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NOTE

Using Elastomers and Rubbers for Heat-Conduction Damping of Sound and Vibrations

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Airborne noise and structural vibrations have become unfortunate attributes of life, with many unwanted health, social, and economic effects. Viscoelastic polymers and rubbers have been widely used nowadays for acoustic and vibration damping.[1] Thanks to their remarkably high molecular friction, such materials can efficiently dissipate mechanical energy by means of spatial momentum transfer driven by the velocity gradient. Layered dampers consisting of alternating polymer and metal sheets have been commonly used in various applications.[2] In such damping devices, the motion of boundary sections of polymer layers is constrained by attached metal layers, whereas internal sections of polymer layers can still move relative to the metal sheets, thus yielding the velocity gradient required for dissipation via the molecular-friction mechanism.

Thermal conduction constitutes an alternative physical mechanism of dissipation of mechanical energy realizable by means of heat transfer driven by the temperature gradient.[3,4] The amount of heat produced by a given pressure is proportional to the thermal expansion coefficient,[4] and among solids, it is elastomers and rubbers that have the largest, liquid-like thermal expansion coefficients. Here we show that by optimizing the thickness of sheets of traditional layered dampers, one can activate and successfully utilize this alternative channel of energy dissipation. We present both numerical and testing results demonstrating that the heat-conduction dampers can be efficient and that under certain conditions of practical significance, they can compete with and even outperform traditional molecular-friction dampers. Our results thus suggest potential for a more efficient and tailored use of viscoelastic polymers and rubbers in a variety of existing acoustic and vibration damping applications such as reduction of railway-, highway-, and air-traffic-borne noise as well as vibration insulation of buildings, bridges, and other constructed structures.

Consider a film of thickness, h, equilibrated at temperature, T_0. Suppose that at time $t = 0$, the temperature of film's surfaces (boundaries) was suddenly changed to T_1 and has then been maintained at this value for all $t > 0$. Depending on the sign of temperature change, the heat will flow either in or out of the film until the whole film is equilibrated at this new temperature, T_1. The heat transfer is governed by equation $T_t = \chi T_{xx}$ with χ standing for the thermometric conductivity and subscripts t and x referring to the time and spatial derivatives, respectively. The solution of this equation states that the terminal approach to prescribed boundary temperature, T_1, will be exponential with characteristic time $\tau = h^2/\pi^2\chi$.

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It is known that adiabatic deformation of solids is accompanied by some temperature change, and for isotropic solids, the temperature change is proportional to the volume deformation. Suppose that an oscillating volume deformation of frequency, f, is applied to the film while the boundary temperature is maintained fixed. The resulting oscillating heat fluxes will then dissipate the mechanical energy, and the maximum of dissipation will be reached when condition $f\tau \approx 1$ is fulfilled. Accordingly, the related mechanical losses will also reach maximum under the same condition. For a rubber film of $h \approx 1$ mm with $\chi = 2 \times 10^{-7}$m^2/s from Table 1, one obtains $\tau \approx 1$ s, which corresponds to a peak frequency of $f \approx 1$ Hz, and upon thickness variations, the peak frequency should obviously shift as $f \propto h^{-2}$.

We have fabricated and tested a family of layered dampers made up of alternating equal-thickness layers of silicone rubber (MVQ Silicones GmbH, Weinheim, Germany) and steel. (See Figure 1). The frequency-dependent dynamic Young's modulus was measured on an Instron 1343 servo-hydraulic biaxial machine using static compression preload of 40 kN and oscillating tension/compression force with an amplitude of 5 kN. Delightfully, one observes the loss peaks exactly within the expected frequency range, and upon thickness variations, the peak frequency shifts as h^{-2}. All in all, it is the heat conduction mechanism that determines the loss characteristics of fabricated dampers.

The heat-conduction dampers operate in uniaxial, tension/compression mode of loading. However intrinsically, their performance is controlled by the magnitude of volume deformation inside the polymer layers. In general, the deformation fields inside layered dampers are spatially nonuniform, in both the lateral and transverse directions, and they also depend on the shape and size of the layers. However, in the limiting case of infinite-aspect-ratio layers, the lateral deformation is getting spatially uniform.[5] As a result, the governing equation set[4]

$$C\frac{\partial T}{\partial t} + \alpha K T_0 \frac{\partial}{\partial t}\,\mathrm{div}\,\mathbf{u} = \kappa \Delta T$$
$$(1-2\nu)\Delta\mathbf{u} + \mathbf{grad}\,\mathrm{div}\,\mathbf{u} = \frac{2}{3}(1+\nu)\alpha\mathbf{grad}T \qquad (1)$$

becomes 1D, and one can readily solve it numerically to estimate the utmost performance of heat-conduction dampers. In eq 1, variable t denotes the time, $\mathbf{u}$ is the displacement vector, T is the temperature, and T_0 is the initial, reference temperature before the deformation. For the definition of materials' moduli, see Table 1. All of them are supposed to be isotropic and spatially uniform inside polymer and steel layers. In finite element calculations, we have used implicit Crank−Nicolson time-stepping algorithm resulting from the weighted-residual Galerkin method

