APPLICABILITY OF URICK'S THEORY TO THE ULTRASONIC WAVE PROPERTIES IN THE PARTICLE COMPOUNDED GELS

43.35.Bf Ultrasonic velocity, dispersion, scattering, diffraction, and attenuation in liquids, liquid crystals, suspensions and emulsions.

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ABSTRACT

Ultrasonic wave properties (attenuation and velocity) in the particle compounded gels have been experimentally studied in the range from 1 to 30 MHz. Properties were precisely measured using an ultrasonic transmission technique at a stable temperature. The particles used were talc, graphite and glass beads. The observed properties were in good accordance with the Urick's theory for viscous liquid suspensions, introducing the apparent shear viscosity. The applicability of the theory was carefully checked by changing the particle properties (diameter, density and elasticity) and the volume concentration of the particles.

INTRODUCTION

The particle-compounded gels are considered as a composite material. In the area of ultrasonic diagnostic studies, it has been used as a tissue mimicking materials (phantoms), which is expected to have similar ultrasonic wave properties with human tissues. The composite material has a lot of parameters and shows complex ultrasonic wave properties. There, however, seems to be few theoretical studies about the wave propagation in the medium like these gels. We have then applied Urick's theory for viscous suspension to understand the propagation phenomena.

URICK'S THEORY FOR VISCOUS SUSPENSIONS[1,2]

Urick has described longitudinal wave attenuation α in viscous suspensions.

$$2\alpha_1 = \sum_r C_r \left[\frac{1}{3} k^4 a_r^{\ 3} + k(\sigma - 1)^2 \frac{s}{s^2 + (\sigma + \tau)^2} \right] \tag{1}$$

where

$$\left\{ \quad s = \frac{9}{4a_r \boldsymbol{b}}\left\{1+\frac{1}{a_r \boldsymbol{b}}\right\}, t = \frac{1}{2}+\frac{9}{4a_r \boldsymbol{b}}, \quad s = \frac{\boldsymbol{r}_2}{\boldsymbol{r}}, \quad b = \sqrt{wr/2h} \quad \right\}$$

a_r is the compounded particle r, C_r is the volume concentration of the particle r, $\boldsymbol{h}$ is the shear viscosity of the fluid, k is the wave number, $\boldsymbol{w}$ is the angular frequency, $\boldsymbol{r}_2$ and $\boldsymbol{r}$ are the densities of particle and fluid. In equation (1), the first term shows the viscous loss, whereas the second term shows the scattering loss. The longitudinal wave velocity V in the suspension is given as follows,

$$\frac{V_1}{V} = \frac{\sqrt{2\left(-M+\sqrt{M^2+N^2}\right)}}{N} \qquad (2)$$

where

$$\left\{ \begin{array}{l} M+iN = \left\{1+\sum_r C_r\left(m_2-m\right)/m\right\}\left[1+\sum_r C_r \dfrac{3s'}{\left(s'+3X\right)^2+9Y^2}\left\{\left(Xs'+3X^2+3Y^2\right)+iYs'\right\}\right], \\ s' = \dfrac{\boldsymbol{r}_2-\boldsymbol{r}}{\boldsymbol{r}}, \quad X = \dfrac{1}{2}\left(1+\dfrac{3}{2a_r \boldsymbol{b}}\right), \quad Y = \dfrac{3}{4a_r \boldsymbol{b}}\left\{1+\dfrac{1}{a_r \boldsymbol{b}}\right\}. \end{array} \right\}$$

V_1 is the velocity in the fluid, and m_2 and m are the compressibility of particles and fluid, respectively. In these equations, one should take the particle size distribution into consideration. In addition, it should be noted that equation (2) was derived from the assumption of negligible viscosity of the fluid. In Urick's theory, the introduction of the parameter $a\boldsymbol{b}$ results in an interesting behavior of velocity and attenuation. $\boldsymbol{b}$ is the characteristic thickness of the shear boundary layer around the particle, expressed as $\boldsymbol{b} = \sqrt{\boldsymbol{wr}/2\boldsymbol{h}}$. Here, $\boldsymbol{h}$ was used as a fitting parameter.[3)] The estimated $\boldsymbol{h}$ values were shown in Table 1.

