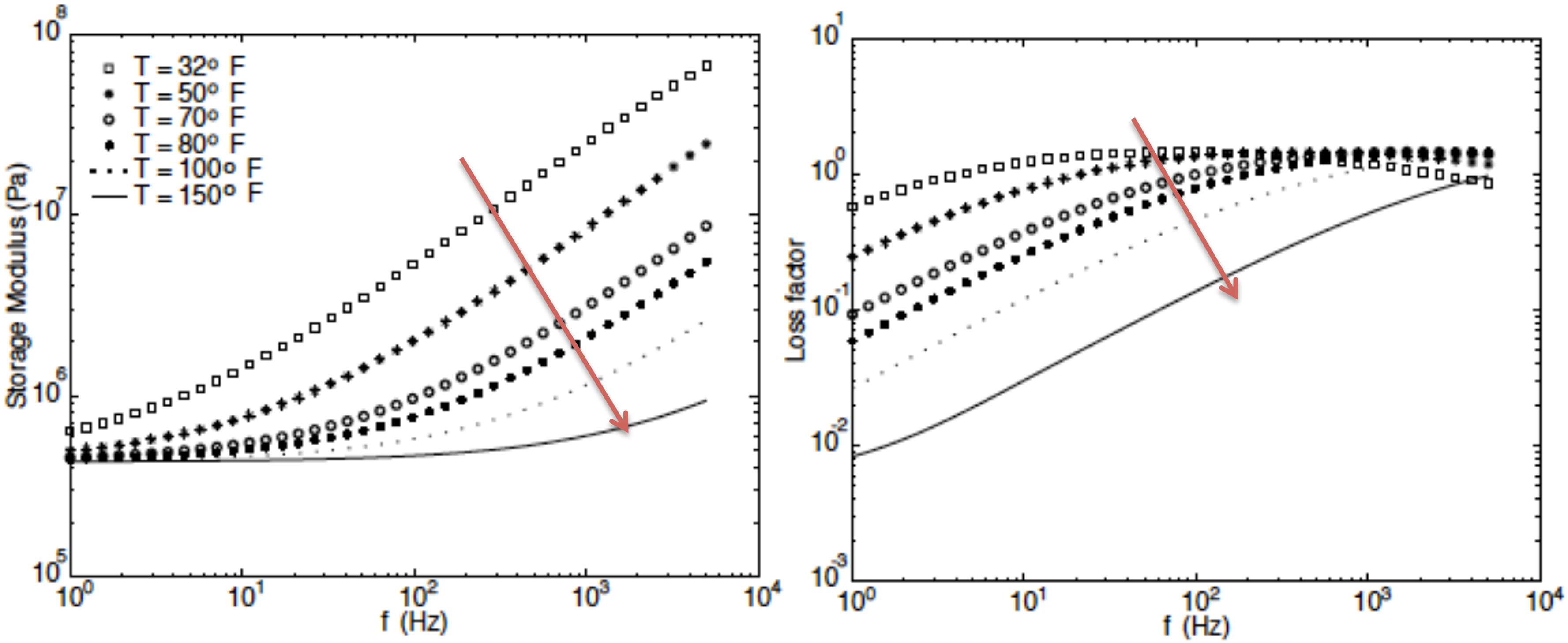
$$\tan\delta=\frac{E''}{E'}=\frac{\text{loss modulus}}{\text{storage modulus}}$$

Forming the basis of measurement schemes:





