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Theoretical analysis of the conversion from electrical into thermal energy in piezoelectric-conductive damping composites

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Abstract: Based on the principles of electrical conduction and transformation, a model was put forward for the electrical conversion of piezoelectric damping composites, and a related formula was derived. The results show that the best effect of conversion can be achieved by reducing the imaginary part of the impedance and matching the frequency. The optimal damping effect at a certain frequency requires resistance of conductive phase (R) satisfying the condition of $R=1/(\omega C)$, but this condition may cause the damping effect at other frequencies to deviate away from the optimum condition. It is suggested that in order to make the damping effect more efficient and objective, frequency matching should be considered during the design of piezoelectric damping composites.

Key words: electrical analysis; piezoelectric; damping composites.

1. Introduction

Economic growth has promoted the rapid development of transportation technology. High-speed rail transportation has provided a fast, convenient, and safe method for travel, but with associated problems of noise and vibration. Recent studies on damping and sound-absorption materials based on gradient materials, liquid crystal polymers, smart magnetostrictive, and piezoelectric damping materials, etc., have become an important topic [1]. To date, damping control based on the piezoelectric effect has been of significant interest.

There have been several damping technologies based on the piezoelectric effects such as active damping design, hybrid damping control, piezoelectric shunt-dampings and piezoelectric damping composites (PDCs). PDCs, first proposed by Forward [2], are composed of a polymer matrix and two kinds of functional additives: piezoelectric material and conductive agent. Davis and Lesieutre [3] predicted the principle of shunt damping in the composites using a stress-strain model. It has been postulated that, through the synergy of the polymer viscoelasticity, interface friction and "piezo-damping" effect, the damping properties of materials can be improved [4-7].

There have been many reports focusing on different polymer matrices, such as thermosetting epoxy resin [8], polyvinylidene fluoride [9], polystyrene [10], vinylidene fluoride-trifluoroethylene [11], chlorinated polyethylene [12] or chlorobutyl rubber [13], and different piezoelectric materials such as piezoelectric lead zirconate titanate [8,14], BaTiO3 [6,9] or lead magnesium niobate [14], as well as different conductive agents including carbon black or polyaniline [15]. The influence of frequency, conductivity, and capacity on the damping effect have been studied experimentally [4,12]. Law et al. [16] simulated the vibration behavior of composites using parallel and series models, and the results indicated that the piezoelectric damping effect was subject to the connections between the components.

In addition to the experimental works focused on different kinds of components of PDC, related theoretical analyses concerning electro-mechanical coupling have been carried out [3,4,16]. Nevertheless, there is still a gap in knowledge concerning the conversion from electrical energy to heat in PDCs, which is essential and important for understanding the mechanism and for design and preparation of this kind of material. In the present paper, we suggest a novel model for simulating the aforementioned conversion from electrical to thermal

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energy in the damping composite of a piezoelectric-sconductive system.

2. Electrical modeling

Electrical energy, generated from the deformation of the piezoelectric phase by being applied a force of F from damping, is actually a distribution of charge separation, and will be dissipated through the conductive agent with a resistance of R in the composites, as illustrated in Fig. 1. Obviously, the piezoelectric phase has both the characteristics of a capacitor (C) and a power source (U). Thus, we regard the piezoelectric phase as an ideal power supply and a capacitor connected in series, as shown in Fig. 2. In order to facilitate the calculation, we assume that the power supply is sinusoidal.

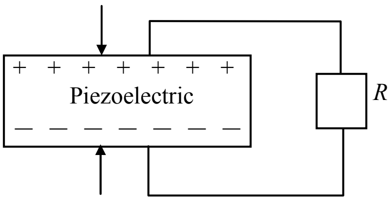

Fig. 1 Schematic diagram of piezo-damping principle

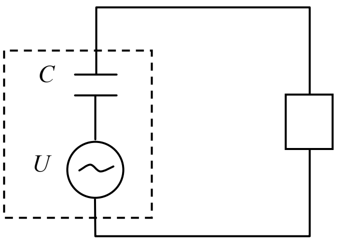

Fig. 2 Electrical schematic diagram of piezo-damping

The impedance (Z) of the entire circuit in Fig. 2 can be expressed as

$$Z = R - \mathrm{j}\frac{1}{\omega C}, \tag{1}$$

where R and C are illustrated in Fig. 2, and ω is the frequency of the sinusoidal power supply.