Particles	Estimated viscosity [Pa¥s]
TiO_2	0.04
Talc	0.03
Graphite S,M,L	0.07
Glass beads	0.03

Table 1 The estimated viscosities of samples.

Particles	Median particle diameter [μm]	Density [10^3 kg/m^3]	Young's modulus [G Pa]	Poisson's ratio	Compressibility [10^{-11} m^2/N]
TiO_2	1.0	4.0	243	0.31	0.47
Talc	1.8	2.8	25.3	0.34	3.9
Graphite S	4.0	2.2	11.7	0.20	15.2
Graphite M	14				
Graphite L	37				
Glass beads	12.3	2.5	69.0	0.21	2.5

Table 2 Characteristics of the particles used.

SAMPLE GELS AND EXPERIMENTS

Samples

The particles used are TiO_2, talc, graphite and glass beads. The characteristics of these particles are shown in Table 2. The sample gels were made as follows. A mixture of degassed water, agar powder and particles was degassed for 30 minutes, heated at about 60^{0}C for 30 minutes with stirring. The mixture was then poured into two acrylic vessels to make different thickness samples (5 or 10 [mm]). Mixtures are then slowly cooled to the room temperature and congealed completely. In these samples, the weight ratio of agar powder to the degassed water was 3%. The volume concentration of particles was varied from 0 to 7%.

Experiments

A block diagram and the apparatus of the measurement system are shown in Fig.3.1 and 3.2. Two fixed PVDF transducers were used as a transmitter and a receiver. A function generator excites the transmitter with a sinusoidal burst wave in the frequency range from 1 to 30 MHz. The emitted ultrasonic longitudinal wave propagated water - sample - water and was received by the receiver. After amplification, a digital oscilloscope observed waves. The wave velocity in the sample was obtained by comparing the propagating times of ultrasonic wave with or without the sample. The wave attenuation was obtained by comparing the observed wave amplitudes of different thickness samples. Experiments were performed in the temperature range of 24.7 ± 0.2 [.].

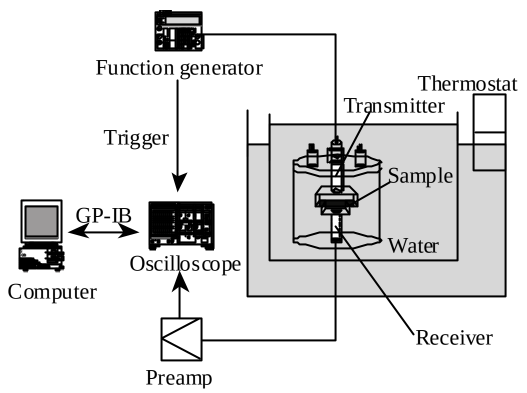


Fig.3.1 Block diagram of measurement system.

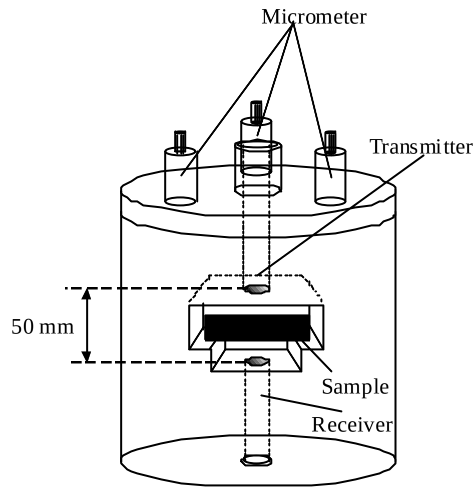


Fig.3.2 Measurement cell.

RESULTS AND DISCUSSIONS

Figures 4.1 shows theoretically estimated and observed velocity. As a function of ab, velocity shows dramatic changes and same tendency with the theoretical estimation. The velocity decreased as the concentration of particles increased at lower ab values, whereas the velocity increased at higher ab values. The same tendency was observed in all samples. This interesting behavior seems to come from the viscous drag process, which is the basis of Urick's theory.[4] This process implies the out of phase motion of particles, which causes the decrease of longitudinal wave velocity. As the shear boundary layer becomes small or the radius of the particles becomes large, which means larger ab values, the scattering loss becomes dominant. It results in the conventional additive properties of particles and gel medium in velocity.