Temperature and Frequency Dependence of a Typical Commercial Damping Material



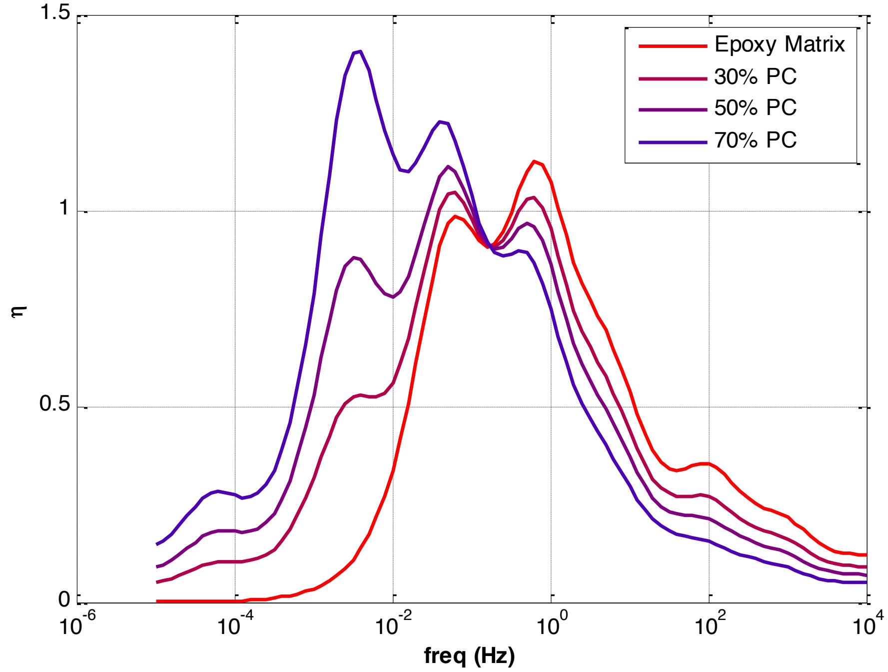
The Major Issues

- A need for material systems and structures with *uniform* damping properties at harsh and extreme conditions
- Predictive macro scale models for such materials
- Predictive models of damping properties the span a range of frequencies and temperatures
- A need for multifunctional damping materials that:
  - Can be used to predict damage
  - Can heal themselves
  - That can respond to the environment
- Test apparatus capable of measuring damping at extremes
  - Frequency and temperature limit current abilities to measure properties
  - Coupon testing versus structure testing is an issue

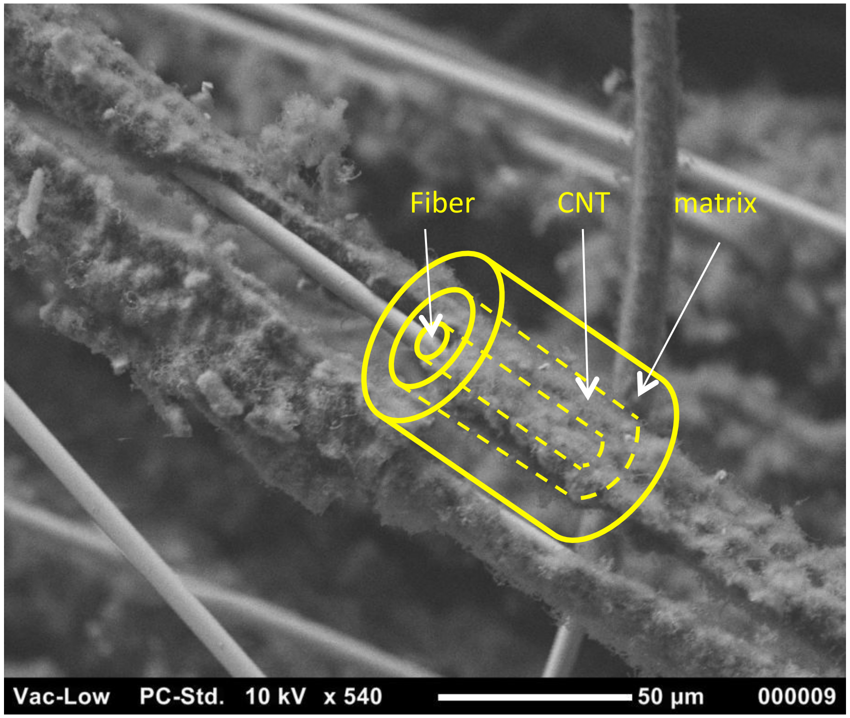
Some Random Examples and Ideas Follow

- Infusion of nano particles to tailor damping properties
- Combining SMA with High Temperature materials
- Vascular Damping
  - Fluid induced damping
  - Particle induced damping
- Multifunctional approaches
  - Integrated with active components and sensing

