1P4-9

Viscosity Dependence of Acoustic Emission Spectra from Single Bubble Oscillation
単一気泡振動放射音スペクトルの粘度依存性

Yuto Hatanaka[1†] and Takanobu Kuroyama[1] ([1]NIT, Gifu college)
畑中 佑斗 [1†]，黒山 喬允 [1] ([1]岐阜高専)

1. Introduction

The viscosity is the important property of liquid, and its measurement is demanded in almost all fields, which handle liquids such as, engineering, pharmacy, food processing. Thus, novel viscosity measurement methods are studied actively. Yasuda *et. al.* proposed a method based on dynamics of metal ball revolted by electromagnetic force[1)]. It is also proposed that the method determining viscosity from the vibrational response of liquid surface excited by pulse laser[2)]. However, it is still not achieved to develop the method, which has both advantages of simplicity and in-situ measurement.

Therefore, we focus on viscosity measurement based on dynamics of acoustic cavitation, which is fine bubbles generated by high instensity ultrasound. The bubbles oscillate nonlinearly, and it is known that the oscillation significantly depends on physical property of liquid. The bubbles themselves emit the acoustic wave called acoustic cavitation noise. The spectral characteristics of the noise is also depends on the property of liquid. Hence, we hypothesize that the viscosity can be measured based on the acoustic emission spectra. In this paper, as a first step, we tried to reveal the relationship between the acoustic emission spectra and the viscosity in single bubble system by numerical simulations with several initial radius, surface tension, and acoustic pressure.

2. Simulation principle

To analyze the bubble oscillation, we employ the Keller-Miksis equation shown as,

$$\rho_1\left[\left(1-\frac{\dot{R}}{c_1}\right)R\ddot{R}+\frac{3}{2}\dot{R}^2\left(1-\frac{\dot{R}}{3c_1}\right)\right] = \left(1+\frac{\dot{R}}{c_1}+\frac{R}{c_1}\frac{d}{dt}\right)\left[p_1-p_0-p_a\sin\left(2\pi f t\right)\right], \quad (1)$$

where ρ_1, R, c_1, p_0, p_a, and f are the liquid density, the bubble radius, the sound speed in the liquid, the atmospheric pressure, the pressure amplitude of driving ultrasound, and the frequency, respectively. The dot denotes the time derivative. The liquid pressure at the gas-liquid interface, p_1, is given by

$$p_1 = p_g\frac{T_0}{T}\left(1+\frac{\dot{R}}{c_g}\right)^{-1}-\frac{2\sigma}{R}-\frac{4\mu\dot{R}}{R}, \quad (2)$$

where p_g, T, σ, and μ are the inner pressure, the inner temperature, the surface tension, and the viscosity of the liquid, respectively[3)]. Suffix 0 means the initial state. The sound speed, c_g, is given by

$$c_g = \sqrt{\gamma R_g T}, \quad (3)$$

where γ and R_g are heart capacity ratio and gas constant, respectively.

The pressure of the acoustic emission from the bubble, p, is calculated as

$$p = \frac{\rho_1}{r}\left(R^2\ddot{R}+2R\dot{R}^2\right), \quad (4)$$

where r is distance from the bubble center. When the acoustic emission is observed by hydrophone which is approximated as secondary system, the output signal of the hydrophone, U, is obtained by solving

$$\ddot{U}+2\zeta\pi f_c\dot{U}+4\pi^2 f_c U = p, \quad (5)$$

where ζ and f_c are the damping coefficient and the upper cut-off frequency[4)]. The driving pressure on the hydrophone is neglected and only the acoustic emission from the bubble is considered.

The parameters are set as below through the all calculation; ρ_1 = 998.2 kg/m^3, c_1 = 1483 m/s, p_0 = 101.3 kPa, f = 28 kHz, T_0 = 293 K, γ = 1.4, r = 10 mm, ζ = 1, and f_c = 5 MHz. The parameters, p_a, μ, σ, and initial radius, R_0, are varied in order to reveal these contribute on the acoustic emission spectra. The temporal change of radius and acoustic emission are obtained in the steady state.

3. Simulation result

The temporal changes of bubble radius for μ = 1, 5, and 10 (mPa·s) in **Fig. 1**. The driving pressure is adjusted to the pre-calculated appropriate amplitude shown in **Table I**, which maximizes the variation of acoustic emission spectra by the viscosity. The acoustic emission spectrum significantly varys when the driving pressure amplitude is near the Blake threshold[5)]. Thus, the appropriate pressure decreases with decreasing the surface tension, and with increasing the initial bubble radius.

In Fig. 1(i), quick contraction and subsequent rebounds are observed after the expansion. In the same initial radius, such as Figs. 1(i-a) and (i-b), although the rebound intensity is different, the center frequency of rebound is almost the same in spite of different driving pressure. In contrast, in the case of different initial radius shown in Figs. 1(i-e), (i-f), the center frequency is different, because the bubbles rebounds around its resonance frequency[6)], $f_r \approx 3/R_0$.

