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Mechanisms in damping of mechanical vibration by piezoelectric ceramic–polymer composite materials

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The piezoelectric ceramic (piezoceramic) component of a polymer–piezoelectric ceramic composite converts mechanical energy into electrical energy and this electrical energy is dissipated as heat in a load resistance, R_x, simulated by a shunted resistance, but provided in practice by a conductive polymer composite matrix. The composite therefore dissipates the input mechanical energy via the damping mechanism provided by piezoelectric ceramic–conductive matrix material, as well as the conventional viscoelastic damping provided by the polymer. Mathematical models have been developed to characterize the damping behaviour of the composites, and the maximum damping ratio of composites can be as high as 23%. A two degrees-of-freedom (2DOF) experimental setup was developed to test the validity of the models. The experimental results are in good agreement with the theoretical predictions.

1. Introduction

The damping of mechanical vibrations is important because vibration not only results in the fatigue of materials but also generates noise, and much effort has been expended in attempting to minimize unwanted vibrations.

The use of high loss factor viscoelastic materials is one of the most common passive damping methods [1]. As the maximum damping properties of a polymer are located in the glass transition region, a polymer with a wide transition region can show damping behaviour over a large range of temperature or frequency, and can dampen efficiently if it shows a high loss factor at a given frequency and temperature. Thus, it is desirable for damping applications that a polymer possesses a broad, high damping peak. However, this may not be possible for either a single polymer or interpenetrating polymer networks (IPNs) which are often used, since the height and width of the loss peak cannot be independently adjusted, as the broadening of the loss peak usually results in a decrease in its maximum height [2]. This trade-off in width and height of polymeric loss limits further development of these materials for damping applications. In addition, polymers have a low modulus; their damping capacity is quite temperature dependent and prestressing decreases their loss factor [1]. In the development of new damping materials, composites containing piezoelectric material have attracted great attention, as the composites can show both high stiffness and a high loss factor [3–6].

For piezoceramic powder–polymer composites in damping applications, the reported composites were mixtures containing piezoelectric ceramic powder, e.g. lead zirconate titanate (PZT) and $BaTiO_3$, a polymeric material (polyester or epoxy) into which an electrically conductive material (e.g. carbon black) has been dispersed [3–6]. The damping mechanism of the mixtures was believed to be due to the piezoceramic powder first generating an electrical charge upon deformation and then dissipating this charge within the conductive materials.

Contrasted with this, it was reported that adding piezoceramic PZT powder to a high damping Eccogel epoxy increased storage modulus, E', but lowered the loss factor, η, [7]. Further study into the possibility of using piezoelectricity in a composite for passive and active vibration damping applications by these workers concluded that there was no significant contribution to the composite damping by the piezoelectric filler [8]. Therefore, when the piezoelectric ceramic powder was used in a composite for transducer backing applications, it was concluded that the primary reason for the beneficial effect was observed the high density of the piezoceramic (7.8 $g\,cm^{-3}$) as opposed to any piezoelectric effect [9].

The damping capacity of piezoceramics shunted by a resistor or a resonant circuit has been examined by [10] and [11]. It has been demonstrated that a matched resistance or RLC circuit is a prerequisite for the piezoceramics to possess any significant damping ability. Models had been developed [12] for characterizing the damping behaviour of piezoelectric materials shunted by a load resistor. These models gave a good prediction of the optimal resistance and the damping capacity of the piezoelectric materials.

However, the damping mechanisms of composites containing piezoelectric materials are not well understood, as indicated by conflicting reported results. Questions unanswered are: how large is the damping

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from piezoceramics, under what circumstances will piezo-damping work in the composite, what is the maximum possible damping of the composites and the relationship between the total damping and the damping of each component?

This paper reports the current investigation on the damping mechanisms of piezoelectric ceramic–polymer composites. A "parallel model" and a "series model" have been proposed for characterizing the piezo-damping of such composites. A two degrees-of-freedom (2DOF) experimental configuration was used to test the validity of the models. Instead of using a conductive polymer, an adjustable resistor was connected to the piezoelectric ceramic to simulate the conductivity of the polymer matrix. Equations for the total composite damping and the individual polymer and piezoceramic damping are derived. Experimental results validate the proposed models and demonstrate the feasibility of using piezoceramic systems for practical damping of mechanical vibrations.

2. Modelling of damping in a composite containing piezoceramics

The piezoelectric ceramic component of a polymer–piezoelectric ceramic composite converts mechanical energy into electrical energy and this electrical energy is dissipated by a load resistance, R_x, provided by the conductive polymer matrix, as shown in Fig. 1. This energy dissipation is termed the "piezo-damping", while the energy dissipated by the polymer matrix alone is referred to as "polymer damping".