Effects of Adding Viscoelastic Particles To an Epoxy Matrix

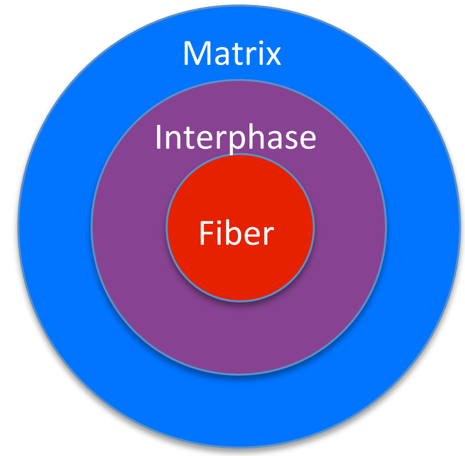


Fuzzy fiber coated with CNT



Sample composite analysis

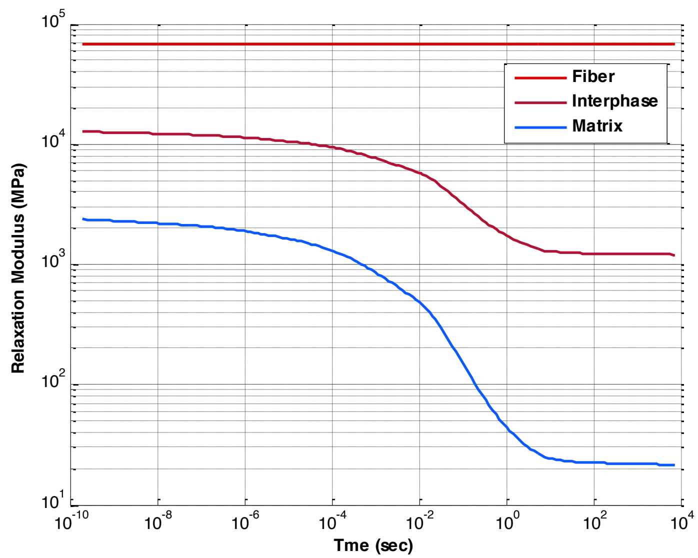
Fuzzy fiber (Glass fiber with CNT on surface)-Epoxy composite

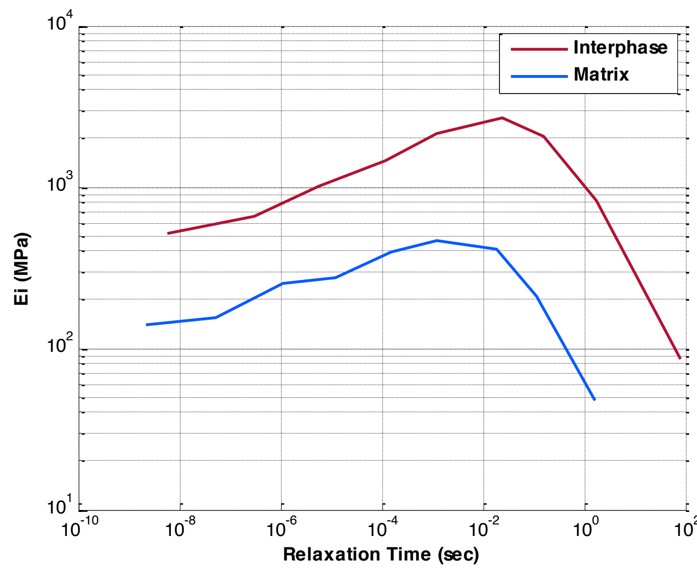


Assumptions

- Unidirectional fibers
- Fiber diameter: 7 µ
- Interphase thickness: 5 µ
- Interpolating the relaxation functions of the fiber and matrix to obtain that of the interphase layer.

