SONIC INSPECTION OF BONDS IN VISCOELASTIC COMPOSITES

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INTRODUCTION

Vibration isolation is frequently accomplished by placing rubber pads between a structure and its foundation. In typical industrial situations, the weight of the structure can be used to keep the pads in place and to ensure contact at the interface. However, when dampers are used for small electronic components, they are frequently glued to the component and to the support. The total unit then consists of the component, a glue interface, the rubber damper, a second glue interface, and the foundation. If the interfaces fail, compressive waves can usually be transmitted, but tensile stress waves encounter the separated layer which markedly affects the transmissivity and damping. Consequently, the damper effectiveness generally is reduced. Many modern dampers employ viscoelastic rubber whose frequency characteristics and damping rely less upon resonance than upon the wide frequency spectrum of damping [1].

Because debonding reduces the damping effectiveness it is important to determine if the interfaces are sound. One way to do this is to use sound waves and to measure the reflectivities. Generally when an interface fails it does so in small local areas which gradually coalesce to produce complete debonding. If large diameter sound beams are used, the problem is clearly three dimensional. If, on the other hand, the beams are small in diameter, the problem may be considered to be one dimensional.

This paper describes the one dimensional propagation of sound waves through viscoelastic vibration dampers to characterize the nature of reflection from debonded interfaces.

EQUATIONS OF MOTION AND MATERIAL PROPERTIES

Consider a material subjected to steady state oscillating conditions such that the strain can be represented by

\[ \varepsilon(t) = \varepsilon_0 e^{i\omega t} \]  

(1)
For isotropic materials, the stress strain relationship is

\[ \sigma(t) = M_k(t - \tau) \frac{\partial \varepsilon}{\partial \tau} d\tau \]  

(2)

where \( k = 1 \) or \( 2 \) and refers to the dilational or deviatoric components respectively. If the modulus is decomposed into two parts,

\[ M_k(t) = M_k' + M_k''(t) \]  

(3)

and \( \varepsilon(t) \) is expressed in terms of equation (1), we may write the stress strain relationship as

\[ \sigma(t) = M^*(\omega)\varepsilon_0 e^{i\omega t} \]  

(4)

where \( M^*(\omega) \) is termed the complex dynamic modulus

\[ M_k^*(\omega) = M_k'(\omega) + iM_k''(\omega) \]  

(5)

and \( M_k' \) and \( M_k'' \) are often referred to as the storage and loss moduli respectively and are given by

\[ M_k'(\omega) = M_k' + \omega \int_{-\infty}^{t} \sin(\omega \eta) M(\eta)d\eta \]  

(6a)

\[ M_k''(\omega) = \omega \int_{-\infty}^{t} \cos(\omega \eta) M(\eta)d\eta \]  

(6b)

\( M_k''(\omega) \) satisfies the conditions

\[ M_k''(0) = 0, \quad M_k''(\infty) = 0 \]  

(6c)

Figure 1 illustrates the general form of \( M' \) and \( M'' \).
The equations of motion, the wave equations, are expressed in terms of the Fourier transforms as

\[ M_k^{ij} \bar{u}_{k,ij} = -\rho \omega^2 \bar{u}_k \]  

(7)

where \( \bar{u} \) is the transform of the displacement vector. \( u_1 \) is the displacement in the direction of the wave - a P wave - and \( u_2 \) is transverse to the wave - the S wave.) Letting the displacement be given by

\[ u_k(t) = U_k e^{i(\omega t - \eta x)} \]  

(8)

the complex velocity is given by

\[ c^* = \sqrt{\frac{M^*}{\rho}} \]  

(9)

and

\[ \eta = \frac{\omega}{c^*} = \eta' + i \eta'' \]  

(10a)

\[ k = 2\pi f/c' \]  

(10b)

\[ \lambda = c'/f \]  

(10c)

The three most common waves are the dilational wave (P), the shear wave (S), and the longitudinal waves. For these different waves, the complex modulus is given by

\[ \text{dilational} \quad M^* = \lambda^* + 2\mu^* \]

\[ \text{shear} \quad M^* = \mu^* \]

\[ \text{longitudinal} \quad M^* = E^* \]

where \( \lambda \) and \( \mu \) are the Lame constants and \( E \) is Young's modulus. Most experiments are done with small diameter rods and the waves are longitudinal. For probing for interface debonding, the waves are more likely to be dilational waves and strongly dependent upon Poisson's ratio. Since most rubbers are nearly incompressible, \( \nu \sim 0.5 \), the moduli can become very large and care is needed in evaluating the Lame constants from measurements of \( E \) and \( \nu \) [2]. Irrespective of which waves are being used in the testing, the general form is that of equation 4.

