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Effect of Poisson's loss factor of rubbery material on underwater sound absorption of anechoic coatings

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A B S T R A C T

Rubbery coatings embedded with air cavities are commonly used on underwater structures to reduce reflection of incoming sound waves. In this paper, the relationships between Poisson's and modulus loss factors of rubbery materials are theoretically derived, the different effects of the tiny Poisson's loss factor on characterizing the loss factors of shear and longitudinal moduli are revealed. Given complex Young's modulus and dynamic Poisson's ratio, it is found that the shear loss factor has almost invisible variation with the Poisson's loss factor and is very close to the loss factor of Young's modulus, while the longitudinal loss factor almost linearly decreases with the increase of Poisson's loss factor. Then, a finite element (FE) model is used to investigate the effect of the tiny Poisson's loss factor, which is generally neglected in some FE models, on the underwater sound absorption of rubbery coatings. Results show that the tiny Poisson's loss factor has a significant effect on the sound absorption of homogeneous coatings within the concerned frequency range, while it has both frequency- and structure-dependent influence on the sound absorption of inhomogeneous coatings with embedded air cavities. Given the material parameters and cavity dimensions, more obvious effect can be observed for the rubbery coating with a larger lattice constant and/or a thicker cover layer.

1. Introduction

Rubbery coatings are commonly used as attachments on underwater structures to reduce reflection of incoming sound waves. To achieve a good anechoic property, the rubbery coatings should possess good sound absorption ability. Although the characteristic impedance of rubber material is close to water, its compressional-wave dissipation is much less efficient than that of shear wave. Hence, rubbery coatings are usually embedded with various scatterers, such as air-filled cavities [1–10], microspheres [11–15], or locally resonant phononic crystals [16,17], to induce scattering and wave mode conversion, and thus to enhance the sound energy dissipation.

Cavity-type scatterers were firstly introduced into the rubber matrix to constitute the so-called Alberich anechoic coating in the Second World War [1], and have received much attention over the past few decades. Early modeling studies for rubbery coatings with cavities were mainly based on homogenization [18–20] with effective medium properties and simplified analytical models, such as the lumped system approximation [1], one-dimensional [3] and two-dimensional [4] waveguide

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models. In recent years, a semi-analytical method, the layer-multiple scattering method, borrowed from Phononic Crystals is extended to study the echo reduction by rubbery coatings with spherical or super-ellipsoidal cavities [7–9], microspheres [13,14] and locally resonant scatterers [10,16,17]. However, these methods require either lots of specific algebraic developments or special simplifying hypotheses, which restrict their application to a small number of given geometries. Apart from the analytical or semi-analytical method mentioned above, the finite element method (FEM) has also been used to modeling the acoustic properties of rubbery coatings [17,21–36]. An important advantage is the flexibility to model different types of scatterers. Periodicity can be utilized to restrict the computer intensive finite element (FE) modeling to an individual unit cell.

It is shown that accurate knowledge of the material properties of the rubbery coating is the premise to precisely describe the real acoustic properties of the rubbery coatings and then achieve good agreement between experimental data and numerical predictions. In the case of a homogeneous and isotropic material, only two elastic constants (along with the density) are needed to completely characterize the material; and other elastic modulus can then be computed from the chosen elastic constants [37,38]. Among the published works on modeling the acoustic properties of rubbery coatings, different combinations of elastic parameters were chosen to characterize the dynamic mechanical properties of rubber coating. In some analytical or numerical research works, two complex moduli [12,15,35,36] or complex wave speeds [7–11,13,30,39–42] were chosen; while a more common choice for other investigations, especially that using the FEM, was the combination of the complex Young's modulus and Poisson's ratio [2,3,5,6,17,21–26,28,29,32–34,43]. Generally, these two types of combinations of elastic constants should be equivalent. However, a potential problem comes from the description of attenuation in the rubbery materials. In the former case, the loss factors (attenuation constants) of two complex moduli (complex wave speeds) could be either identical or different; while in the latter case, the corresponding modulus loss factors are always forced to be identical due to the real Poisson's ratio using in the model [44,45], in spite of the claim that the Poisson's ratio of viscoelastic materials should be a complex value [37,45–51].

Poisson's ratio is defined by the ratio of lateral strain to axial strain when the body is subjected to a uniaxial direct stress. The complex Poisson's ratio comes from the fact that the lateral strain lags behind the axial dynamic strain due to material damping. The Poisson's loss factor, named by Pritz in his series of articles on complex Poisson's ratio [45,48–50], is then defined as the ratio of the imaginary part to the real part of the complex Poisson's ratio. The available experimental data show that the Poisson's loss factor is always low, the measured magnitudes are of the order of $10^{-3} - 10^{-2}$ [46,51–53]. Pritz investigated the magnitude of the Poisson's loss factor for homogeneous, isotropic, linear viscoelastic materials, integrating both theoretical derivation and experimental data. Conclusions were drawn that the Poisson's loss factor is smaller than the shear loss factor usually by one order of magnitude at least and its magnitude normally does not exceed 0.1 even in the case of rubbers and other high-damping elastomers [45]. In spite of it, this tiny quantity plays important role in the material behavior. The sequence of the magnitudes of several modulus loss factors were deduced and amended under the condition that the real and imaginary parts of the complex Poisson's ratio are positive and negative, respectively; while these modulus loss factors would be identical for a real Poisson's ratio [51,52].

Unfortunately, the direct measurement of Poisson's ratio is very difficult to perform accurately. It is shown that some contradictory beliefs on the value of Poisson's loss factor are due to experimental difficulties [49]. These experimental difficulties, combined with the fact that its loss factor is very low often leads researcher to ignore the imaginary part of Poisson's ratio, or even to erroneously assume that it is a purely real quantity [44,54,55], in spite of theoretical predictions [51,52] and experimental observations [46,51–53]. However, this ignorance may lead to contradictions in characterizing the dynamic behavior of materials, and cause erroneous results in the acoustical calculus. As an important application of viscoelastic materials, this situation is also very common on the modeling of underwater acoustic performances of rubbery coatings. As mentioned before, lots of researchers investigated the underwater sound absorption of rubber coatings characterized by the parameters group of complex Young's modulus and real Poisson's ratio, while the effects of the ignored Poisson's loss factor was not checked thoroughly.

In this paper, the relationships between the Poisson's and the modulus loss factors are theoretically derived, with the emphasis on the different effects of Poisson's loss factor on characterizing the loss factors of shear and longitudinal moduli, which have not been reported in the literature. Then, the effects of the Poisson's loss factor on the sound absorption of rubbery coatings are investigated by using the FEM.

2. Theory and analysis model

2.1. Poisson's loss factor: definition and its relationship with modulus loss factors

The complex Poisson's ratio of rubbery materials can be given as [45,48–50].

$$\bar{\nu}(j\omega) = \nu_d(\omega) - j\nu_l(\omega) = \nu_d(\omega)[1 - j\eta_\nu(\omega)] \tag{1}$$

where $\omega = 2\pi f$, f is the frequency in Hz, ν_d is the dynamic Poisson's ratio, ν_l is the relevant loss part, and η_ν is referred to as Poisson's loss factor and is always a positive quantity, i.e. $\eta_\nu > 0$ [51,52].

The complex shear modulus, $\overline{G}$ and the complex longitudinal wave modulus, $\overline{L}$ can be deduced as the functions of the complex Young's modulus, $\overline{E}$ and the complex Poisson's ratio, $\bar{\nu}$, given by