The piezoelectric ceramic–polymer composites are classed as either parallel composites, with the piezoceramic and polymer mechanically in parallel (constant strain), or as series composites with piezoceramic and polymer mechanically in series (constant stress), as shown in Fig. 2a, b. Parallel composites are modelled using two spring dashpot sets joined in parallel, Fig. 2c. The first dashpot, C_1, is the equivalent dashpot describing the damping of the polymer, and the second dashpot, C_2, is the equivalent dashpot describing the piezo-damping from the piezoceramic. The elastic properties of the polymer and piezoceramic are represented by two springs with stiffnesses, k_1 and k_2, respectively. Series composites are modelled by using the two spring dashpot sets joined in series, as shown in Fig. 2d.

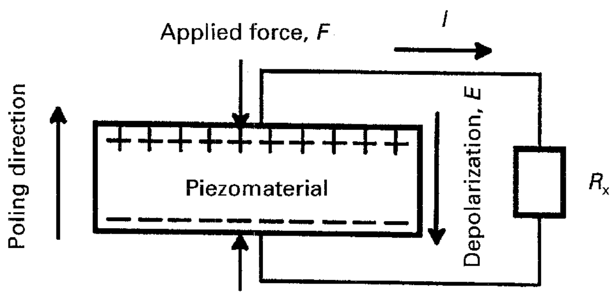

Figure 1 Schematic diagram of the piezo-damping principle: the piezomaterial transfers the mechanical energy into electrical energy and this electrical energy is dissipated by load resistance as Joule heat.

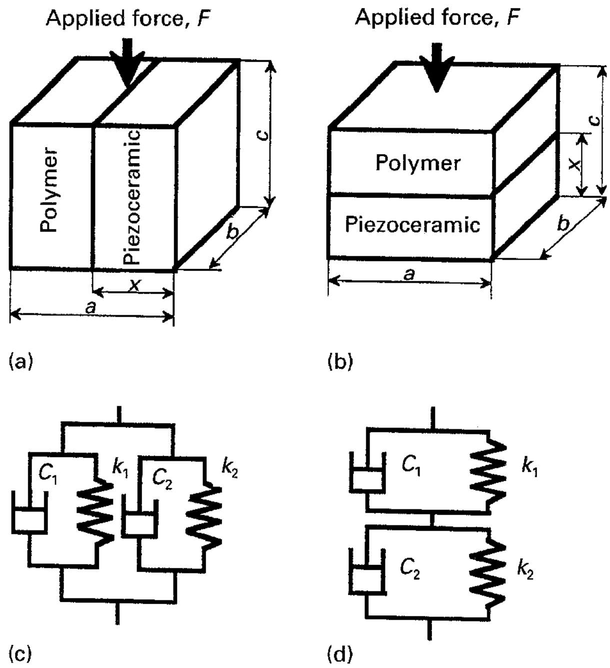

Figure 2 (a) Parallel and (b) series composites and (c, d) their corresponding dashpot-spring models.

2.1. The damping behaviour of parallel composites: the parallel model

The piezoceramic in a parallel composite is continuous in only one direction, while the polymer matrix can be continuous in one, two or three directions. Therefore, in terms of the connectivity of composites, parallel composites include 1–1, 1–2 and 1–3 type composites.

If a force F, equals $F_0 e^{j\omega t}$ is applied to the composite, the total energy, U_T, dissipated by the composite is

$$U_T = U_1 + U_2 \quad (1)$$

where U_1 is the energy dissipated by the polymer and U_2 is the energy dissipated by piezoceramic. As k_1 and k_2 are in parallel, the total stiffness of the composite, k_T, is therefore given by

$$k_T = k_1 + k_2 \quad (2)$$

The amplitudes of the displacement, X, are the same for both polymer and ceramic, as polymer and ceramic are in parallel

$$X_T = X_1 = X_2 \quad (3)$$

where X_T, X_1 and X_2 are the displacement of the composite, polymer and piezoceramic parts, respectively. Then the energy dissipated by the composite and each component is given by [13]

$$U_T = 2\pi\xi_T k_T X_T^2 \quad (4)$$

$$U_1 = 2\pi\xi_1 k_1 X_1^2 \quad (5)$$

$$U_2 = 2\pi\xi_2 k_2 X_2^2 \quad (6)$$

where ξ_T, ξ_1 and ξ_2 are the damping ratio of composite, polymer and piezoceramic, respectively. From

Equations 1 and 2, the damping ratio of composite is found to be

$$\xi_T = \frac{1}{1+q}(q\xi_1 + \xi_2) \quad (7)$$

where q is the stiffness ratio of polymer and ceramic, $q = k_1/k_2$. The stiffness of a material is given by

$$k = E\frac{A}{L} \quad (8)$$

where E is Young's modulus, A is the area and L is the length. If v is the piezoceramic volume fraction of the composite, with dimension of $a \times b \times c$, as shown in Fig. 2a, then the volume of this composite is $V_T = a \times b \times c$. The volume fraction of the piezoceramic and polymer are $V_1 = b \times c \times x$ and $V_2 = b \times c \times (a - x)$, respectively. Thus the piezoceramic volume fraction can be expressed as $v = x/a$. As a parallel composite, the force acting is parallel to the "c-axis" and the stiffness of each component is found to be

