Vibration damping

Topic 12

Reading assignment

1. http://www.sensorsmag.com/articles/0202/30/main.shtml Magnetorheological fluid damping
2. No. 22 under "Publications: other" in http://www.wings.buffalo.edu/academic/department/eng/mae/cmrl
3. Chung, Composite Materials, Ch. 12.
4. Google: "Viscoelastic Damping 101"

Supplementary reading

No. 124 under "Publications : cement" in
http://www.wings.buffalo.edu/academic/department/eng/mae/cmrl

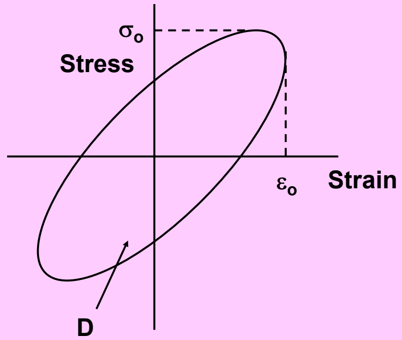
Methods of vibration reduction

- Increase damping capacity
- Increase stiffness (modulus).

- http://www.kettering.edu/~drussell/Demos/SHO/damp.html
- The black mass is undamped and the blue mass is damped (underdamped). After being released from rest the undamped (black) mass exhibits simple harmonic motion while the damped (blue) mass exhibits an oscillatory motion which decays with time.

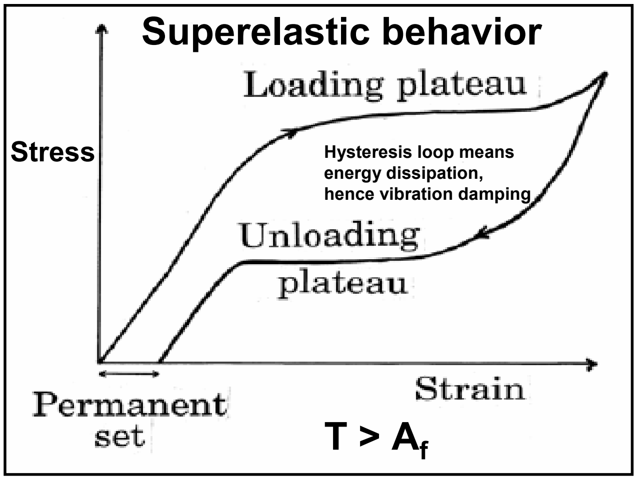
- **Damping is the conversion of mechanical energy of a structure into thermal energy.**
- **The amount of energy dissipated is a measure of the structure's damping level.**
- **Damping is very important with earthquakes since it dissipates the destructive energy of an earthquake which will help reduce the damage to the building.**

Hysteresis loop for a viscoelastic material



D = energy dissipation per cycle

Superelastic behavior

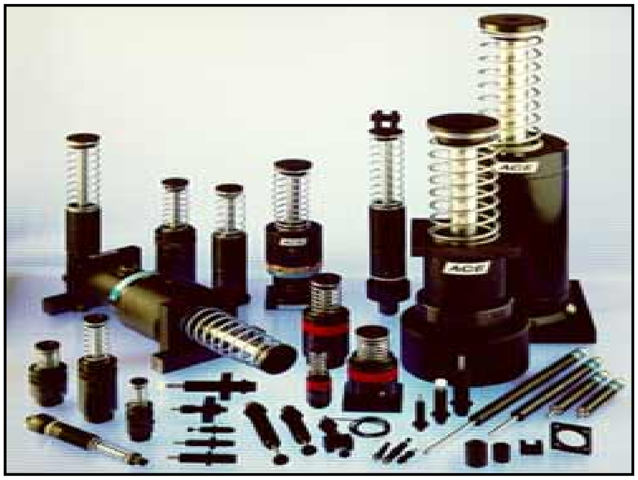


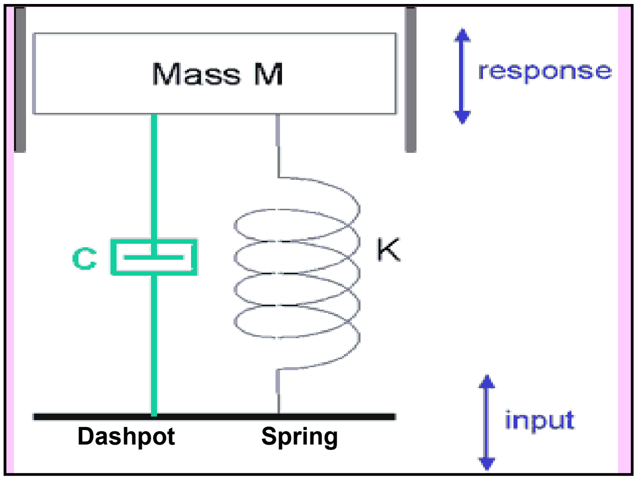
Hysteresis loop means energy dissipation, hence vibration damping

T > A_f

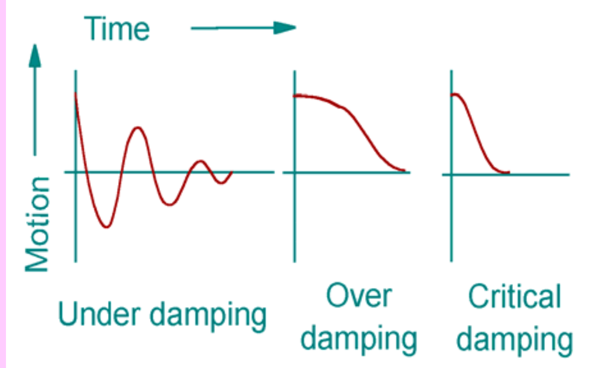
The more is the hysteresis in the stress-strain curve, the greater is the energy dissipation, and hence the higher is the damping ability.

