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Theoretical Study on Relationship between Particle Diameter and Peak Frequency in Blood-Mimicking Suspension

擬似血液試料における粒度―ピーク周波数の関係に関する理論的検討

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1. Introduction

An ultrasonic technique which noninvasively and quantitatively estimates the aggregation degree of red blood cell ("RBC" hereafter) has been studied. The aggregation degree of RBC has a strong relationship with the blood viscosity. In our former study, blood- mimicking suspensions were prepared by dispersing fine acryl particles in water. The reflection spectrum is obtained with the wave transmission and receive by an ultrasonic transducer to the suspension. The ultrasonic transmission from a transducer is reflected at a reflection board through the suspension, and the reflected wave is received by the transducer. Thus, the power spectrum is formed by an attenuation iteration. The frequency at the maximum power of the spectrum ("peak frequency" hereafter) is regarded as a function which logarithmically declines with the particle diameter [1]. In this study, a theoretical examination is executed to confirm the experimental function.

2. Experimental conditions in former study

The experimental setup used in the former study is drawn in Fig. 1. A 20-MHz wideband ultrasonic transducer with 6.3 mm of element diameter and non-focus was employed. Monodisperse acryl particles with diameters of 6, 15, 32, 46 and 110 ㎛ were dispersed in deionized water. As the acryl particle, mimicking the RBC, had the specific gravity of 1.18, particle sedimentation had generated in water. To prevent the sedimentation, suitable amount of a thickener (carboxymethyl cellulose, 10 g/L) was added to the suspension. Furthermore, the suspensions were gently stirred with a magnetic stirrer for the same purpose.

The spectrum is formed by the processes of: (a) the transducer is oscillated by a pulser, (b) the ultrasonic wave is attenuated by the particles inside the cylindrical volume of the beam form, (c) the ultrasonic wave is reflected on the reflection board, (d) the attenuation on the return path is arisen. The spectrum derived with these attenuation processes was theoretically discussed whether to correspond to the experimental result.

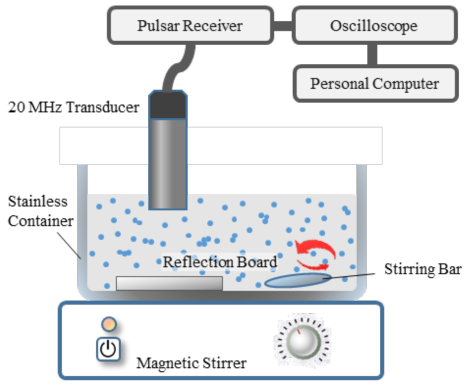

Fig. 1 Experimental setup for detecting peak frequency of ultrasonic reflection spectrum.

3. Numerical modeling

Acoustic attenuation is consisted of viscous loss, thermal loss, scattering loss, structural loss, intrinsic loss and electrokinetic loss [2].

In the case of this study, the main factor for the ultrasonic attenuation is scattering; in particular, Rayleigh scattering is practically dominant because the particle size is sufficiently smaller than the wavelength. Thus, calculations of the peak frequency would be done based on the modeling of the attenuations.

An attenuation coefficient is formulated by the equations as follows;[3]

$$\alpha_s = \epsilon k_c \frac{k_c^3 a^3}{6}\left(\gamma_k^2 + \frac{\gamma_p^2}{3}\right) \quad \text{[1/m]} \qquad (1)$$

where $\epsilon = (4/3)\pi a^3 N$, $N = C/m$, $m = (4/3)\pi a^3 \rho_0$, $k_c = 2\pi/\lambda$, $\gamma_k = (\kappa^* - \kappa)/\kappa$, $\gamma_\rho = 3(\rho_{0'} - \rho_0)/(2\rho_{0'} + \rho_0)$. The coefficients necessary for the calculation are listed in Table 1.

Lambert-Beer law originally describes the attenuation of the light. However, the light scattering has a similarity with the acoustic wave [4], and this law can be extended to the scattering attenuation in the case of dilute system of less than 100 g/L, therefore, in this study, the equation 2 was employed, defining the propagation distance to be 2d, the iteration distance between the transducer and the refection board.

Table 1 Coefficients used in calculations.

ϵ	Volume fraction	0.0424
a[m]	Particle diameter	6-110μ
N[1/m^3]	Number density	
c[g/m^3]	mass concentration	
m[g]	Mass of a particle	
$\rho_{0'}$ [g/m^3]	Mass density of acryl particle	1.18
k_c[1/m]	Wave number	
λ[m]	Wave length	
κ'_s [1/Pa]	Compressibility of acryl	
ρ_0 [g/m^3]	Mass density of water	1.00×10^6
κ* [GPa]	Bulk modulus of water	2.19

$$I = I_0 \exp(-2d\alpha_s) \quad (2)$$

where I is the transmitted intensity, and I_0 is the incident intensity.

4. Results

Fig. 2 shows the frequency characteristics of α_s by varying the particle diameter from 6 to 110 ㎛. It was suggested that the higher the frequency and the larger the particle diameter, the stronger the scattering coefficient.

The reference spectrum was acquired with fresh deionized water, and thus, without particles. After considering the scattering attenuation, the reflection spectra shown in Fig.3 were obtained.

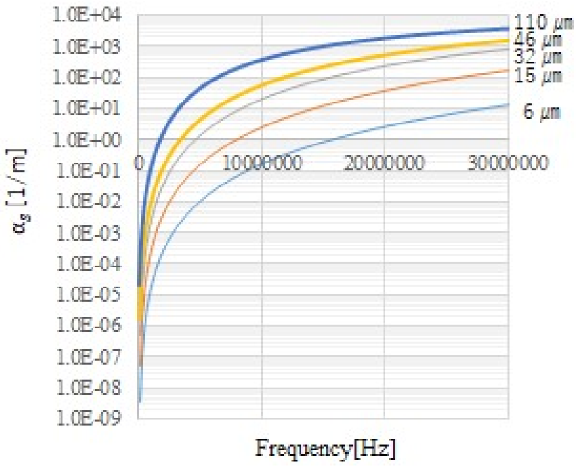

Fig. 2 Calculated frequency characteristics of α_s.

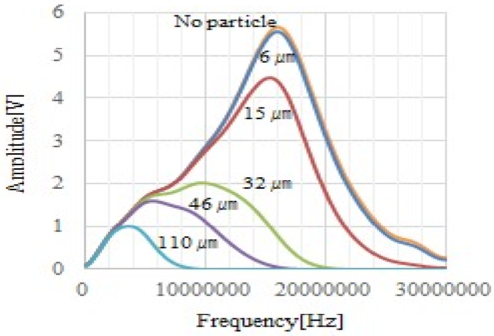

Fig. 3 Attenuated spectra by scattering .with acryl particles of various diameters.

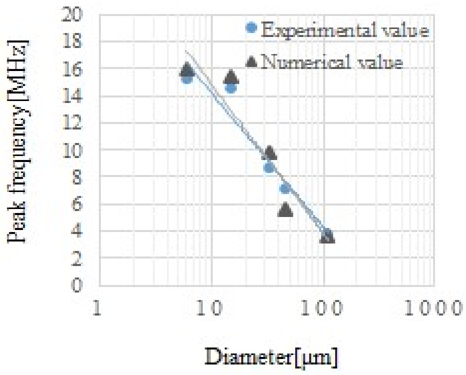

Fig. 4 Comparative plots of peak frequencies between experimental values and numerical values.

5. Conclusion

In this study, (a) the numerical results of the peak frequency were consistent with the past experimental results, and (b) the logarithmic approximation was also possible.

References

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