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Analysis of Ultrasonic Velocity and Attenuation in Particle-Dispersed Viscoelastic Composites for Acoustic Materials Design
音響材料設計のための粒子分散粘弾性複合材料の超音波伝搬速度と減衰係数の解析

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1. Introduction

The optimization of acoustic properties of a backing material, acoustic matching layers and an acoustic lens is required in a design of a medical ultrasonic probe. Particle-dispersed composites are used as these components, but their compositions are mostly selected empirically and are not designed on the basis of theoretical principles to design their acoustic properties [1]. The purpose of our study is to help the optimization of acoustic properties of probe materials by developing a theoretical model that can evaluate the effect of different matrices and particles as well as particle concentration and size on the ultrasonic velocity and attenuation in particle-dispersed composites. We apply a dynamic generalized self-consistent multiple scattering model to particle-dispersed composites accounting for viscoelastic nature of the constituents, and discuss the effect of some parameters.

2. Analysis methods

We consider a random distribution of spherical elastic inclusions embedded in a viscoelastic matrix. We apply Yang's dynamic generalized self-consistent multiple scattering model [2], by accounting for the viscoelastic properties explicitly. In this way, the effective longitudinal (P) and shear (S) wave numbers $\langle k \rangle$, $\langle K \rangle$ of the composite are determined by the forward and backward scattering amplitudes $f(0)$, $f(\pi)$, $g(0)$, $g(\pi)$ of a plane wave propagating in the three-phase model composed of particle-matrix-effective medium as shown in **Fig. 1**, by

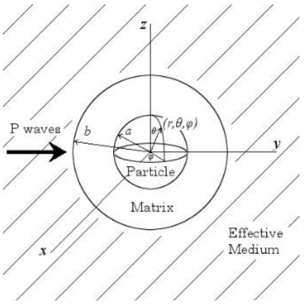

Fig. 1 Analysis model.

$$\left[\frac{\langle k \rangle}{k_2}\right]^2 = \left[1 + \frac{2\pi n_0 f(0)}{k_2^2}\right]^2 - \left[\frac{2\pi n_0 f(\pi)}{k_2^2}\right]^2 \quad (1)$$

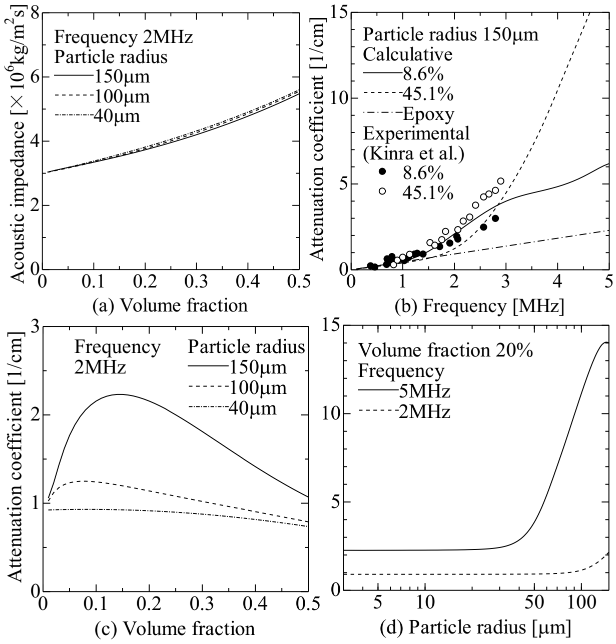

Fig. 2 Acoustic impedance and attenuation coefficient of P wave in a Glass-Epoxy composite.

$$\left[\frac{\langle K \rangle}{K_2}\right]^2 = \left[1 + \frac{2\pi n_0 g(0)}{K_2^2}\right]^2 - \left[\frac{2\pi n_0 g(\pi)}{K_2^2}\right]^2 \quad (2)$$

where k_2 and K_2 are P and S wave numbers of the matrix, respectively, and n_0 is the number of particles per unit volume. The ultrasonic velocity and the attenuation in the composite are given by the effective wave numbers $\langle k \rangle$ and $\langle K \rangle$. Then, the acoustic impedance (AI) in the composite, which is one of the important indexes for design of probe materials, is given by the product of the ultrasonic velocity and the density.

3. Numerical results

Numerical calculations are first performed for a glass-particle-dispersed epoxy composite used as acoustic matching layers, and the results are shown in **Fig. 2**. For the acoustic impedance, the particle size does not affect the AI too much and the particle volume fraction is a dominant factor. For the attenuation, the frequency dependence is close to the experimental data [3]. The attenuation has a peak at a specific particle concentration and its peak shifts with the particle size. As the particle size decreases, the attenuation also decreases, and exhibits essentially no particle-size dependence in the range of small particle size.