- Consider the suspension of your automobile, supporting the body mass. You have four springs.
- You also have four friction elements, variously called dampers or dash pots or shock absorbers. Don’t try to drive without them!
- Here are some friction elements – dampers – that you can see.





- Let's diagram our hardware. We have a "sprung mass" **M** and a spring with stiffness **K**.
- We also have a friction or damping element **C**.
- **C** is not always visible, but is always present. No system exists without some damping

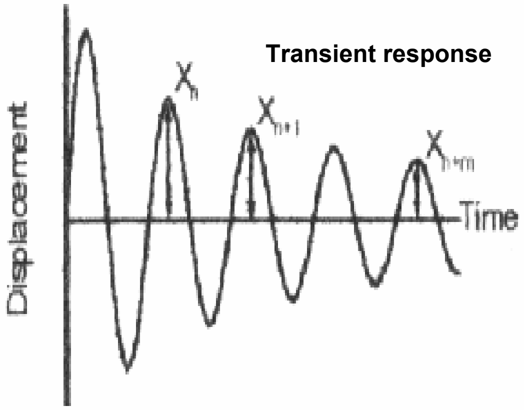


- **Damping is the decrease in amplitude with time due to the resistance of the medium to the vibration.**
- **Damping occurs progressively as energy is taken out of the system by another force such as friction.**
- **If the damping is enough that the system just fails to oscillate, then it is said to be critically damped. Damping more than this is referred to as over damping and less is similarly underdamped.**

Critical damping

The minimum damping that will prevent or stop oscillation in the shortest amount of time.

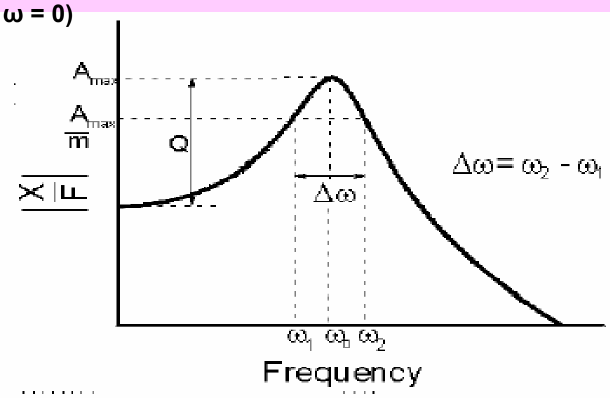
Underdamped



Log decrement

$$\delta = \frac{1}{m} \ln \frac{x_n}{x_{n+m}}$$

Q = amplification factor (ratio of the response amplitude at resonance ω_0 to the static response at $\omega = 0$)



Half-power bandwidth method (3 dB method)

Loss factor

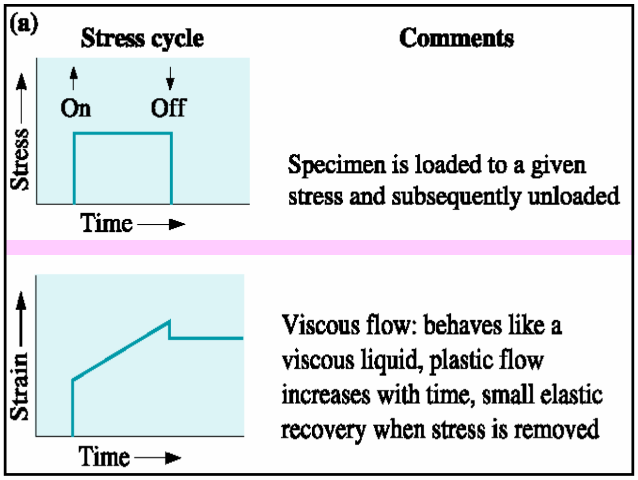
$$\eta = \frac{\Delta\omega}{\omega_o}$$

Vibration damping

- Passive damping
- Active damping

Viscous material

A material in which the strain develops over a period of time and the material does not go to its original shape after the stress is removed.

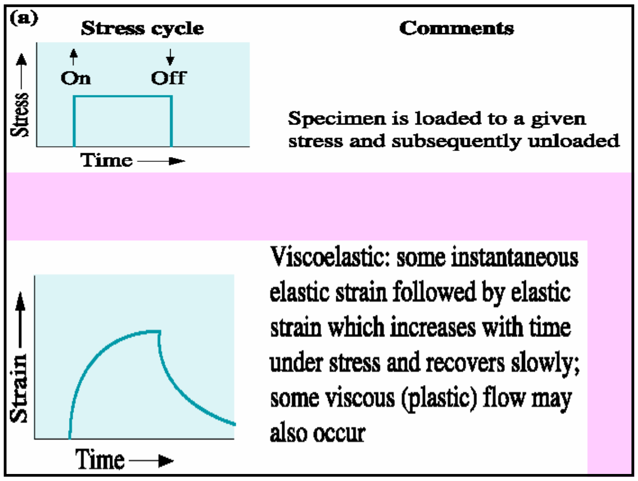


Specimen is loaded to a given stress and subsequently unloaded

Viscous flow: behaves like a viscous liquid, plastic flow increases with time, small elastic recovery when stress is removed

Viscoelastic material

- A material in which the total strain developed has elastic and viscous components.
- Part of the total strain recovers similar to elastic strain.
- Some part of the total strain recovers over a period of time.
- Examples: polymer melts.