$$k_1 = E_1\frac{A_1}{c} \quad (9)$$

$$k_2 = E_2\frac{A_2}{c} \quad (10)$$

where $A_1 = bx$ and $A_2 = b(a - x)$. Thus the stiffness ratio is found to be

$$q = p\left(\frac{1}{v} - 1\right) \quad (11)$$

where p is the modulus ratio of the two components, $p = E_1/E_2$. Therefore the stiffness ratio of the composite can be determined by the modulus ratio and the volume fraction of the piezoceramic and, accordingly, the composite damping becomes

$$\xi_T = \frac{1}{1 + p\left(\frac{1}{v} - 1\right)}\left[p\left(\frac{1}{v} - 1\right)\xi_1 + \xi_2\right] \quad (12)$$

The damping ratio of piezo-damping is given by [12]

$$\xi_2 = \frac{1}{2\omega C^T} \times \frac{R_x}{Z^2 + R_x^2} \times \frac{K_{ij}^2}{1 - rK_{ij}^2} \quad (13)$$

where $\omega = 2\pi f$, f is the working frequency of the piezomaterial, Z is the magnitude of electrical impedance of the piezoceramic, C^T is the capacitance of the piezomaterial (at low frequency) in free stress state, R_x is the load resistance, r is a constant determined by Z and R_x such that [12]

$$r = \frac{R_x}{(Z^2 + R_x^2)^{1/2}} \quad (14)$$

and K_{ij} is the electromechanical coupling factor [14]. "Modes 33" means that the piezomaterial is vibrated in the same direction, and "mode 31" means that the piezomaterial is vibrated in one direction. The electromechanical coupling factor in mode 33, which is K_{33}, is much larger than that in mode 31, which is K_{31}. The composite damping ratio, by substituting Equation 13 into Equation 12, is found to be

$$\xi_T = \frac{1}{1 + p\left(\frac{1}{v} - 1\right)}\left[p\left(\frac{1}{v} - 1\right)\xi_1 + \frac{1}{2\omega C^T} \times \frac{R_x}{Z^2 + R_x^2} \times \frac{K_{ij}^2}{1 - rK_{ij}^2}\right] \quad (15)$$

where the damping contribution of the polymer is given by

$$\xi_T' = \frac{p\left(\frac{1}{v} - 1\right)}{1 + p\left(\frac{1}{v} - 1\right)}\xi_1 \quad (16)$$

and the component of damping provided by the piezo-damping is

$$\xi_T'' = \frac{1}{1 + p\left(\frac{1}{v} - 1\right)} \times \left[\frac{1}{2\omega C^T} \times \frac{R_x}{Z^2 + R_x^2} \times \frac{K_{ij}^2}{1 - rK_{ij}^2}\right] \quad (17)$$

As the energy dissipated by R_x is a maximum when R_x equals the magnitude of the internal impedance of the piezomaterial, Z, the maximum damping ratio of the piezo-damping component is [12]

$$\xi_{T-\max}'' = \frac{1}{1 + p\left(\frac{1}{v} - 1\right)} \times \left[\frac{1}{4\omega C^T} \times \frac{1}{Z} \times \frac{K_{ij}^2}{1 - \frac{1}{2^{1/2}}K_{ij}^2}\right] \quad (18)$$

and the corresponding maximum damping ratio of the composite is equal to

$$\xi_{T-\max} = \frac{1}{1 + p\left(\frac{1}{v} - 1\right)}\left[p\left(\frac{1}{v} - 1\right)\xi_1 + \frac{1}{4\omega C^T} \times \frac{1}{Z} \times \frac{K_{ij}^2}{1 - \frac{1}{2^{1/2}}K_{ij}^2}\right] \quad (19)$$

Since Z is frequency dependent, the maximum damping ratio of the composite varies as frequency changes. For mode 33, Z is given by

$$Z = \frac{1}{\omega C^T}\left[\left(1 + \frac{K_{33}^2}{1 - K_{33}^2}\right) - \left(\frac{K_{33}^2}{1 - K_{33}^2}\right) \times \left(\frac{2}{\pi} \times \frac{F_a}{f}\right)\tan\left(\frac{\pi}{2} \times \frac{f}{F_a}\right)\right] \quad (20)$$

where K_{33} is the electromechanical coupling factor in mode 33 and F_a is the antiresonant frequency of the material itself [12]. Therefore the frequency characteristics of the composites can be determined by substituting Z into Equation 15

$$k_1 = E_1 \frac{A_1}{c - x} \quad (30)$$

$$\xi_{T-\max} = \frac{1}{1 + p\left(\frac{1}{\nu} - 1\right)} \left\{ p\left(\frac{1}{\nu} - 1\right)\xi_1 + \frac{K_{33}^2}{4\left(1 - \frac{1}{2^{1/2}} K_{33}^2\right)} \times \left[\frac{1}{\left(1 + \frac{K_{33}^2}{1 - K_{33}^2}\right) - \left(\frac{K_{33}^2}{1 - K_{33}^2}\right)\left(\frac{2}{\pi} \times \frac{F_a}{f}\right)\tan\left(\frac{\pi}{2} \times \frac{f}{F_a}\right)} \right] \right\} \quad (21)$$

2.2. Damping behaviour of series composites: the series model

The piezoceramic in a series composite is isolated by the polymer and not continuous in the direction of applied force. The polymer matrix, however, can be continuous in one, two or three directions. Therefore in terms of the connectivity of a composite, series composites include the 0–1, 0–2 and 0–3 type composites.