COMPOSITE DAMPER

Figure 2 is a schematic of a viscoelastic damper in which a wave is incident upon the bond and a wave is transmitted and one is reflected. The left region, a, represents the structure, region c the foundation, region b the rubber damper, and region s the void due to failure of the glue bond. If debonding has taken place, region s is assumed to be a thin layer of air. Regardless of the materials which compose these different regions, continuity of displacement and stress must be enforced at the interfaces. Let

\[ u(x, t) = Ae^{i(\omega t - \eta x)} + Be^{i(\omega t + \eta x)} \]

where \( A \) refers to a right moving wave and \( B \) to a left moving wave.
The continuity of displacement requires an equation of the form

\[ A_a e^{-i\eta_a x_{ab}} + B_a e^{i\eta_a x_{ab}} = A_b e^{-i\eta_b x_{ab}} + B_b e^{i\eta_b x_{ab}} \]  

(11)

where \( x_{ab} \) is the location of the interface between regions a and b. \( B_c = 0 \) since region c extends to positive infinity and no reflected waves can exist. Using equation 4 for the stresses, the continuity of stress at the interface requires that

\[-\eta_a A_a e^{-i\eta_a x_{ab}} + \eta_a B_a e^{i\eta_a x_{ab}} = -\eta_b A_b e^{-i\eta_b x_{ab}} + \eta_b B_b e^{i\eta_b x_{ab}} \]  

(12)

Equations 11 and 12 are sufficient to determine \( B_a, A_b, B_b, A_c, A_s, B_s \), in terms of \( A_a \), the incident wave.

CHARACTERISTIC RESULTS

In order to provide some insight into the nature of the reflected wave for a viscoelastic damper, a material was chosen with moduli as shown in Figure 3. It is common to characterize viscoelastic materials by their loss factor, \( \delta = M''/M' \), which is generally of the order of 0.1. That for the material shown in Figure 3 is of the order of 1, a very lossy material. We will assume that layers a and c are of steel, b is the viscoelastic rubber with a thickness of 1 or 5 mm, and s (when debonding has occurred) is extremely thin (10 microns) and of air.

Good Interfaces

Figure 4 shows the effect of viscoelasticity on a rubber damper when the interfaces are good. The elastic damper shows the half wave interference effects characteristic of composite dampers [3]. The reflection coefficient is essentially unity except at the half wave points, \( kL/\pi = n \) where it is reduced by approximately 1 dB. When the material is
viscoelastic, the sharp dips at the half wave points disappear and the reflection coefficients tend to be relatively constant for $kL/\pi > 3$. Only the first two half wave points are still apparent. Figure 5 illustrates how the frequency varying properties of the viscoelastic material affect the reflection coefficient. For a constant modulus, $(M' = M'' = 5 \times 10^6)$ the interference effects completely disappear for large wave numbers, while for the frequency dependent moduli it continues to decrease slowly as $k$ increases. It is important to note that the effect of the frequency varying moduli is of the same order as the difference between elastic and viscoelastic materials and, as will be shown later, of the effect due to debonding.
Debonding

Figure 6 demonstrates the strong effect of the location of the debonding and the material. For an elastic material, debonding at the front is easily detectable. In contrast to the case of good bonds in which the reduction in the reflection coefficient is equal at each half wave point, the presence of 10 microns of air shows an increasing effect as the wave number increases and the wave length approaches the thickness of the air layer. For a 1 micron thick layer, the maximum reduction remains approximately constant until the wavelength is small enough, $kL/\pi = 5.5$, so that the air and rubber layers interact, whereupon it begins to exhibit the same effect as shown for the 10 micron layer. Debonding at the rear of an elastic damper shows only a few measureable points and even these have such a small reduction (less than 1dB) that accurate experiments will be required. The effect of viscoelasticity is the reverse; front debonding is much harder to detect than debonding at the rear. However, for the rear debonding the maximum effect is only of the order of 4dB.

Figure 7 compares the reflection coefficients for sound and debonded viscoelastic dampers. Two points are important: a) only front debonding can be detected; b) the frequency must be such that $kL/\pi$ exceeds 2. At lower frequencies, the effects are negligible.

![Fig. 6. Effect of Debonding Position and Material (lower 2 curves offset by 8dB for clarity)](image)

![Fig. 7. Comparison of Bonded and Debonded Viscoelastic Dampers (lower 2 curves offset by 8dB for clarity)](image)

CONCLUSIONS

Although these calculations are limited to one dimensional waves, several important conclusions can be reached for viscoelastic dampers.

- Only front debonding of viscoelastic materials can be detected. Because of the frequency dependent damping, rear debonding effects are overshadowed by the thickness effects of the damping material. These findings agree with the experimental results of reference 4 and the computer simulations of reference 5.
b Debonding of elastic materials is qualitatively different from that for viscoelastic materials.

c Debonding is detectable only for large wave numbers. This means that the frequency dependency of the sound speed must be known, i.e., \( M^*(\omega) \). Such evaluations are difficult to make and are extremely sensitive to temperature effects.

d The effects of the frequency dependent moduli are of the same order as the debonding effects.

REFERENCES


5 J. Sullivan et al., in *Review of Progress in Quantitative NDE*, op. cit.