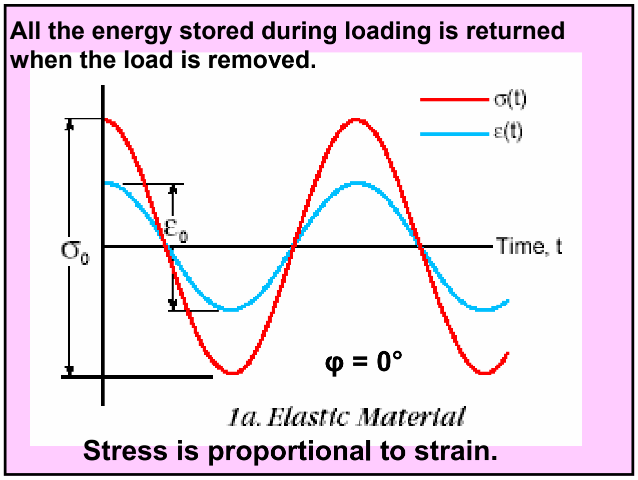


Comments

Specimen is loaded to a given stress and subsequently unloaded

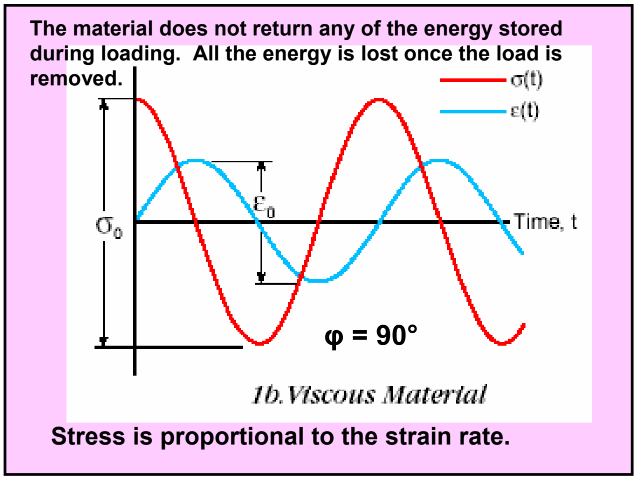
Viscoelastic: some instantaneous elastic strain followed by elastic strain which increases with time under stress and recovers slowly; some viscous (plastic) flow may also occur

The combined viscous and elastic behavior (viscoelasticity) can be examined by determining the effect that an oscillating force has on the movement of the material.


All the energy stored during loading is returned when the load is removed.

1a. Elastic Material

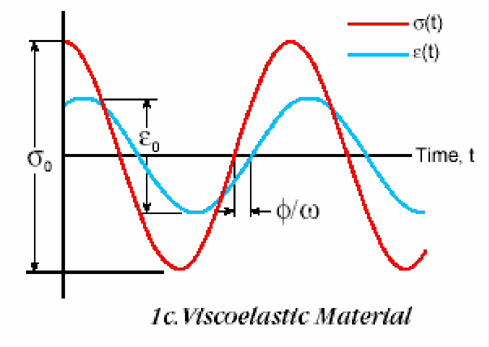
Stress is proportional to strain.


The material does not return any of the energy stored during loading. All the energy is lost once the load is removed.

1b. Viscous Material

Stress is proportional to the strain rate.

Some of the energy stored is recovered upon removal of the load; the remainder is dissipated in the form of heat.



1c. Viscoelastic Material

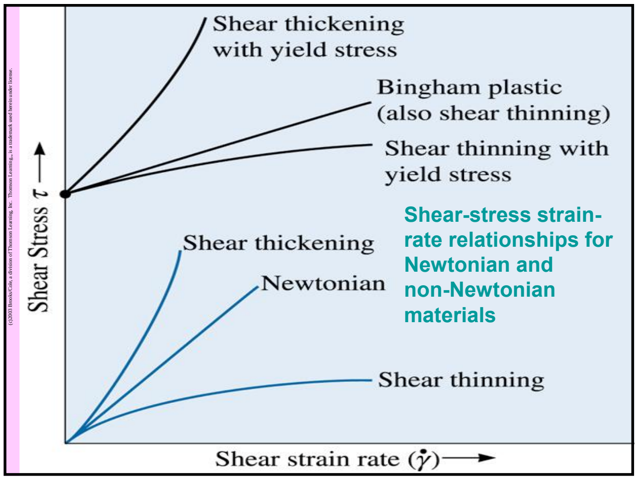
The angel φ (0 < φ < 90°) is a measure of the damping level.