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Table 1. Some Typical Properties of Rubbers and Steels[a]

	C [J/(m^3·K)]	K (GPa)	ν	κ (W/(m·K))	α (1/K)
rubber	1.5×10^6	3	0.5	0.3	5×10^{-4}
steel	4×10^6	160	0.3	40	3×10^{-5}

[a] In solids, the difference between specific heats at constant volume and pressure is usually very small, so in this work, C stands for some mean specific heat per unit volume. As for the other parameters, K denotes the isothermal bulk modulus, ν is Poisson's ratio, κ is the thermal conductivity, and α is the volumetric thermal expansion coefficient. The thermometric conductivity, χ, is defined as the ratio of κ to C.

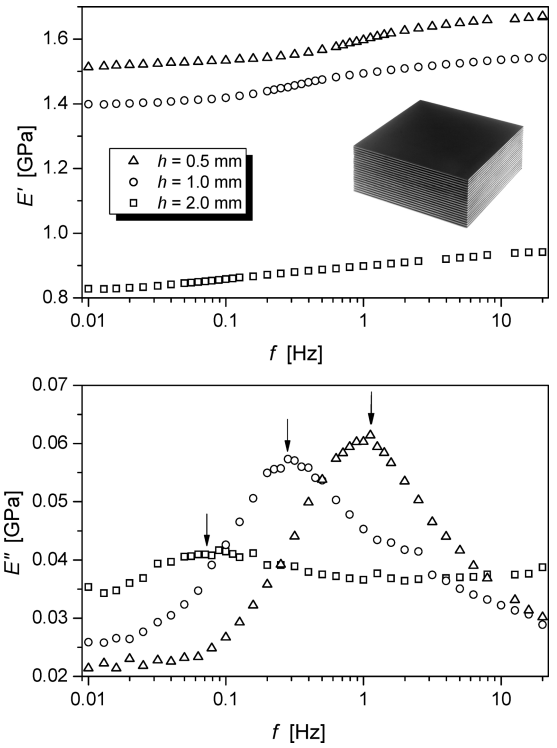

Figure 1. Measured dynamic Young's modulus $E = E' + iE''$ of heat-conduction dampers made up of alternating steel and polymer layers of equal thickness, h. E' stands for the stiffness modulus, whereas E'' stands for the loss modulus. The damper with $h = 1$ mm is shown in the Figure. All dampers had dimensions of about $10 \times 10 \times 4$ cm^3, with the latter value being the dampers' height. The three arrows are drawn at frequency positions related as 1:4:16, thus indicating that the peak frequency follows the thickness-frequency superposition principle $E''(f, h) = E''(fh^2)$ characteristic of diffusion-type thermal conduction process.

applied on semidiscrete time-space approximation of the governing equation set.[6] Periodic boundary conditions were applied in all directions. The (time) average rate of dissipation of mechanical energy by irreversible process of thermal conduction was evaluated by using the formula[4]

$$\overline{\dot{E}}_{\text{mech}} = -(1/T) \int \kappa(\mathbf{grad}T)^2 \, \mathrm{d}V \qquad (2)$$

In-house time-domain code was run on the ETH Zürich STARDUST/PEGASUS cluster using grids of 100 to 1000 identical linear elements per unit cell and 10^4−10^6 integration time steps per period of applied harmonic deformation of strain amplitude of 10^{-2}. Perfect adhesion was assumed at the interfaces between the layers. All calculations were carried out at $T_0 = 300$ K.

Figure 2 presents numerical predictions obtained assuming equal-thickness steel and polymer layers with thickness $h = 1$ mm and material properties from Table 1. In a favorable agreement with measured data of Figure 1, one observes a pronounced loss