The current and voltage of the whole circuit is

$$i = \sqrt{2}I \sin \omega t \tag{2}$$

$$u = u_R + u_C = \sqrt{2}U \sin(\omega t + \varphi), \tag{3}$$

where I and U are the effective current and voltage of the entire circuit, respectively; u_R and u_C are the instant voltage of R and C, respectively; t is time variable; and φ is the phase angle between the voltage and current.

According to Eq. (2) and Eq. (3), the instant power p of the whole circuit is

$$p = UI[\cos\varphi - \cos(2\omega t + \varphi)]. \tag{4}$$

Then the effective work P_T in one cycle could be obtained through integration of p according to Eq. (1) and Eq. (4):

$$P_T = \frac{1}{T}\int_0^T p\mathrm{d}t = \frac{U^2}{R^2 + \left(\frac{1}{\omega C}\right)^2} R, \tag{5}$$

where $T = 1/\omega$.

Eq. (5) indicates the PDC's ability for transforming electrical energy to heat from the perspective of the electricity, which involves the resistance of the conductive phase (R), capacity of the piezoelectric phase (C), frequency (ω), and amplitude (U) of the power supply. This ability can be a key factor in the evaluation of the PDC's piezo-damping effect. In an earlier report [4], it was proposed that the best piezo-damping effect can be obtained if the resistance of the conductive phase R meets the condition of $R=1/(\omega C)$, which is a special case of Eq. (5).

3. Results and discussions

Fig. 3 shows the example spectra of current i, voltage u, and instant power p of the whole circuit, assuming $\phi = \pi/3$ according to Eqs. (2) to (4). Because of the existence of a capacitor of the piezoelectric phase, there is a storage and release of electrical energy, companied by the dissipation of electrical energy through the resistance of conductive phase R, which causes a negative result of p. The release of electrical energy in the capacitor of the piezoelectric phase means that electrical energy converts back into mechanical energy. In addition, by adding an inductive structure, e.g. helical carbon fibers, into the composite, we can, to some extent, offset the imaginary part of the impedance brought by the capacitor of the piezoelectric phase. This will make the impedance tend to be resistive and contributes to the dissipation of electrical energy.

Fig. 4 shows the continuous ωC-R-P_T 3D map of effective work P_T according to Eq. (5) with three arguments ω, C, and R. Supposing R and C to be constants, if there is $\omega_2 > \omega_1 > 0$, then one has $P_{T2} > P_{T1}$ according to Eq. (5), which indicates a more intensive piezo-damping effect at high frequencies. Jiang et al. [17] reported proximal results in experiments on sound absorption of the composites of $Pb(Mn_{1/3}Nb_{2/3})O_3$/nitrile-butadiene rubber/carbon fiber. Similarly, considering the capacity, if R and ω are set to be constants and $C_2 > C_1$, we have $P_{T2} > P_{T1}$ according to Eq. (5). That is, the higher frequency (ω) or larger capacity (C) leads to a higher efficiency of electrical energy dissipation.

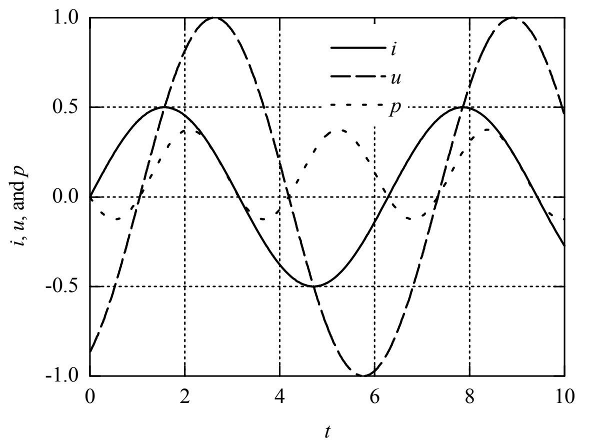

Fig. 3 Spectra of instant power according to Eqs. (2) to (4), where $I=\frac{1}{2\sqrt{2}}$, $U=\frac{1}{\sqrt{2}}$, ω=1, and $\phi=-\frac{\pi}{3}$