Viscosity

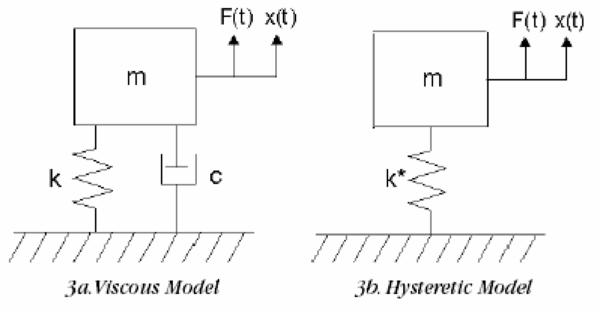
- Measure of resistance to flow
- Defined as the ratio of shear stress to shear strain rate
- Unit: Poise or Pa.s
- 1 Pa.s = 10 P = 1000 cP

The viscosity (η) is the tendency of the fluid to resist flow and is defined by:

$$\eta = \frac{\text{shear stress}}{\text{strain rate}} \quad (\text{Pa s})$$



Shear-stress strain-rate relationships for Newtonian and non-Newtonian materials



3a.Viscous Model

3b. Hysteretic Model

Complex modulus

$$E^* = E_1 + E_2 i = \frac{\sigma_o}{\varepsilon_o} e^{i\phi}$$

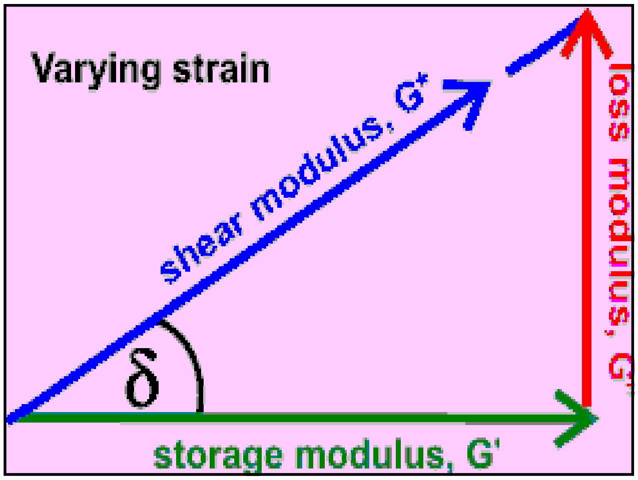
G* = G' + iG"

where G* is the complex shear modulus,

G' is the in-phase storage modulus and

G" is the out-of-phase similarly-directed loss modulus;

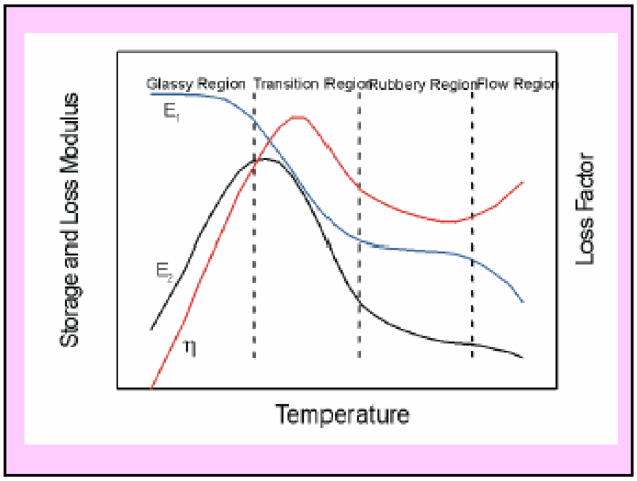
G* = $\sqrt{(G'^2 + G''^2)}$.

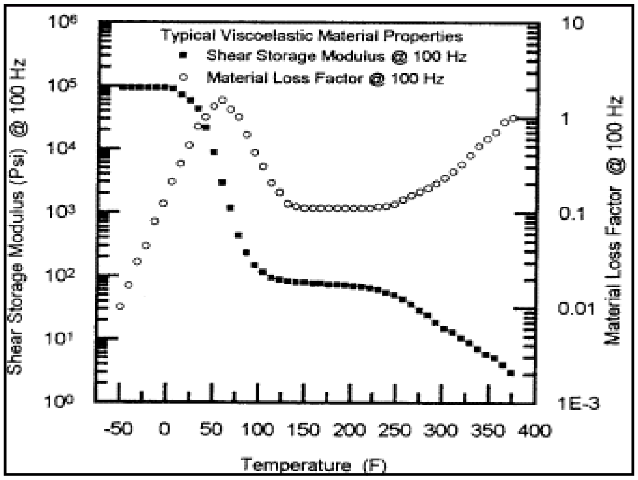


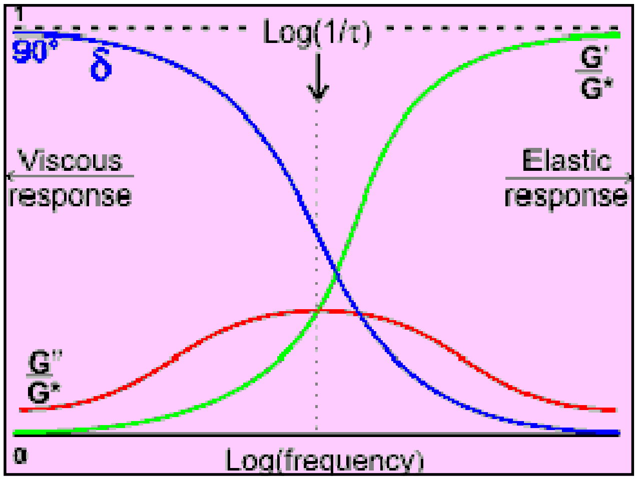
$\tan \delta = G''/G'$

where $\tan \delta$ (also called loss tangent) quantifies the balance between energy loss and storage.