From the series model shown in Fig. 2d, the total energy, U_T, dissipated by the composite is

$$U_T = U_1 + U_2 \quad (22)$$

As k_1 and k_2 are in series, the total stiffness of the composite, k_T, is therefore given by

$$\frac{1}{k_T} = \frac{1}{k_1} + \frac{1}{k_2} \quad (23)$$

and the forces acting on the polymer, F_1, and the ceramic, F_2, are equal to the total applied force, F_T

$$F_T = F_1 = F_2 \quad (24)$$

The energies dissipated by the composite and each component are then given by

$$U_T = 2\pi\xi_T \frac{F_T^2}{k_T} \quad (25)$$

$$U_1 = 2\pi\xi_1 \frac{F_1^2}{k_1} \quad (26)$$

$$U_2 = 2\pi\xi_2 \frac{F_2^2}{k_2} \quad (27)$$

and the damping ratio of the composite is found to be

$$\xi_T = \frac{1}{1 + q}(\xi_1 + q\xi_2) \quad (28)$$

where q is the stiffness ratio. This stiffness ratio of a series composite, q, can also be expressed in terms of modulus ratio, p, and piezoceramic volume fraction, ν, in a similar fashion. The acting force is along the "a-axis" for a series composite, as shown in Fig. 2b. The volume fraction of the piezoceramic is found to be $\nu = x/c$. The stiffnesses of piezoceramic and polymer can be expressed as

$$k_1 = E_1 \frac{A_1}{x} \quad (29)$$

where $A_1 = A_1 = a \times b$. Thus the stiffness ratio is found to equal

$$q = p\left(\frac{\nu}{1 - \nu}\right) \quad (31)$$

where p is the modulus ratio as defined in Equation 11. The composite damping can then be expressed in terms of modulus ratio and piezoceramic volume fraction

$$\xi_T = \left[1/1 + p\left(\frac{\nu}{1 - \nu}\right)\right] \times \left[\xi_1 + p\left(\frac{\nu}{1 - \nu}\right)\xi_2\right] \quad (32)$$

and the composite damping ratio has its final form as

$$\xi_T = \left[1 \Big/ 1 + p\left(\frac{\nu}{1 - \nu}\right)\right] \times \left\{\xi_1 + \left[p\left(\frac{\nu}{1 - \nu}\right) \Big/ 2\omega C^T\right] \times \frac{R_x}{Z^2 + R_x^2} \times \frac{K_{ij}^2}{1 - rK_{ij}^2}\right\} \quad (33)$$

where the fraction contributed by the polymer is given by

$$\xi_T' = \frac{1}{1 + p\left(\frac{\nu}{1 - \nu}\right)}\xi_1 \quad (34)$$

and the fraction provided by the piezo-damping is equal to

$$\xi_T'' = \left[p\left(\frac{\nu}{1 - \nu}\right) \Big/ 1 + p\left(\frac{\nu}{1 - \nu}\right)\right] \times \left(\frac{1}{2\omega C^T} \times \frac{R_x}{Z^2 + R_x^2} \times \frac{K_{ij}^2}{1 - rK_{ij}^2}\right) \quad (35)$$

The maximum damping ratio of the composite occurs when $R_x = Z$, and is found to be

$$\xi_{T-\max}'' = \left[p\left(\frac{\nu}{1 - \nu}\right) \Big/ 1 + p\left(\frac{\nu}{1 - \nu}\right)\right] \times \left[\frac{1}{4\omega C^T} \times \frac{1}{Z} \times \left(K_{ij}^2 \Big/ 1 - \frac{1}{2^{1/2}} K_{ij}^2\right)\right] \quad (36)$$

2.3. Piezo-damping in a composite

From Equations 17 and 35, the contribution to the composite damping from the piezo-damping is determined by:

1. the piezoelectric properties of the piezoceramic (C^T, Z and K_{ij}),
2. the effective load resistance,
3. the modulus ratio,
4. the piezoceramic volume fraction, and
5. whether the composite is in parallel or series.