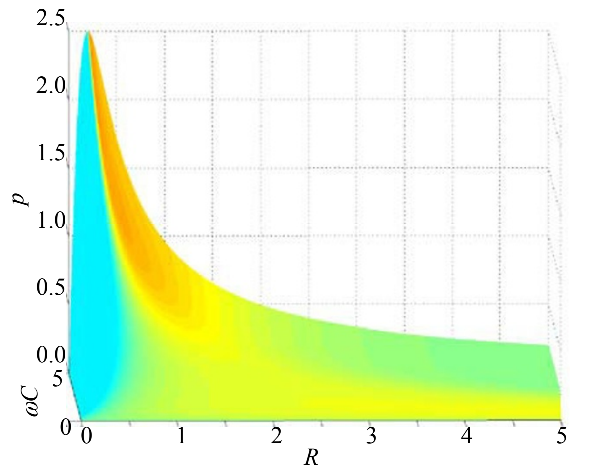

Fig. 4 Continuous ωC-R-P_T 3D map of effective work P_T according to Eq. (5), where we assume U=1

Fig. 5 shows the discrete ωC-R-P_T 3D map of effective work P_T according to Eq. (5) with the three arguments of ω, C , and R. Assuming ωC to be a constant value, the best piezo-damping effect can be obtained if the resistance of the conductive phase R meets the condition of $R=1/(\omega C)$ according to Eq. (5), and this is in accordance with Sumita's report [4,18]. In other words, when the capacity of the piezoelectric phase C and the resistance of conductive phase R are determined, there is only one frequency ω with the optimal ability for the conversion from electrical to thermal energy. This condition, however, may cause the damping effect at other frequencies to deviate from their optimal condition.

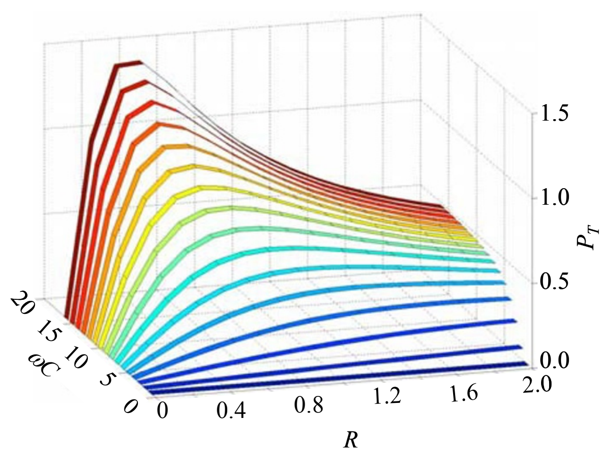

Fig. 5 Discrete ωC-R-P_T 3D map of effective work P_T according to Eq. (5), where we assume U=1

Furthermore, there is an obvious improvement of the piezo-damping effect, mainly at high frequencies, with the conductive phase R in a certain range, e.g. between 0.2 and 1.0 units, as seen in Fig. 4. Cai et al. [19] also studied the sound absorption of the composites of PZT/polyvinylchloride/carbon black, by adjusting the content of the carbon black, and obtained a parabolic result: the maximum efficiency was reached when the carbon black content was at a volume fraction of 4%.

If either $R \approx 0$ or $R \to \infty$, we have the effective work $P_T \approx 0$, according to Fig. 4, which means that the electrical energy will barely be dissipated or transported in these two kinds of composites. This deduction has been experimentally proved by Yan et al. [20], using $BaTiO_3$-chlorinated polyethylene as the piezoelectrical phase, and carbon fiber as the conductive component.

4. Conclusions

In summary, the variations in the process of electrical energy transformation into heat in piezoelectric damping composites have been obtained. This can be used to optimize the structure and composition of PDCs in related research. The best effect of conversion can be achieved by reducing the imaginary part of the impedance that is brought by the capacitor of the piezoelectric phase and further adjusted by controlling the damping frequency (ω), capacity of the piezoelectric phase (C), and resistance of the conductive phase (R), adding the inductive structure, and so on. The optimal damping effect at a certain frequency requires the resistance of the conductive phase (R) to satisfy the condition of $R=1/(\omega C)$, but this condition might cause the damping effect at other frequencies to move away from the optimal condition.

Therefore, frequency matching should be considered during the design of a piezoelectric damping composite, thereby making the damping effect more efficient and objective.

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