As tan 45° =1,
a value for $\tan \delta$ greater than unity indicates more "liquid" properties, whereas one lower than unity means more "solid" properties, regardless of the viscosity.







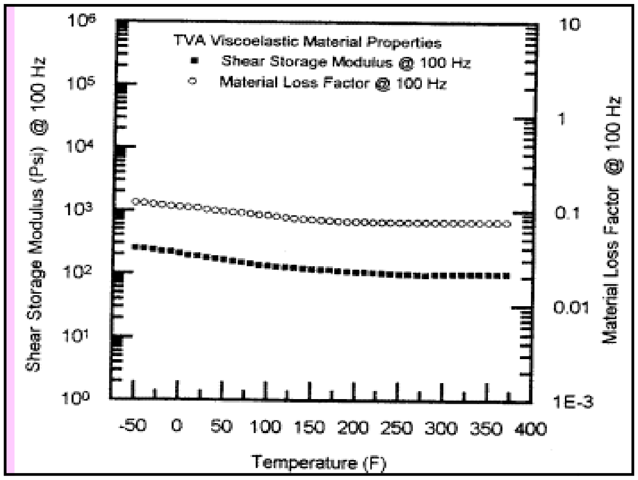
$G^* = G' + iG''$

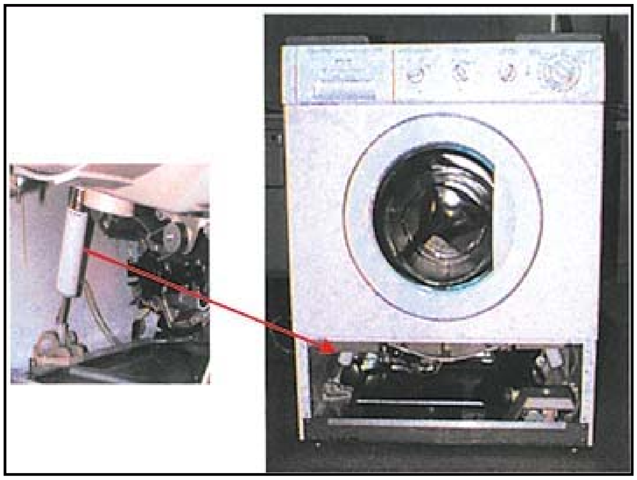
G is the storage modulus and

G'' is the loss modulus;

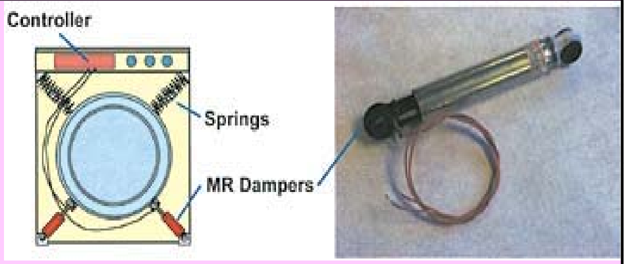
The frequency where these parameters cross over corresponds to a relaxation time (τ) specific for the material.

Application of a **Tuned Vibration Absorber (TVA)** is sometimes the best option for control of unwanted noise/vibration. This countermeasure is particularly appropriate when the noise/vibration issue occurs for a single frequency, or across a very narrow frequency range.

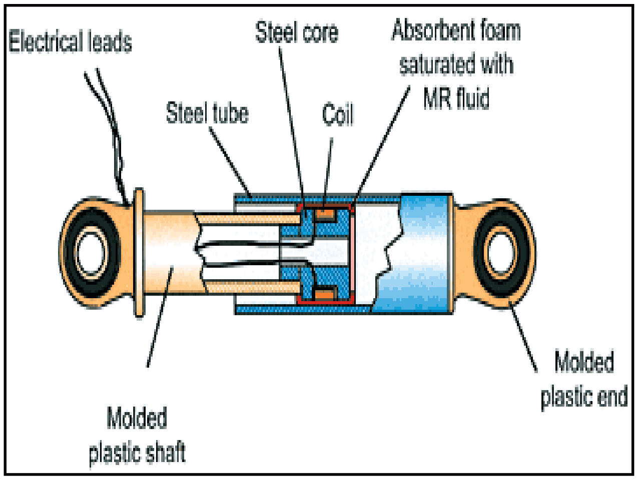




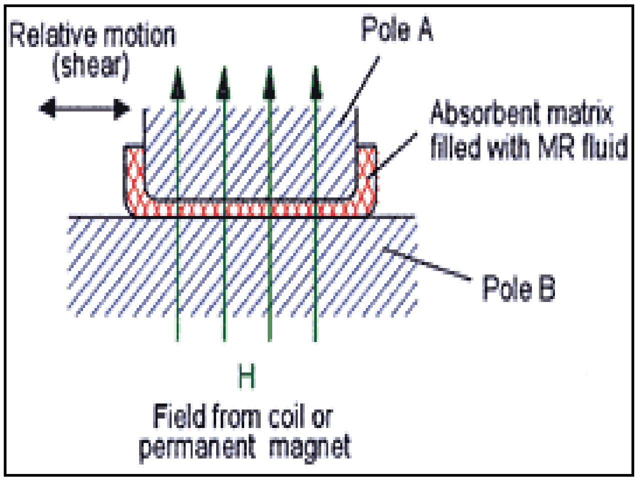
A variable damping system based on magnetorheological fluid sponges can help control the vibratory motion of a household washing machine during its spin cycle. Damping is switched on as the drum passes through resonance and off again at the highest speeds for optimum vibration isolation. The system permits the drum to rotate at speeds high enough to function as a centrifuge, but without the violent shaking familiar to every user.