Relaxation modulus and relaxation spectrum of the interphase layer obtained by interpolation





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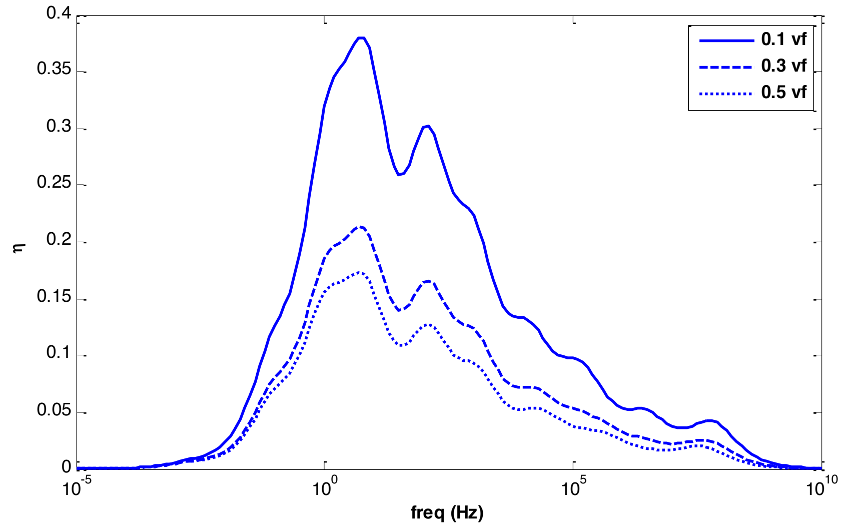
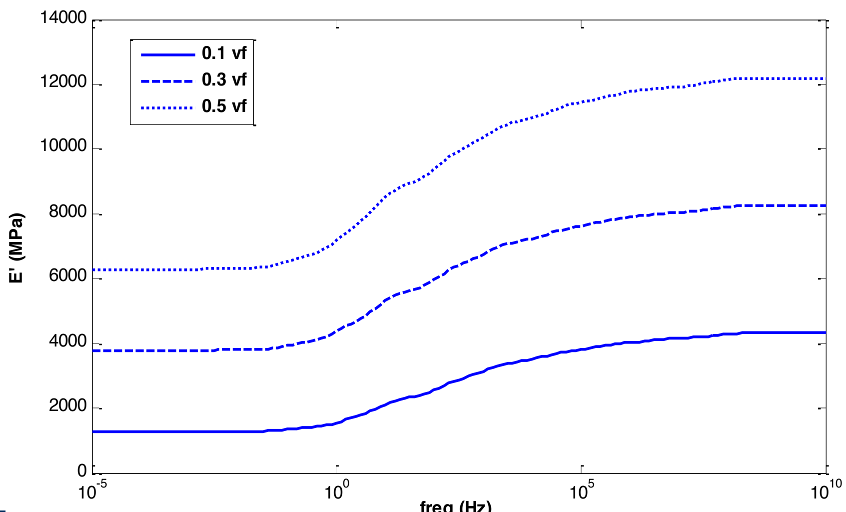
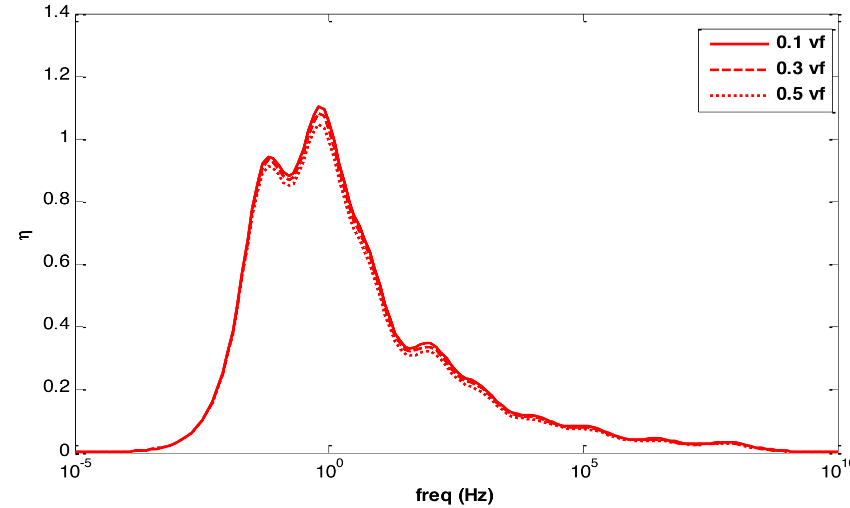
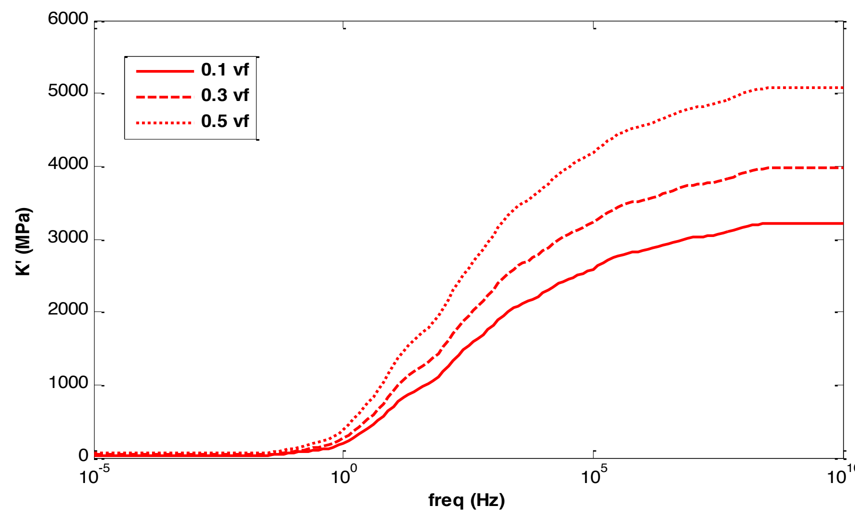
Axial Young's Modulus (E_{11})