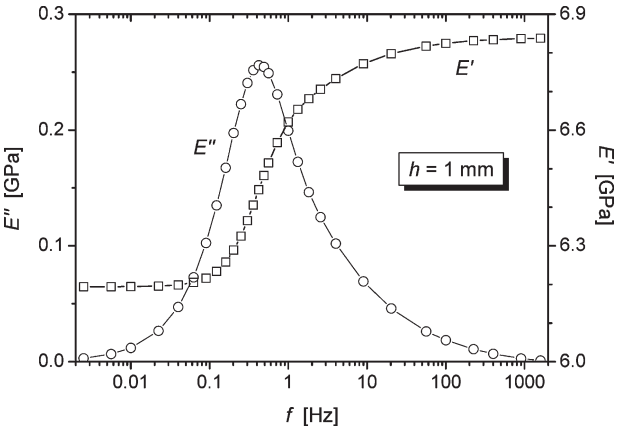

Figure 2. Numerical predictions of dynamic Young's modulus $E = E' + iE''$ of heat-conduction dampers made up of alternating steel and rubber layers of equal thickness, $h = 1$ mm. One can readily evaluate dynamic Young's modulus, E, at any thickness, h, using the thickness-frequency superposition principle $E(f,h) = E(fh^2)$. Chronologically, we had first conducted the finite element calculations and then used the results to fabricate the dampers with predefined layers' thickness; see Figure 1.

peak at a frequency of ≈0.5 Hz. At much higher frequencies, the period of mechanical oscillations becomes much smaller than the characteristic time of heat transfer between adjacent layers of rubber and steel. In this case, no significant heat transfer between adjacent layers can occur, and local temperature variations closely follow the oscillations of local volume deformations. In such adiabatic oscillations, the heat evolution is reversible, and no dissipation takes place. In the opposite case of low frequencies, the heat transfer between adjacent layers is much faster than the period of oscillations. As a result, at any instant, the temperature across the system is practically uniform, so again, no dissipation occurs, even despite the fact that in oscillations the heat is being transferred between the layers. The reason is that the heat transfer is driven by vanishingly small temperature gradients, so the resulting energy dissipation rates are also vanishingly small; see eq 2. In the intermediate region, a considerable fraction of generated heat can be transferred between the layers, whereas the temperature gradients are still substantial, thus resulting in the appearance of resonance-type loss peak depicted in Figure 2.

Both the positions and the widths of numerically predicted and measured loss peaks are in reasonable agreement; compare Figures 1 and 2. One can see, however, that the magnitudes of predicted and measured moduli differ quite considerably, and apart from the peak frequency, the measured moduli do not exactly follow the thickness-frequency superposition principle $E(f,h) = E(fh^2)$ intrinsic to the governing equation set of eq 1. In calculations, we assumed infinite-aspect-ratio layers, whereas the tested dampers were fabricated from layers of finite aspect ratio varying from 50 to 200;[5] see Figure 1. In such dampers, the displacements of boundary (perimeter) sections of rubber layers are much less constrained than those of their inner sections. Consequently, near the boundaries, the deformation fields are shear dominated, whereas in the inner sections, the volume deformation prevails. As a result, the boundary sections of rubber layers mostly dissipate via the molecular-friction mechanism, whereas their internal section mostly dissipates via the heat-conduction mechanism. Upon increasing aspect ratio, the heat-conduction dissipation becomes dominant, and accordingly, the overall stiffness increases, and the loss peak becomes more pronounced; see Figure 1. But even with the largest aspect-ratio damper tested, we are still clearly away from the limiting case of infinite-aspect-ratio layers assumed in our 1D finite element calculations.

The stiffness of idealized, infinite aspect-ratio dampers can readily be estimated by realizing that the steel layers are much stiffer than the rubber ones, so that upon overall deformation, practically all deformation is accumulated inside the rubber layers. As we consider equal-thickness layers, the strain inside the rubber layers is simply twice as large as the overall one, and because the shear modulus of rubbers is typically three or more orders of magnitude smaller than the bulk modulus, the overall dampers' stiffness (perpendicular to the layers) should be simply twice the bulk modulus of the rubber layers. The bulk modulus of rubbers is typically ~3 GPa, thus yielding an estimate of 6 GPa, which is a factor of 4 or so larger than the maximum measured stiffness; compare Figures 1 and 2.

The lateral dimensions of tested dampers are also considerably (an order of magnitude or so) smaller than those of typically used in various industrial applications. We are thus optimistic that in practice, it should prove feasible to approach the theoretically predicted stiffness and dissipation levels depicted in Figure 2.

In calculations, we assumed rubber layers with a Poisson's ratio of $\nu = {}^1/_2$; see Table 1. In terms of bulk modulus, K, and shear modulus, μ, Poisson's ratio is given by[4]

$$\nu = \frac{1}{2}(3K - 2\mu)/(3K + \mu) \tag{3}$$

One can see that a value of $\nu = {}^1/_2$ can correspond to either a fully incompressible material behavior with infinitely large K but finite μ (a standard mathematical model commonly employed in computational fluid dynamics studies) or to a behavior with finite, physically realistic K but a zero-valued μ. In this work, the latter case was considered. This seems to be appropriate and physically adequate because the bulk moduli of elastomers and rubbers are finite, whereas their shear moduli are significantly, three and more orders of magnitude, smaller than the bulk moduli. In contrast with the traditional incompressible approximation, such model behavior does allow for volume changes upon the deformation. (See eq 1.)