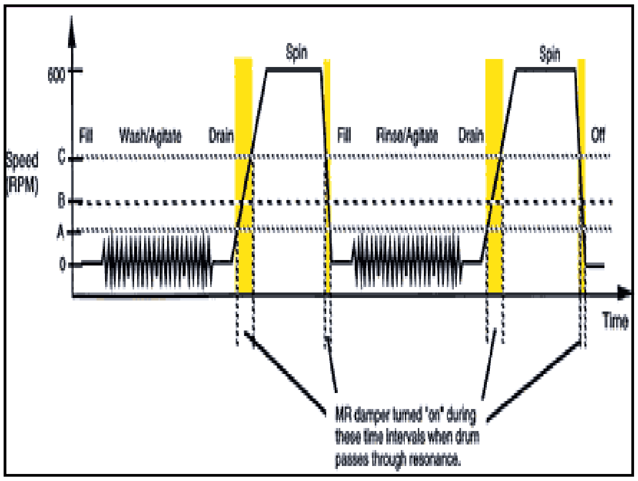


Conventional springs and magnetorheological dampers work together to stabilize a home washing machine during the spin cycle.



- A simple, inexpensive magnetorheological fluid sponge designed for incorporation into washing machines consists of a steel bobbin and coil surrounded by a layer of foam saturated with MR fluid. The elements constitute a piston on the end of the shaft that is free to move axially inside a steel housing that provides the magnetic flux return path. The damping force is proportional to the sponge's active area.





By activating the damper while the washing machine tub is passing through resonance, a degree of vibration control is achieved not possible with conventional springs alone. The damping mechanism is switched off at the greatest speeds, when the mechanical springs provide vibration isolation.

Constrained layer damping

- **Embedding a viscoelastic layer in a structural material**
- **Shear deformation of viscoelastic layer provides energy dissipation.**

Damping due to interfaces

Slight slippage at interface during vibration providing a mechanism for damping

Damping due to defects

Defects such as dislocations contribute to damping.

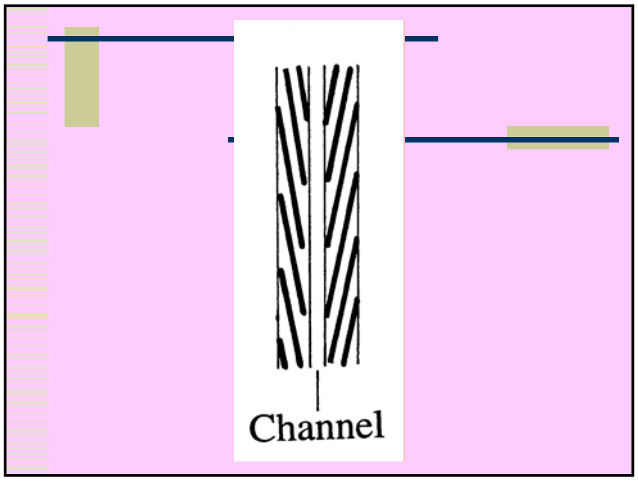
Use of interfaces for damping

Discontinuous nanofiber between continuous conventional fiber layers for damping enhancement

Tough competition with composites with viscoelastic interlayer for damping

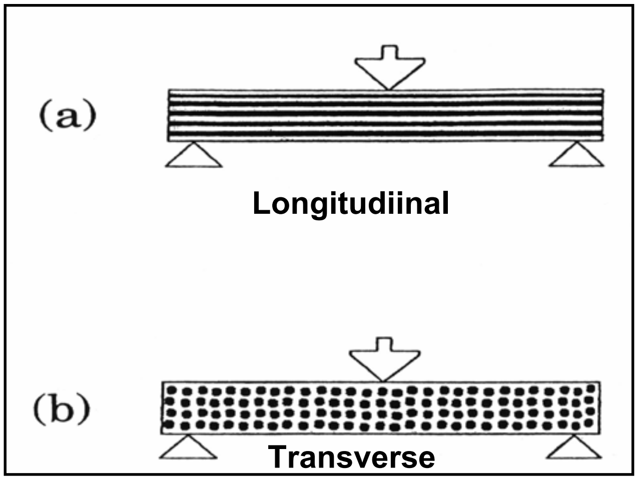
Hybrid composite composition

- Nanofiber: 0.6 vol.%
- Continuous carbon fiber: 56.5 vol.%



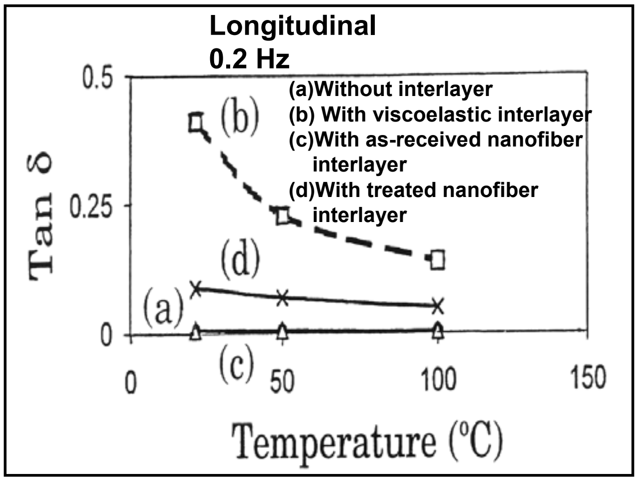
Carbon nanofiber

- Fishbone morphology
- 0.16 micron diameter
- Discontinuous
- Intertwined
- Hollow channel along axis of nanofiber
- Grown catalytically from methane