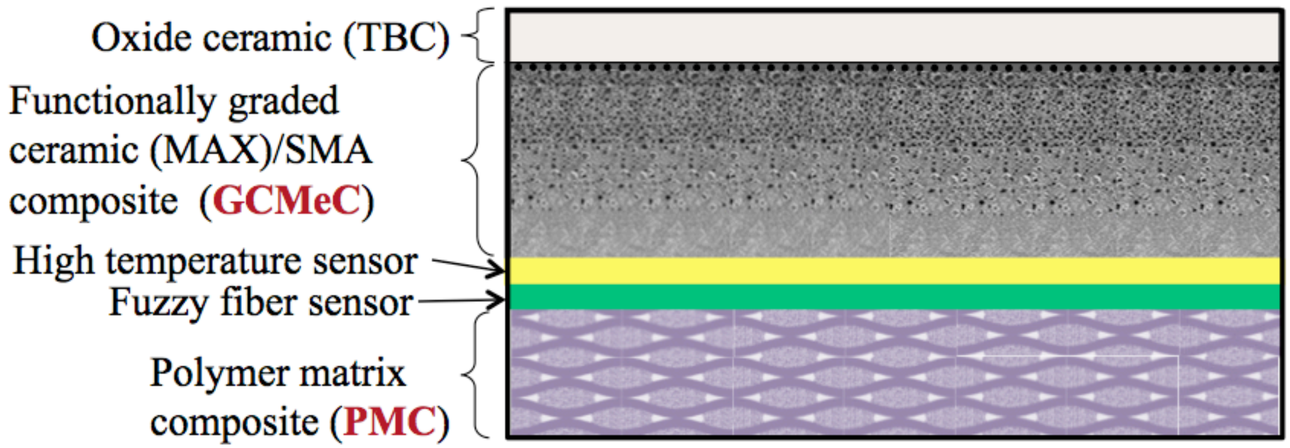


In Plain Bulk Modulus (K_{23})





Combining SMA with Max Phase materials to produce hybrid composites
(TAM MURI/AFOSR, Stargel PM, Lagoudus, PI)