If $K_{ij} = 0$, i.e. the material is not piezoelectric, Equation 13 yields $\xi_2 = 0$. If $R_x = 0$ or $R_x = \infty$, i.e. the piezoceramic is either shortcircuited or opencircuited, there is no energy dissipation in R_x, and Equation 13 gives $\xi_2 = 0$. Therefore in any of these cases, there is no damping provided by the piezoelectric material through the piezo-damping mechanism, and the total damping is only provided by the polymer. Thus, a matched load resistance is essential for the piezoceramic to provide effective piezo-damping, and this is in a good agreement with the results reported by [10]–[12]. The optimum resistance is frequency dependent, and the damping ratio has a peak value at this resistance [12].

However, even when a matched resistance is provided to the piezoceramic, the amount of piezo-damping in a composite is altered by the modulus ratio and the piezoceramic volume fraction, as indicated in Equations 17, 18, 33 and 35. Increasing the modulus ratio results in a lower piezo-damping effect in a parallel composite, but a higher piezo-damping effect in a series composite, as shown in Fig. 3. This figure is plotted out using Equation 18, with a maximum piezo-damping of 0.23 (when $K_{33} = 0.75$) and a piezoceramic volume fraction of 0.5. The piezo-damping is much higher in parallel composites than in series composites when the modulus ratio is lower than one. In a series composite the piezo-damping is almost zero when the modulus ratio of the composite is lower than 0.1, as shown in Fig. 4. Since the modulus ratio of polymer and piezoceramic is less than 0.1 in most cases, the piezo-damping in a series composite is extremely small, even when an optimal load resistance and a piezoceramic with high K_{ij} are employed. This conclusion explains the experimental results reported by [7] and [8] for composites containing piezoceramic particles.

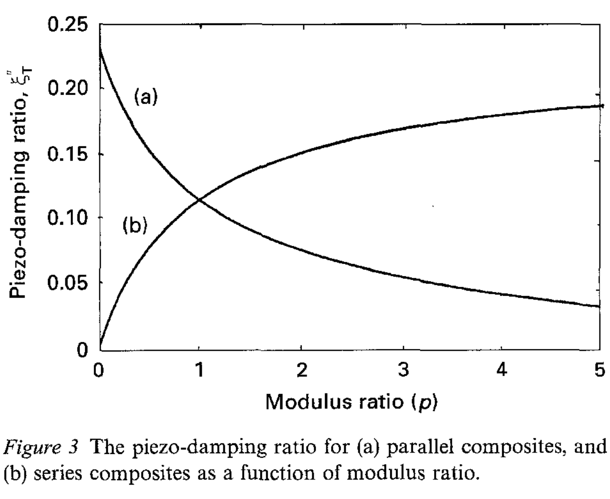

Figure 3 The piezo-damping ratio for (a) parallel composites, and (b) series composites as a function of modulus ratio.

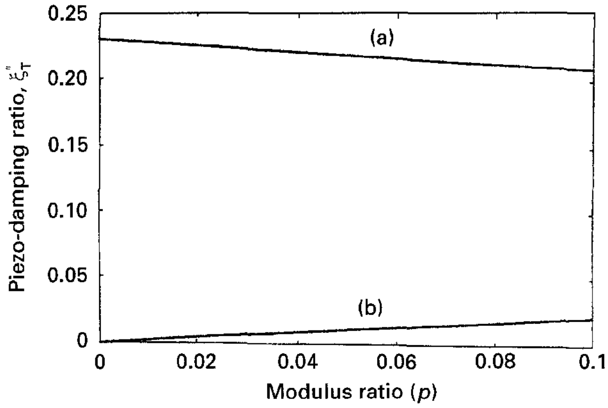

Figure 4 The piezo-damping in (a) a parallel composite, and (b) a series composite when the modulus ratio is lower than 0.1.

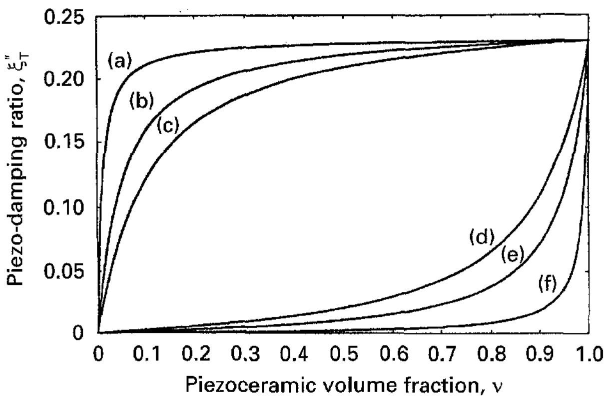

Figure 5 The piezo-damping in composites as a function of the piezoceramic volume fraction: parallel composite (a) $p = 0.01$, (b) $p = 0.05$, (c) $p = 0.1$; series composite (d) $p = 0.01$, (e) $p = 0.05$, (f) $p = 0.1$.

It is very clear from these models that the parallel mode results in the largest piezo-damping. In a series composite, only with a piezoceramic volume fraction of over 0.8 can the composite show a reasonable increase in the piezo-damping if the modulus ratio is 0.1, Fig. 5. The lower the modulus ratio, the less increase of piezo-damping by increasing the piezoceramic volume fraction. However, for a parallel composite, the piezo-damping reaches its maximum value as soon as the volume fraction is over 0.25, and this value becomes even lower with decreased modulus ratio.