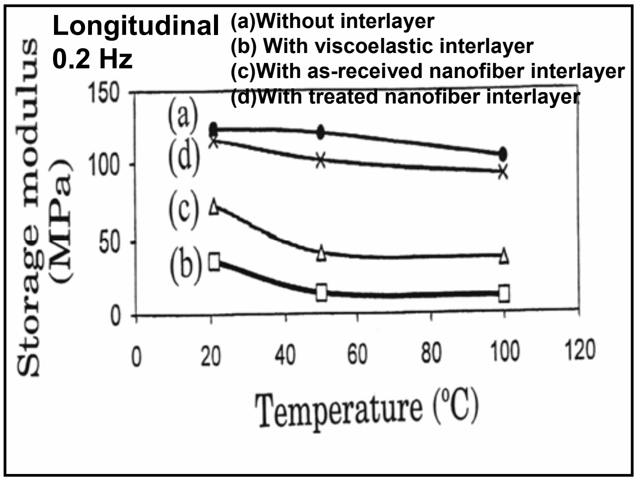
Nanofiber as interlaminar filler

- Nanofiber enhances both transverse and longitudinal vibration damping ability (due to large area of the interface between nanofiber and matrix)
- Nanofiber increases the transverse storage modulus (due to presence of nanofibers that are oriented near the direction perpendicular to the fiber layers)
- Nanofiber decreases the longitudinal storage modulus slightly.



Longitudinal
0.2 Hz

(a)Without interlayer
(b) With viscoelastic interlayer
(c)With as-received nanofiber interlayer
(d)With treated nanofiber interlayer



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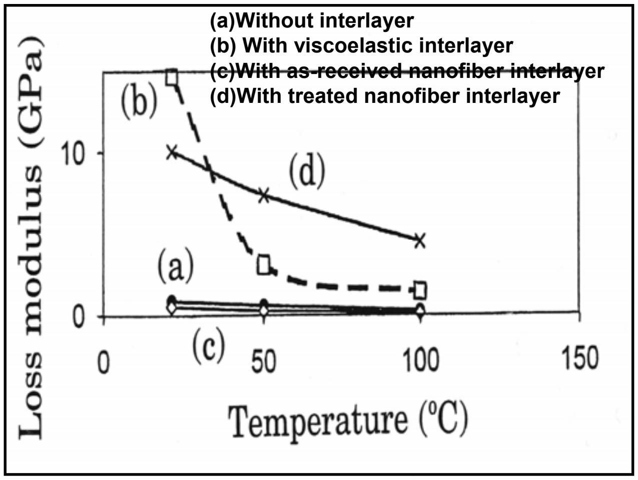

(a)Without interlayer
(b) With viscoelastic interlayer
(c)With as-received nanofiber interlayer
(d)With treated nanofiber interlayer

Table 2 Dynamic flexural properties of continuous carbon fiber nylon-6 matrix composites with and without interlayers, as determined by three-point bending [81]

Interlayer	None	Viscoelastic	As-received carbon filaments	Treated carbon filaments
1. tan δ				
Longitudinal				
0.2 Hz 1.0 Hz	0.008 ± 0.001 <0.0001	0.43 ± 0.05 0.36 ± 0.05	0.007 ± 0.001 0.001 ± 0.001	0.09 ± 0.02 0.001 ± 0.001
Transverse				
0.2 Hz 1.0 Hz	0.065 ± 0.005 0.080 ± 0.005	0.24 ± 0.05 0.22 ± 0.06	0.060 ± 0.005 0.090 ± 0.005	0.052 ± 0.005 0.073 ± 0.005
2. Storage modulus (GPa)				
Longitudinal				
0.2 Hz 1.0 Hz	127 ± 8 132 ± 9	37 ± 4 67 ± 5	66 ± 5 67 ± 3	115 ± 6 97 ± 5
Transverse				
0.2 Hz 1.0 Hz	9.6 ± 0.2 9.9 ± 0.3	3.8 ± 0.2 4.4 ± 0.2	6.1 ± 0.2 6.3 ± 0.2	10.2 ± 0.3 10.8 ± 0.3

Table 2 Dynamic flexural properties of continuous carbon fiber nylon-6 matrix composites with and without interlayers, as determined by three-point bending [81]

Interlayer	None	Viscoelastic	As-received carbon filaments	Treated carbon filaments
3. Loss modulus (GPa)				
Longitudinal				
0.2 Hz	1.0 ± 0.3	16 ± 1	0.35 ± 0.10	9 ± 5
1.0 Hz	<0.013	23.5 ± 1.5	0.067 ± 0.002	<0.097
Transverse				
0.2 Hz	0.62 ± 0.03	0.90 ± 0.20	0.067 ± 0.002	0.60 ± 0.05
1.0 Hz	0.79 ± 0.04	0.94 ± 0.20	0.500 ± 0.003	0.78 ± 0.05

Loss modulus = Storage modulus X Loss tangent

Table 3. Loss tangent, storage modulus and loss modulus of various polymers.