Produces unique damping and temperature properties

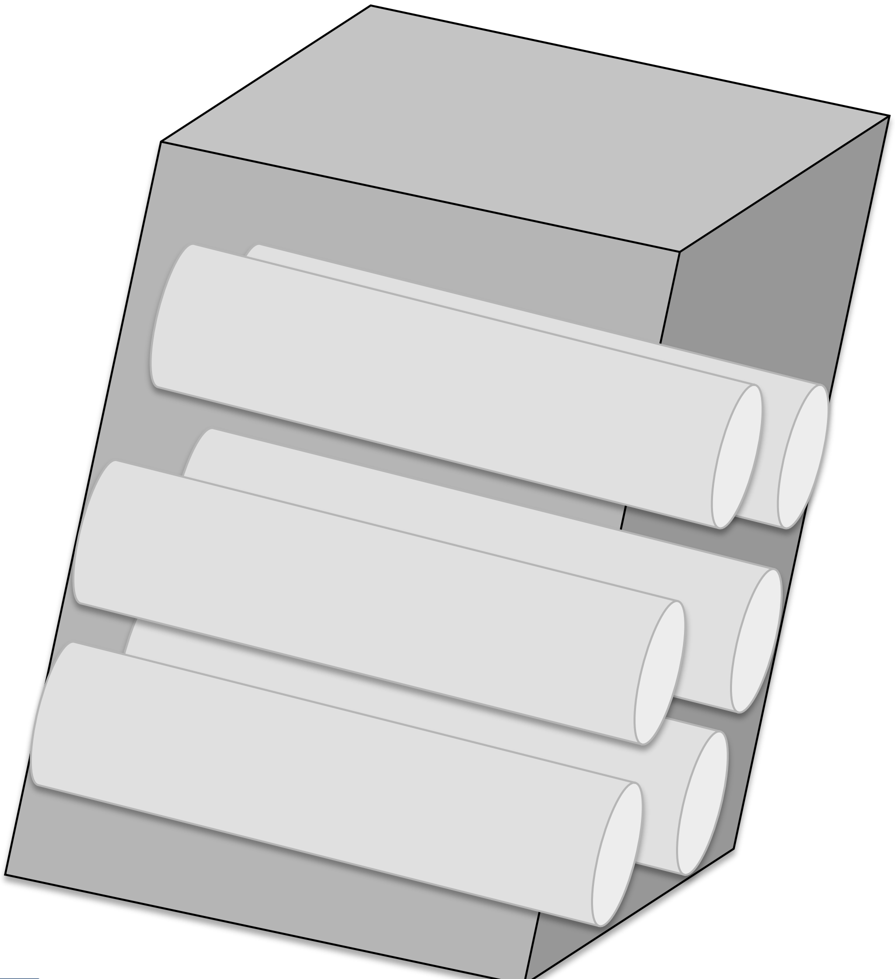
*Graded Ceramic Metal Composite

A metric proposed by Rod Lakes

- From the material measurement point of view the $|E^*|\eta > 0.6\ \text{GPa}$

  for good damping properties
- Here E^* is the complex modulus
- For most materials this is only true for a narrow range of temperature near the glass transition temperature
- He uses the concept of "negative stiffness" to try and solve this problem

An Idea: Vascular Damping



- Starting with the Vascular work of White and Sottas, add either:
  1. Fluid flow to control damping
  2. Or in closed cells with particles to form particle dampers