2.4. The addition of polymer damping and piezo-damping in a composite

The polymer damping adds to the piezo-damping in both parallel and series composites according to Equations 12 and 32. Since the modulus ratio is generally small, the composite damping is dominated by the piezo-damping in a parallel composite and by the polymer damping in a series composite. Since the piezo-damping stems from the piezoelectric properties of the ceramic, these properties are not affected by changing temperature, provided it is below the Curie

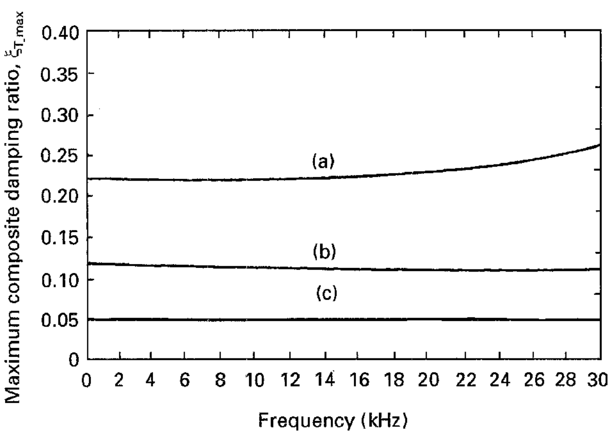

Figure 6 The maximum damping ratio of a parallel composite as a function of frequency: (a) $K_{33} = 0.75$, (b) $K_{33} = 0.6$, (c) $K_{33} = 0.4$.

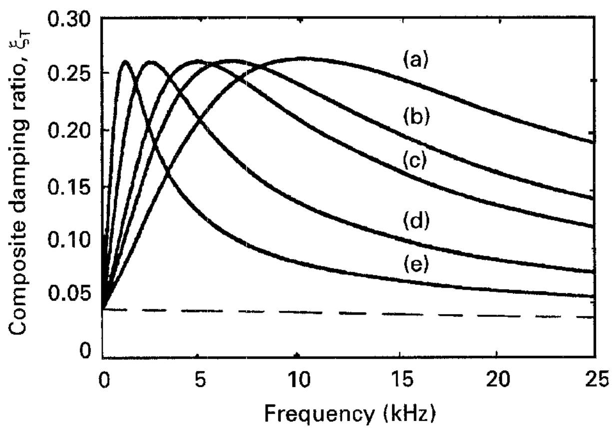

Figure 7 Shift of the maximum damping peak to different frequencies as the resistance varies: (a) $R_x = 100$ kΩ, (b) $R_x = 150$ kΩ, (c) $R_x = 200$ kΩ, (d) $R_x = 400$ kΩ, (e) $R_x = 900$ kΩ.

point. As most of the piezoceramics have their Curie point at a few hundred degrees, parallel composites do not lose their damping ability over the range of most service temperatures. As such they are less temperature sensitive than polymers, where damping decreases at temperatures above the glass transition region.

According to Equation 22 the maximum damping ratio of piezo-damping is frequency dependent, and this is true also for the maximum damping ratio of the composite. However, the maximum damping ratio of the composite is almost frequency invariant, as long as the frequency is below the antiresonant frequency of the piezoceramic itself, as shown in Fig. 6. As a result, the maximum damping ratio of the composite can be effectively "tuned" to any required frequency merely by changing the resistance, R_x, as shown in Fig. 7 for a parallel composite. This figure is plotted out by using Equation 1 with $K_{33} = 0.75$, $\nu = 0.5$, $p = 0.1$, $f_r = 3.21$ kHz and $\xi_1 = 0.1$. The dashed line is added to indicate the polymer damping level. At each value of R_x, the total damping is the addition of the piezo-damping and polymer damping, and the maximum damping ratio is about 0.23. Increasing the polymer-damping provides a higher background damping, and this results in a higher total damping of the composite. If a polymer with broad loss peaks is used as matrix (for example, IPNs), the piezoceramic–IPNs composites can have a high and broad damping peak due to the addition of the piezo-damping to the polymer damping. Therefore the composites not only dampen well over a large range of temperature and frequency, but also efficiently at any specific frequency due to the contribution of piezo-damping.

3. Experimental procedure

A two degrees-of-freedom (2DOF) system was developed with two mass blocks hanging horizontally, and the piezoelectric sample was placed between the blocks, as shown in Fig. 8. These two mass blocks were tapered at one end; both were of equal weight of 2.272 kg. The system was excited by a shaker (B&K type 4809), which was driven by a power amplifier, B&K type 2706. The signal source was a noise generator, B&K type 1405. The input force was measured by a force transducer and the response was measured by an accelerometer. Both input and response signals were fed into two charge amplifiers (B&K conditioning amplifier type 2626), respectively, and then into a two channel FFT analyser (AND AD-3525 FFT analyser). This 2DOF setup has two advantages for piezo-damping measurement: (a) the system damping is equal to the material damping, and (b) the piezomaterial vibrates in a direction parallel to its poling direction (mode 33). The electromechanical coupling factor under this vibration mode, K_{33}, is the largest among all the vibration modes.