The change of temperature accompanying the deformation of a solid is usually small. Let us assume that in the absence of external forces the body is at some temperature, T_0. The change of temperature, $T - T_0$, due to the deformation is given by $T - T_0 = -T_0 K\alpha \operatorname{div} \mathbf{u}/C$.[4] Assuming a relative volume change of $\operatorname{div} \mathbf{u} = 0.01$and properties of rubber from Table 1, one obtains $T - T_0 = 3$K. Therefore, it would be also sufficiently accurate to put T_0 to T in the first line of eq 1. (See, for example, chapter V of ref 4.)

In general, eq 2 also contains a second, viscosity (internal friction) energy-dissipation term. As in our calculations, we put the shear modulus to zero, this term could not contribute to the energy dissipation, so it was omitted from eq 2. One can nonetheless provide a rough estimate of the significance of this term. In the 1D periodic lamellar setup studied, the local stresses in the rubber layers are predominantly determined by the C_{11} elastic constant. The latter is given in terms of K and μ by $C_{11} = K + {}^4/_3\mu$. The rate of energy dissipation is determined by the imaginary part of C_{11} and thus by μ'', which for rubbers is typically on the order of 0.1 MPa. This estimate is significantly smaller than the peak value of E'' seen in our calculations; see Figure 2. In practice, however, one uses finite aspect-ratio layers and, as we have mentioned above, considerable shear strains can occur, especially near the layers' boundaries. We believe that it is these shear strains that are responsible for the existence of a finite value of the loss moduli measured at low and high frequencies; see Figure 1.

Industrial dampers usually operate under large preloads, causing significant, both geometrically and materially nonlinear deformations of rubber layers. Those aspects have not been taken into account by our simplified model of eq 1. We have seen, nonetheless, that our model has been appropriate for understanding the physical origin of observed dissipation peaks. However, for reliable industrial design, one should clearly rely on more detailed, both geometrically and materially nonlinear, coupled 3D thermoelastic numerical calculations with realistic values of both bulk and shear moduli of constituent layers.

Rubbers are chemically cross-linked polymers. In their viscoelastic state, they can elastically withstand exceptionally large deformations while dissipating a considerable fraction of related deformation work into heat by means of internal molecular friction. Physically, it is the liquid-like mobility of chain segments that is responsible for the high internal friction of viscoelastic polymers. The efficiency of heat-conduction dissipation depends on the amount of heat developed in deformation. For a given load, this amount is ultimately proportional to the thermal expansion coefficient; see eq 1, and among solids, it is again viscoelastic polymers that have the largest thermal expansion, thanks once more to their liquid-like chain mobility.

Rubbers have almost frequency-independent coefficients of molecular friction.[1,2] As a result, the dissipation characteristics of traditional layered dampers are also practically frequency-independent. On the contrary, the heat-conduction dissipation is very much sensitive to the frequency; see Figures 1 and 2. One can therefore conceive using the heat-conduction dampers for resonance damping of selected natural vibration frequencies of industrial machineries, buildings, and bridges, as well as for absorption of unwanted sound of predefined frequencies emitted by power generators, voltage transformers, air fans, and so on.

Many base-isolated engineering structures (bridges, buildings, etc.) have natural frequencies of 0.01 to 1 Hz. For such frequency range, the peak performance of heat-conduction damping is achieved with rubber layers of thickness on the order of 1 to 0.1 mm; see Figures 1 and 2. In acoustic damping applications, one is interested in a frequency range of 10−20 000 Hz, corresponding to heat-transfer length scales of 0.1 to 0.001 mm. Such length scales are readily realizable with both low-aspect-ratio inclusion and fiber- and platelet-filled polymers. In our previous work, we have successfully used the finite element route to estimate both static and dynamic properties of filled polymers.[7] We are thus optimistic that one can also rely on this numerical route to study the heat-conduction contribution to the damping properties of filled polymers.

Carbon black and silica-filled rubbers (the so-called high damping rubbers) are widely used in tires and vibration-isolation applications.[8] In such materials, the fillers tend to aggregate in complex percolating networks in which the filler particles are held together by van der Waals forces and thin coating layers of immobilized matrix polymer.[8,9] And upon deformation, it is the load-induced breakdown and reformation of the filler network that is responsible for the remarkable stiffness and dissipation characteristics of such materials. Commonly, the primary filler aggregates have dimensions on the order of 10−100 nm, whereas the resulting spatial networks can already exhibit spatial motifs on the order of 100−1000 nm. It would be interesting to understand if and to what extent one could also realize and practically utilize the heat-conduction dissipation of mechanical energy in carbon black and silica-filled rubbers.

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