Numerical calculations are also performed for a silicone rubber (Q-rubber) filled with platinum (Pt) metal particles or aluminum oxide (Al_2O_3) particles. Such composites are used as an acoustic lens. **Fig. 3** shows the influence of the particle concentration and the particle size on the AI and the attenuation of P wave in a Pt-particle-dispersed Q rubber composite. In Fig. 3 (a), the attenuation does not have a clear peak as compared to the glass-particle-dispersed epoxy composite. The attenuation appears to increase monotonically with the particle volume fraction up to 50%. For the particle-size dependence, the calculated data of the AI fits the experimental results by Yamashita et al. [1]. Their experimental data of the attenuation are, however, considerably high as compared to the present calculation. This is considered to be due to the insufficient dispersion of particles or the presence of pores, which are typical problems in dispersion of very small particles of nanometer sizes. Our calculation indicates that composite materials with lower attenuation can be made by the use of particles which are of micrometer sizes within the range without the particle-size dependence of the attenuation.

Fig. 4 shows the effect of the particle concentration and the particle size on the AI and the attenuation of P wave in an Al_2O_3-particle-dispersed Q rubber composite. All results except the particle -concentration dependence of the attenuation show the tendency similar to the glass-particle-dispersed epoxy composite and the Pt-particle-dispersed Q rubber composite. **Fig. 5** shows the particle-concentration dependence of the longitudinal ultrasonic velocity in the Al_2O_3-particle-dispersed Q rubber composite. The ultrasonic velocity is one of the important factors that influence the performance of an acoustic lens. Although the ultrasonic velocity decreases with the particle volume fraction up to about 13%, it increases in the range of higher particle volume fraction.

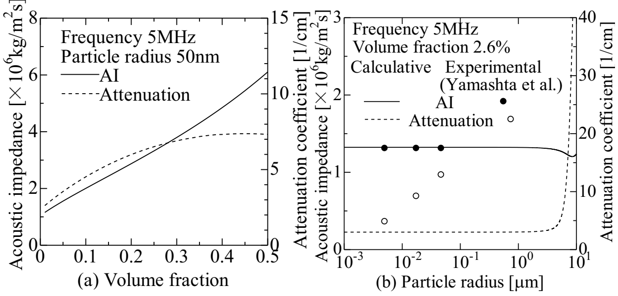

Fig. 3 Acoustic impedance and attenuation coefficient of P wave in a Pt-Q rubber composite.

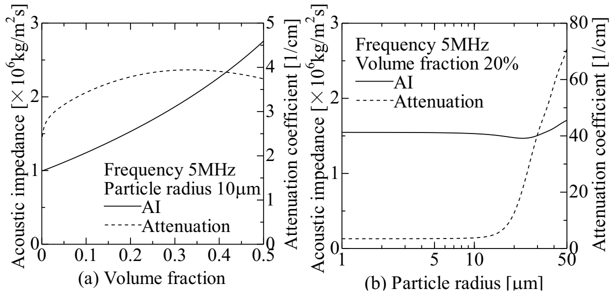

Fig. 4 Acoustic impedance and attenuation coefficient of P wave in an Al_2O_3-Q rubber composite.

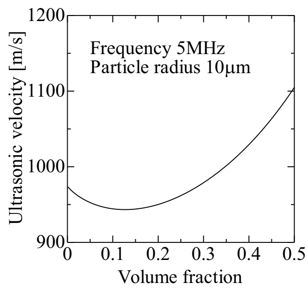

Fig. 5 Variation of the P wave velocity in an Al_2O_3-Q rubber particulate composite with the particle volume fraction.

4. Conclusion

In this study, we investigated the materials design parameter dependence of acoustic properties of particle-dispersed composites on the basis of a dynamic generalized self-consistent multiple scattering model to improve acoustic properties of a medical ultrasonic probe. Consequently, the following results were obtained:

(1) For the acoustic impedance, the influence of the particle size is not significant and the particle concentration is a dominant factor.
(2) The attenuation is affected by the particle concentration and its effect is different for different matrices, particles, and the particle sizes.
(3) As the particle size increases, the attenuation also increases. But the attenuation exhibits essentially no particle-size dependence in the range of small particle size.
(4) As the particle concentration increases, the ultrasonic velocity first decreases but increases for the particle concentration exceeding a certain value.

References

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