Composites were prepared by embedding two piezoelectric ceramic rings in epoxy matrix. The piezoceramics, with diameters of 11.7 and 19 mm and heights of 9.2 mm, were used. The piezoelectric properties of the piezoceramics are listed on Table I. The two piezoceramic rings were placed together with their poling polarities in opposite directions, and a copper shim was inserted between the two ceramic rings as electrode outlets, as shown in Fig. 9. The modulus ratio of the composite is 0.098, the damping

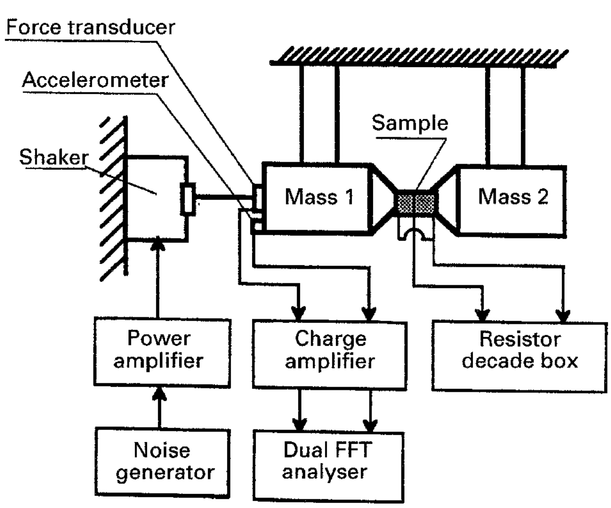

Figure 8 The schematic diagram of the 2DOF damping measurement system.

TABLE I Piezoelectric properties of the piezoceramics

Material	d_{33} (pC/N)	C^{T} (pF)	F_r (kHz)	F_a (kHz)	K_{33}	E (GPa)
PZT	300	220	67	73	0.42	11

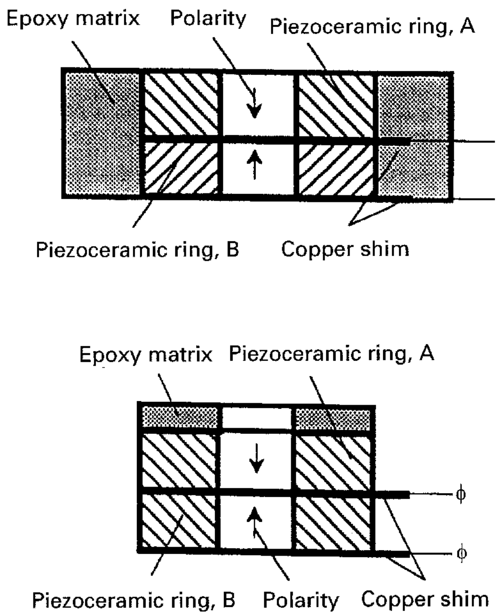

Figure 9 Sample configuration for (a) parallel composite, and (b) series composite.

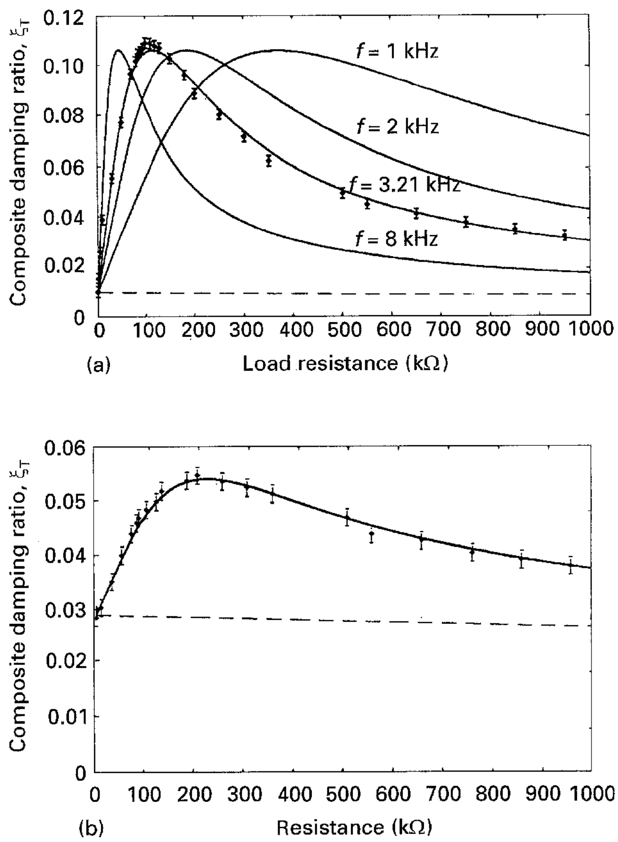

Figure 10 Damping ratio varies as a function of load resistance for (a) parallel composite, and (b) series composite: (●) experimental results, (——) theoretical predictions.

ratio of the epoxy is 0.1 and the piezoceramic volume fraction is 0.5 for parallel composites and 0.8 for series composites. A resistor decade box was connected to the piezoceramics to allow simulation of a conducting polymer matrix and hence allow variation of R_x.