Material	Property	0.2 Hz	1.0 Hz	Ref.
PMMA	Loss tangent	0.093 ± 0.019	0.100 ± 0.038	87
	Storage modulus (GPa)	3.63 ± 0.24	3.49 ± 0.7	
	Loss modulus (MPa)	336 ± 70	375 ± 83	
PTFE	Loss tangent	0.1885 ± 0.0005	0.224 ± 0.008	87
	Storage modulus (GPa)	1.22 ± 0.05	1.34 ± 0.05	
	Loss modulus (MPa)	229 ± 9	300 ± 15	
PA-66	Loss tangent	0.043 ± 0.009	0.078 ± 0.035	87
	Storage modulus (GPa)	4.35 ± 0.05	4.45 ± 0.08	
	Loss modulus (MPa)	187 ± 41	349 ± 161	
Epoxy	Loss tangent	0.030 ± 0.007	0.039 ± 0.015	87
	Storage modulus (GPa)	3.20 ± 0.31	3.50 ± 0.07	
	Loss modulus (MPa)	105 ± 24	116 ± 36	
Neoprene rubber	Loss tangent	0.67 ± 0.14	1.12 ± 0.08	88
	Storage modulus (MPa)	7.45 ± 0.28	7.83 ± 0.11	
	Loss modulus (MPa)	6.72 ± 1.50	8.23 ± 0.76	

Table 1 Damping capacity (tan δ) and storage modulus of cement-based materials at room temperature, as determined by flexural testing (three-point bending). Note that cement paste has no sand, whereas mortar has sand.

	tan δ		Storage modulus (GPa)		
	0.2 Hz	1.0 Hz	0.2 Hz	1.0 Hz	Ref.
1. Cement paste (plain)	0.035	$<10^{-4}$	1.9	/	23
2. Cement paste with untreated silica fume[a]	0.082	0.030	12.7	12.1	71
3. Cement paste with treated[b] silica fume[a]	0.087	0.032	16.8	16.2	71
4. Cement paste with untreated silica fume[a] and silane[c]	0.055	/	17.9	/	23
5. Cement paste with untreated carbon fibers[d] and untreated silica fume[a]	0.089	0.033	13.3	13.8	71
6. Cement paste with untreated carbon fibers[d] and treated[b] silica fume[a]	0.084	0.034	17.4	17.9	71
7. Cement paste with treated[b] carbon fibers[d] and untreated silica fume[a]	0.076	0.036	17.2	17.7	71
8. Cement paste with treated[b] carbon fibers[d]and treated[b] silica fume[a]	0.083	0.033	21	22	71
9. Cement paste with untreated carbon filaments[d] and treated[b] silica fume[a]	0.089	0.035	10.3	10.9	74

a. 15% by mass of cement, b. Treated by silane coating, c. 0.2% by mass of cement, d. 0.5 vol.%, e. 1.0 vol.%, f. 30% by mass of cement

Table 1 Damping capacity (tan δ) and storage modulus of cement-based materials at room temperature, as determined by flexural testing (three-point bending). Note that cement paste has no sand, whereas mortar has sand. (Cont'd)

	tan δ		Storage modulus (GPa)		
	0.2 Hz	1.0 Hz	0.2 Hz	1.0 Hz	Ref.
10. Cement paste with treated[b] carbon filaments[d] and treated[b] silica fume[a]	0.106	0.043	11.3	11.4	74
11. Cement paste with untreated steel fibers[d] and untreated silica fume[a]	0.051	0.012	12.9	13.2	74
12. Cement paste with untreated steel fibers[e] and untreated silica fume[a]	0.046	0.011	13.0	13.6	74
13. Cement paste with latex[f]	0.142	0.112	/	/	24
14. Mortar (plain)	$<10^{-4}$	$<10^{-4}$	20	26	70
15. Mortar with treated[b] silica fume[a]	0.011	0.005	32	33	73
16. Mortar with untreated steel rebars	0.027	0.007	44	44	73
17. Mortar with sand blasted steel rebars	0.037	0.012	46	49	73
18. Mortar with untreated steel rebars and treated[b] silica fume	0.027	0.012	47	48	75

a. 15% by mass of cement, b. Treated by silane coating, c. 0.2% by mass of cement, d. 0.5 vol.%, e. 1.0 vol.%, f. 30% by mass of cement

Table 1 Dynamic flexural behavior of materials at 0.2 Hz.

Material	tan δ	Storage modulus (GPa)	Loss modulus (GPa)
Cement paste (plain)	0.016	13.7	0.22
Mortar (plain)	$< 10^{-4}$	9.43	< 0.001
Mortar with silica fume (treated) (15% by wt. of cement)	0.021	13.11	0.28
Aluminum, pure	0.019	51	1.0
Al/AlN_p (58 vol.%)	0.025	120	3.0
Zn-Al	0.021	74	1.5
Zn-Al/SiC_w (27 vol.%)	0.032	99	3.0
Carbon-fiber epoxy-matrix composite (without interlayer)	0.008	101	0.8
Carbon fiber epoxy-matrix composite (with vibration damping interlayer)	0.017	92	1.6
Neoprene rubber	0.67	0.0075	0.0067
PTFE	0.189	1.2	0.23
PMMA	0.09	3.6	0.34
PA-66	0.04	4.4	0.19
Acetal	0.03	3.7	0.13
Epoxy	0.03	3.2	0.11