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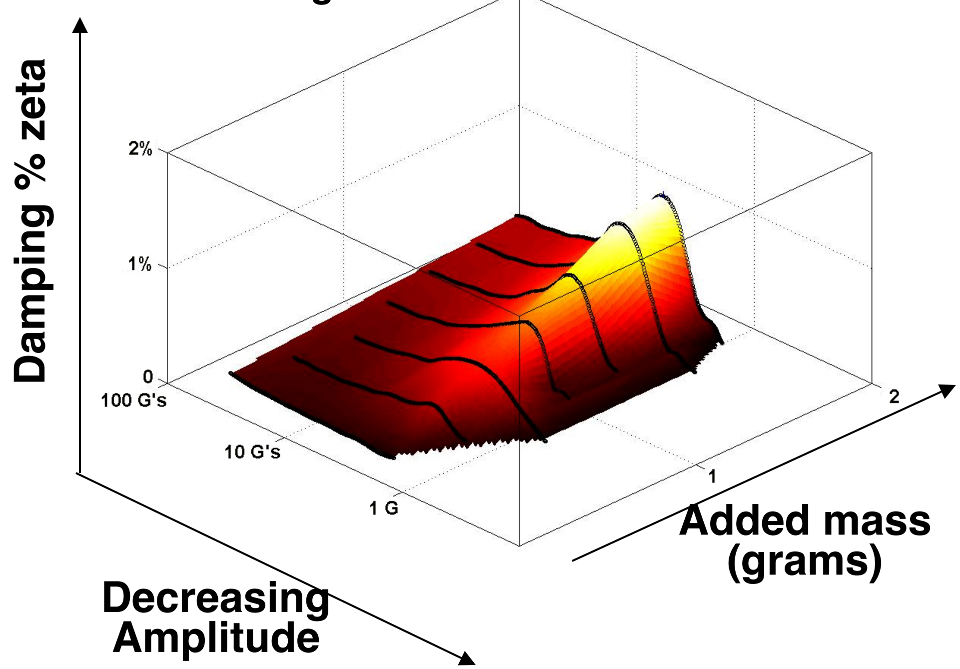
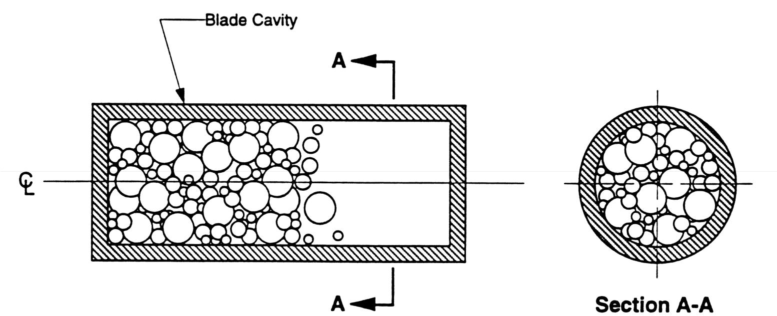
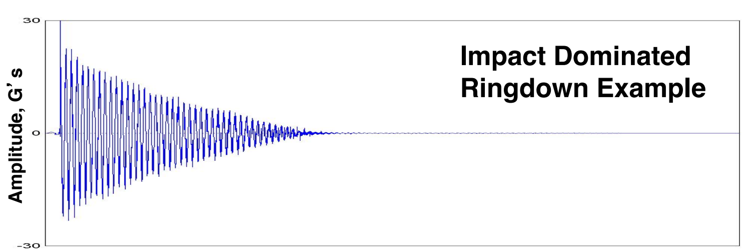
Particle Damping

- Advantages
  - Broad useful temperature ranges
  - Not mode/frequency specific
  - Non-outgassing
- Variety of loss methods
  - Impact (particle-particle & particle/cavity)
  - Friction (particle-particle & particle/cavity)