Samples were bolted together with the two mass blocks by a steel rod with a diameter of 3 mm, so that no adhesive was involved. The damping ratio and resonant frequency were measured as resistance was varied from 0 to 990 kΩ. At each given R_x, the measurement was repeated three times. Coherence between input force and acceleration was above 0.98 for all measurements. The composite damping ratio was then determined from the frequency response function (FRF) by the circle-fit method [15].

4. Discussion

The experimental results are shown in Fig. 10, where the solid lines are the theoretical predictions from Equations 15 and 33, and the dashed line is the damping provided by the epoxy matrix. The resonant frequency of the 2DOF system is 3.21 kHz when the parallel composite is used, and this frequency drops to 1.79 kHz when the series composite is used. When the piezoceramic is shortcircuited, the composite damping equals the polymer damping, as there is no piezo-damping. When the load resistance is increased, the composite damping ratio is a sum of the polymer damping and piezo-damping, and it reaches a maximum value of 11% at a load resistance of 95 kΩ for parallel composites and 5.5% at 200 kΩ for series composites. The optimum resistance increases as the frequency decreases, as shown in Fig. 10a. When compared with the shortcircuited state ($R_x = 0$ kΩ), the resonant peak value decreases by about 20 dB at $R_x = 95$ kΩ for parallel composites, as shown in Fig. 11. Small changes of the composite damping ratio for series composites as a function of load resistance indicate that the piezo-damping effect is very small in the composite, even when the piezoceramic volume fraction is close to 80%. Clearly, the parallel damping is a more desirable mode of operation. As shown in Fig. 10, experimental results correlate well with the theoretical predictions.

By comparison with the conventional polymer damping materials, the main advantages of the composites are:

1. high stiffness, which results from the piezoceramic in parallel with the polymer matrix;

2. less sensitivity to prestress or temperature, which is due to the fact that the piezoceramic (PZT) can retain its piezoelectric properties up to the Curie point of the ceramic (about 350 °C), and the fact that the prestressing increases the piezo-damping effect as it

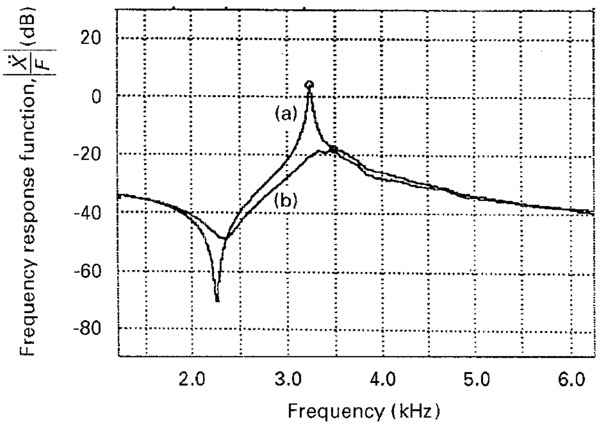

Figure 11 Change of the resonant peak value when (a) $R_x = 0$ kΩ, (shortcircuited state), and (b) $R_x = 95$ kΩ.

enlarges the piezoelectric effect in the piezoceramic [16], and

3. intrinsically high damping ability.

According to Equations 1 and 2, the damping ratio increases sharply as K_{33} increases, and can be as high as 46% when K_{33} is about 0.75, which is the common value for commercially available piezoelectric materials.

5. Conclusions

Polymer damping and piezo-damping are the damping mechanisms of the piezoelectric ceramic–polymer composites, and the piezo-damping adds onto polymer damping. The piezo-damping in a composite depends not only on the piezoelectric properties of the piezoceramic, load resistance, modulus ratio and piezoceramic volume fraction, but also on the connectivity of each component. For series composites, the piezo-damping is too small to be useful due to the mismatch of the polymer and piezoceramic moduli. Therefore the particulate composites (0–3 composites) possess very low piezo-damping. Meanwhile in parallel composites, the piezo-damping dominates the composite damping. The parallel mode is a more desirable mode for piezo-damping. As the piezo-damping is frequency "tunable" and has a high damping level, the parallel composites possess a high damping capacity and their maximum damping ratio can be altered to any required frequency by changing the resistance. In this work this was done by altering an applied resistance, but practically the conductivity of the polymer matrix would be filled by addition of a conducting particulate phase. The experimental results correlate well with the theoretical predictions and therefore validate the models.

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