kuroyama@gifu-nct.ac.jp

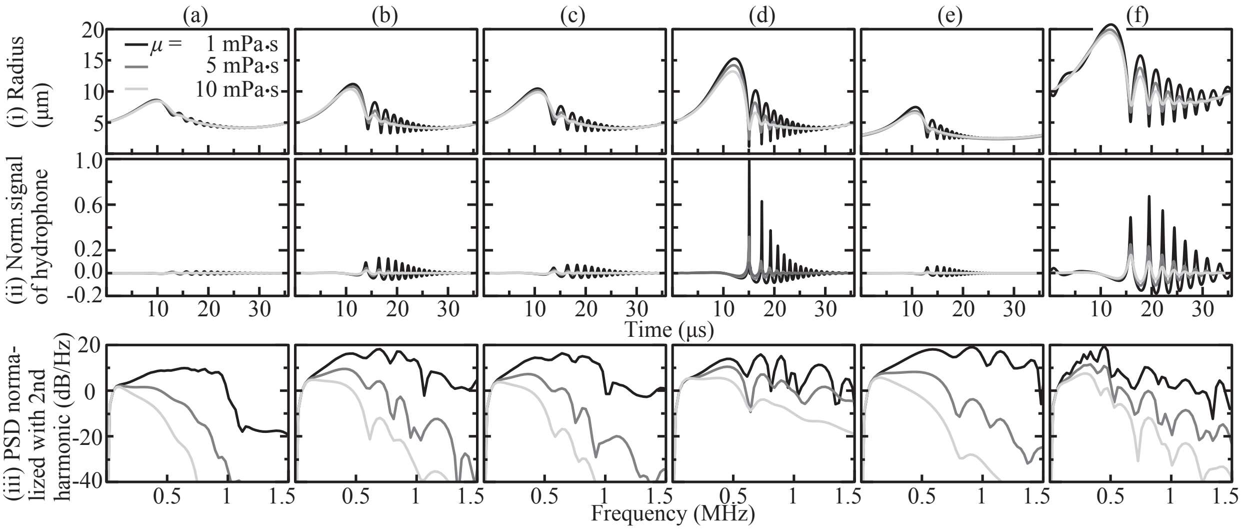

Fig. 1 Simulation result (i)Bubble radius. (ii) Pressure of acoustic emission. (iii) Power spectral density (PSD) of acoustic emission. The parameters σ, R_0, p_a are shown in Table I.

Therefore, the center frequency of rebound especially depends on initial radius, and the rebound intensity depends on driving pressure.

From Fig. 1(iii), the higher viscosity causes the lower power spectral density (PSD) around the resonance frequency because the higher viscosity suppresses the rebounds. The drastic contraction tends to emit sharp pulse shown in Fig.1 (ii-d) and the PSD become flat and the difference due to the viscosity become smaller as shown in Fig. 1(iii-d). In contrast, when the contraction is gentle, the rebounds disappear when the viscosity is high. Thus, we focus on the PSD near the resonance frequency with the appropriate driving pressure.

The relation between the PSD, which is averaged in range ±28 kHz around the resonance frequency and normalized with second harmonic, and the viscosity with the appropriate pressure amplitude is shown in **Fig.2**. The averaged PSD becomes lower with increasing the viscosity in the all condition. The smaller initial radius makes the inclination larger. The difference of the surface tension makes slight variation of the averaged PSD. Thus, the viscosity can be qualitatively evaluated from the averaged PSD, but the parameters such as, initial radius, surface tension should be taken into account for the quantitative measurement.

4. Conclusion

We simulated acoustic emission spectra in single bubble system in order to evaluate the relationship between the spectra and the viscosity. As a result, it was shown that the higher viscosity caused the lower PSD around the bubble resonance frequency when the bubble was irradiated by the appropriate acoustic pressure. However, acoustic emission spectrum is affected by not only the viscosity but also the surface tension, and the initial radius. Thus, while it might able to evaluate the viscosity from the PSD, more consideration is needed for quantitative measurement.

Table I simulation parameters used in Fig. 1.The letters (a) – (f) corresponds to Fig. 1(a) – 1(f).

	(a)	(b)	(c)	(d)	(e)	(f)
R_0 (μm) [f_r (kHz)]	5 [600]				3[1000]	10[300]
σ (mN/m)	73		20		73	
p_a (kPa)	90	100	90	100	110	90

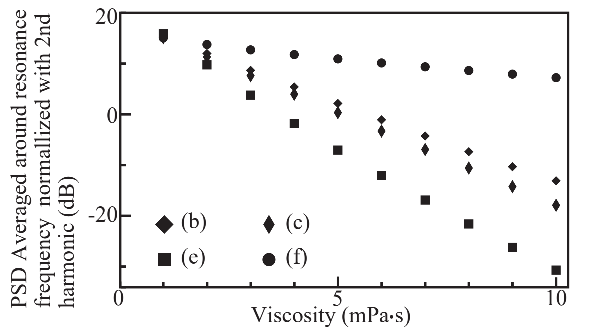

Fig. 2 The relation between viscosity and averaged PSD.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 17840645. The calculations were carried out on the computer of Aerospace research group in NIT, Gifu college.

References

1) M. Yasuda and N. Kurauchi *et al.*: J. Soc. Rheol. Jpn. **40**, 223 (2012) (in Japanese).
2) A. Oya and H. Takiguchi *et al*: Trans. JSME **80,** TEP0369 (2014) (in Japanese).
3) Y. A. G. Man and F.J. Trujillo: Ultrason. Sonochem. **32**, 247 (2016).
4) K. Yasui and T. Tuziuti *et al*: Ultrason. Sonochem. **17**, 460 (2010).
5) T. Kuroyama: Proc. Autumn Meet. 2017 Acoust. Soc. Jpn., 1-Q-24 (2017) (in Japanese) (in printing).
6) K. Yasui: *Fundamentals of acoustic cavitation and sonochemistry*, Springer, (2011).