Example multiple particle behavior for increasing mass

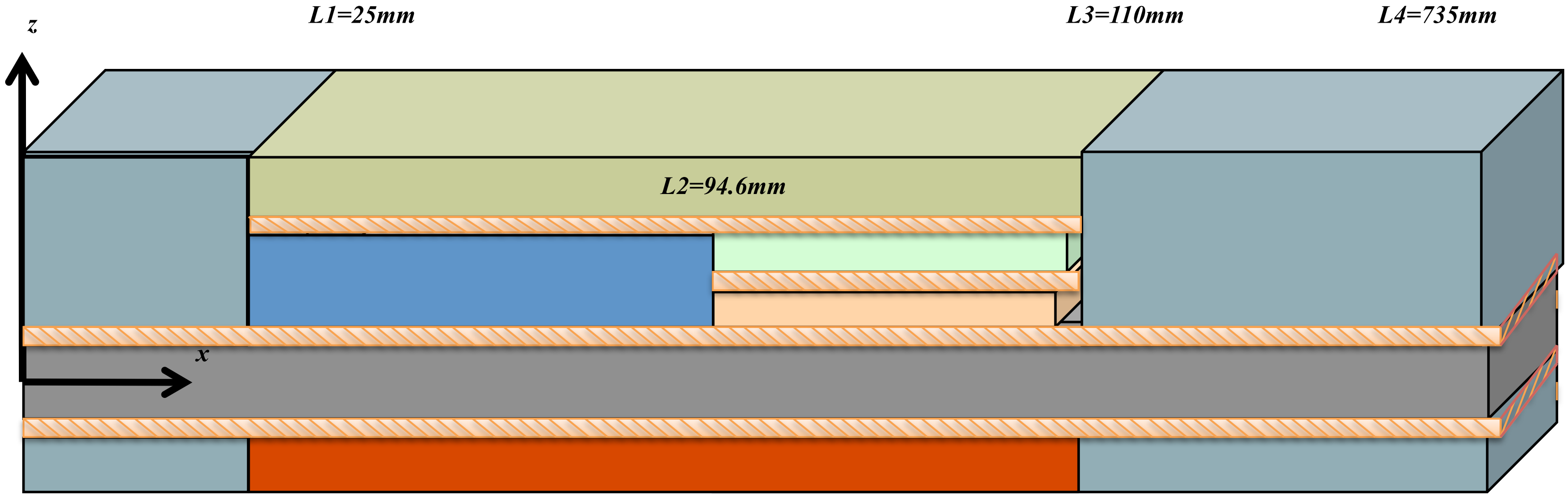






- Caveats
  - Empirical based design
  - Amplitude dependent behavior
  - Behavior is also dependent on cavity orientation to local quasi-static acceleration field
  - Multiple other parameters can influence damping performance

Electronic Damping: Multifunctional Composites



- A. Flexible Solar Panel
- B. QP16N (Harvester, Sensor)
- C. Thinergy Thin Film Battery
- D. Printable Circuit Board (PCB)
- E. Fiberglass Substrate
- F. MFC(Actuator)
- G. Foam, Fiberglass Composite
- H. Epoxy DP 460, Kapton

Self Charging + **Self Sensing** + **Controllable Damping**

Measurement Issues

- Damping requires a dynamic load
- Usually done on coupon size materials using a frequency sweep, but the models needed are structural
- Measurements are at steady state, but transients are often of interest and the loss factor (measured) is twice the damping ratio ONLY AT RESONANCE

Measurement and Modeling Issues are Intertwined

- In order to use material properties effectively they must be fit well into structural mechanics models
- DMA etc. measure properties in limited frequency and temperature ranges and use sine sweeps
- The values are suspect when placed into FEM codes.
- Structural codes are clumsy with hysteresis and nonlinearity

Is there merit in using Macro Ideas at the Material level?

- Many devices are successful at the macro level:
  - Vibration absorbers
  - Vibration isolators
  - Active control
  - Magnetic (eddy current) dampers
  - MR dampers
- Can these concepts be down scaled to a multifunctional material concept?

Is there Merit in Multi scale modeling of damping?

- Only a few papers attempted this (Liu, Wang and Bakis, 2010 for CNT nano ropes)
- Still focused on using the loss factor concept under cyclic loading
- But does have a connection between nano scale and structural scale, a first

Why Should the Air Force Be Interested?

- Bladed disks in low and high temperature stages of jet engines are in need of damping to prevent high cycle fatigue
  - High damping at high temperatures would provide a major breakthrough in blisk designed jet engines
- Precision maneuvering of flexible space craft requires damping to control transients
  - Low temperature damping in space craft (e.g. optical payloads)
  - Damping needed to mitigate shock and vibroacoustic response in lift off
- Aeroelastic stability and sonic fatigue in aircraft

More Potential AF Applications

- Prevention of store induced flutter
  - Current mounts are limited in frequency range
  - Reconfiguration requires new flutter tests
  - A broad band damping material for mounts could solve this problem
- General fatigue of AF structures would be enhanced by higher damped structures

Summary: 3 Main Issues

1. Damping materials are temperature and frequency dependent
2. Damping falls off in extreme environments
3. There is a miss match damping as seen/ measured by material engineers and structural engineers

Can multifunctional approaches solve these problems?