Figure 4.2 shows interesting changes of al (attenuation par wavelength) in the particle-compounded gels. As can be seen, al shows a maximum around ab= 2 and dramatically increased at ab values larger than 10. The maximum seem to depend on the relative movement of the medium and the particle. With extremely small particles the out of phase motion particles seem small and show small absorption. As the particle size increased, the particles lag more behind the movement of the medium, which causes attenuation of the frictional loss. However, because the volume concentration is constant, the decrease of total surface area causes the decrease of attenuation. These opposite factors result in the maximum.[4] The attenuation increases at ab value larger than around 10 caused by scattering. In our particles

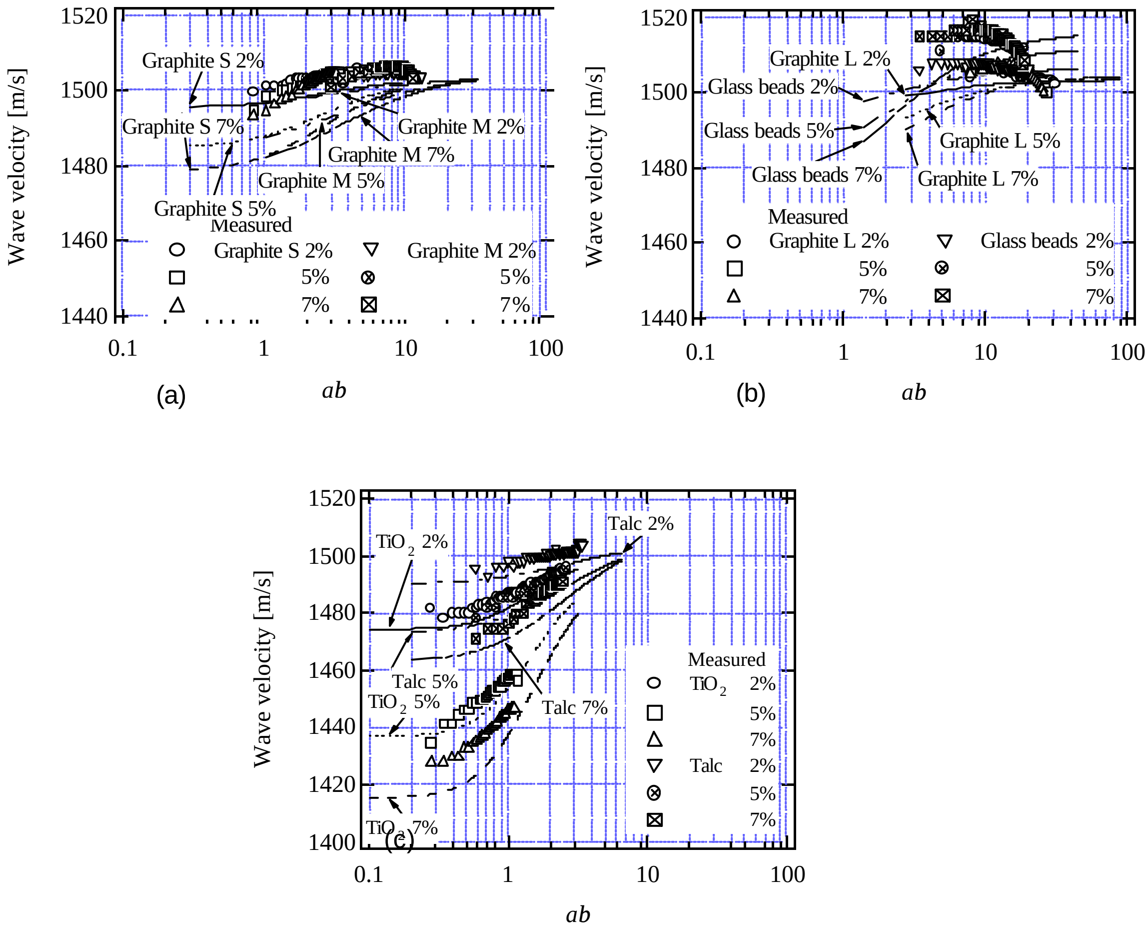


Fig.4.1 Dependence of wave velocity on the values of ab.

compounded gels, the obtained al are in good accordance with the theoretical estimation, which also supports the applicability of the theory.

<u>Effect of shear viscosity and concentration of particles</u>

One of the most difficult parameter in the Urick's theory is the shear viscosity. Wave velocity and attenuation in particle-compounded gels were then measured by changing shear viscosity of the gel medium. The viscosity of the gel medium was controlled by adding glycerol to the water in the making process of the gel. Here, we have only used the graphite S particle. Figure 5.1 shows wave velocity and attenuation in glycerol-water gels. As can be seen, the wave velocity was not varied due to the amount of glycerol. The attenuation, however, decreased as the amount of glycerol increased. Because the ab value decreases as the shear viscosity of the medium increases., this results also supports the existence of attenuation minimum in Fig. 4.2(b). The constant wave velocity reflects the small velocity changes in Fig.4.1(b).

Figure 5.2 shows wave velocity and attenuation in the gels with high concentration of particles. Particles compounded gels were glass beads. As can be seen, neither wave velocity nor attenuation observed is good accordance with theoretical value. Because glass beads are large particles compared with the wavelength, this also indicates the limitation of the theory. The effect of large particle size results in the velocity decreases in the gel, which can also be found in Fig.4.1(b).

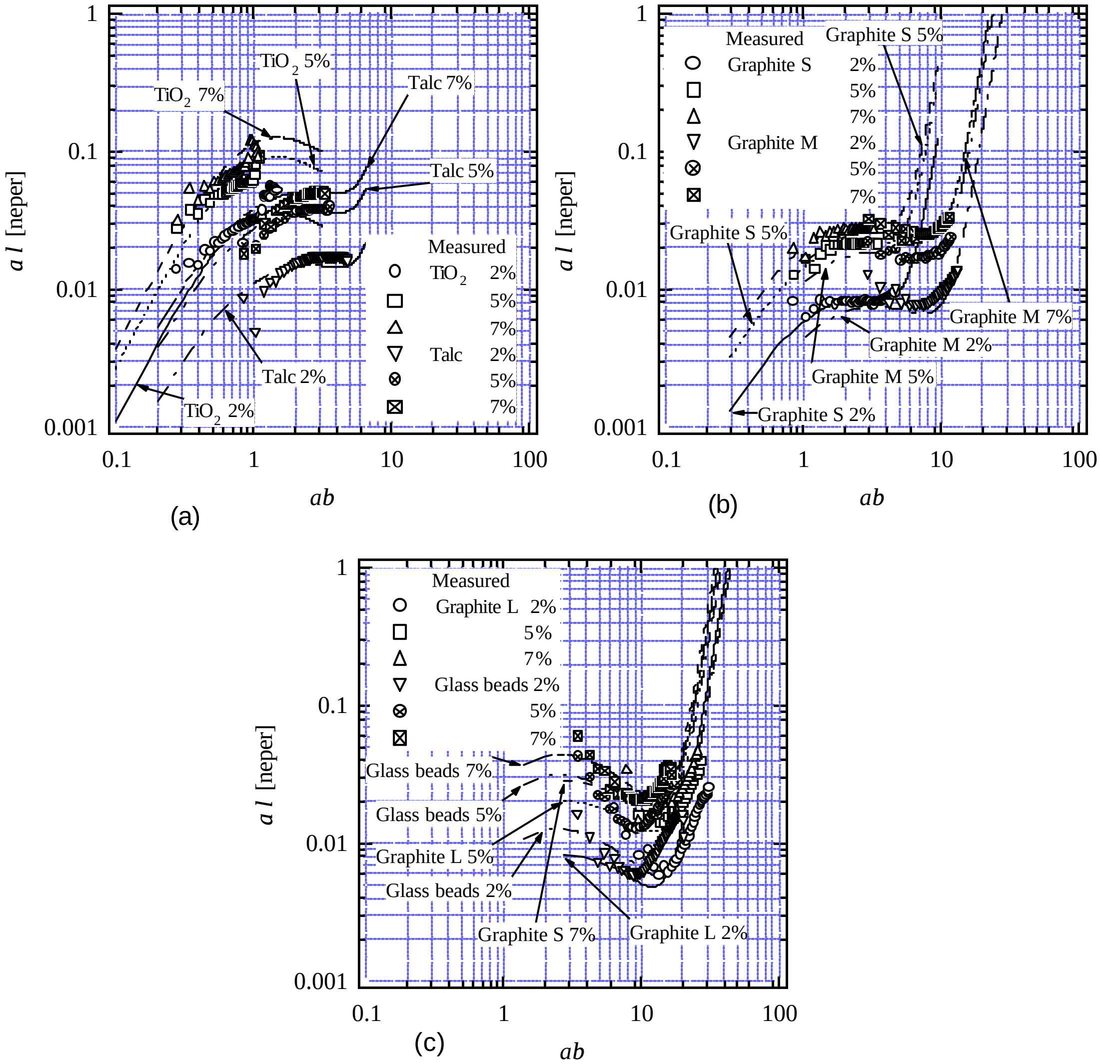


Fig.4.2Dependence of attenuation on *ab*.

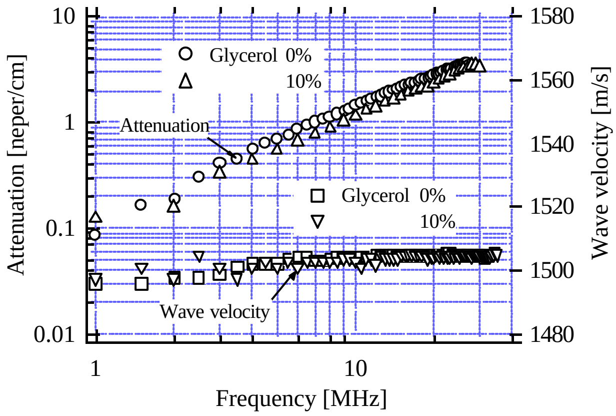
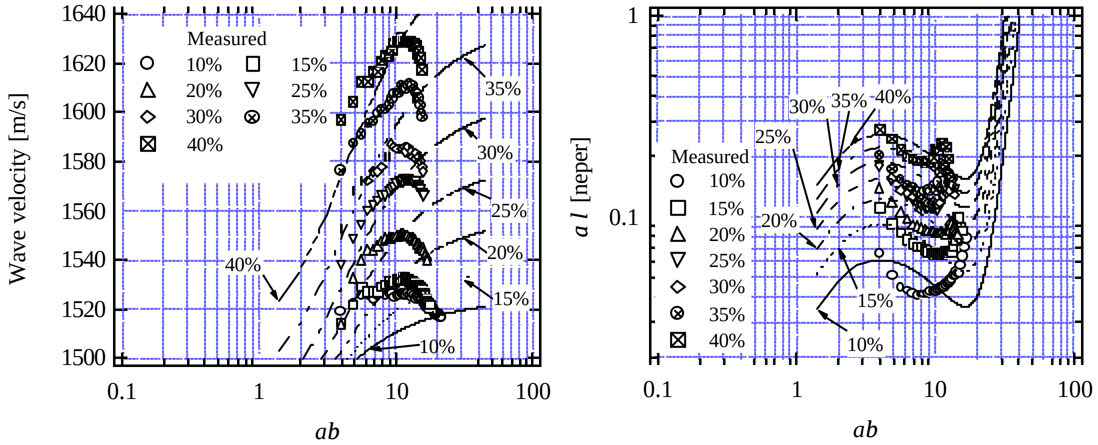


Fig.5.1 Measured ultrasonic wave properties in the glycerol - graphite gel.



(a) Wave velocity (b) Attenuation

Fig.5.2 Ultrasonic wave properties in the glass beads gel.

CONCLUSION

Ultrasonic wave properties in the particle-compounded gels have been experimentally studied in the MHz range. Urick's theory could be used to estimate ultrasonic wave properties in the particles in the particle-compounded gels. One should note, here, the applicability of the theory. The theory could be used in the range of $ab< 10$ and the concentration of particles up to 7% in the present study. We have not confirmed yet, however, there seems to exist a limitation of shear viscosity of the gel medium and the radius of particles. These limitations are considered to result from the Urick's assumption for the theory, that is, the negligible wave attenuation (which means low viscosity) of the medium and multiple scattering.

ACKNOWLEDGMENTS

Part of this study was supported by Grant-in-Aid for scientific Research from the Ministry of Education, culture, Sports, Science and Technology (No.11792012). Authors would like to thank Mr. Tadaaki Akimoto for his help of experimental works.

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