ACOUSTIC EMISSION FROM MICRO BUBBLES IN ULTRASOUND FIELD

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Abstract

Ultrasound is widely applied in the clinical field. It is essential to take a real understanding of dynamics of micro bubbles in these applications. But it has not been clarified yet. In this paper we numerically simulate a single micro bubble and bubble cloud, which consists of micro bubbles, in water. In the case of a single bubble, we conduct FFT analysis of acoustic pressure emitted from the bubble in ultrasound field, and we investigate the amplitude of second-harmonics and sub-harmonics. In the case of bubble cloud, we observe that pressure at the center of cloud drastically changes depending on the frequency of ultrasound.

1 Introduction

Ultrasound is widely applied in the clinical field today, such as ultrasonography, Extracorporeal Shock Wave Lithotripsy (ESWL) and so on. For ultrasonography, micro bubbles are used as contrast agents. It is required to understand sufficiently the amplitude and the power spectrum of acoustic emission from micro bubbles to visualize clearly. In ESWL, focusing of shock wave causes cavitation and the impact pressure when bubbles collapse damages body tissue. Concurrently, it is thought that the impact pressure affects the process of lithotority. So it is needed to understand the phenomenon. In this paper we numerically simulate a single micro bubble and bubble cloud in ultrasound field.

2 Simulation of a Single Micro Bubble

In this simulation a bubble is continuously exposed in ultrasound field. Frequency is 1[MHz] and amplitude is 50[kPa]. Initial bubble radius, R_{b0} is 3.0[μm], 1.7[μm] or 6.0[μm], so that natural frequency of a bubble is 1[MHz], 2[MHz] or 0.5[MHz]. Initial ambient pressure is atmosphere pressure, $p_{atm} = 101.3$[kPa], and initial temperature is 293[K].

We use model of a bubble and numerical algorithm which Matsumoto and Takemura (1994) showed and Shimada et al. (1999) modified. The following assumptions are employed: (1)A bubble moves maintaining spherical symmetry. (2)Pressure and temperature inside a bubble are constant except for neighborhood of the bubble wall. (3)Gases inside a bubble obey the perfect gas law. (4)Temperature at bubble wall is equal to that of liquid. (5)Noncondensable gas obeys Henry's law at the bubble wall. (6)Coalescence and fragmentation of mist inside a bubble are ignored.

We solve following Fujikawa&Akamatsu equation for dynamic equation of a bubble by using Runge-Kutta method.

$$R_b\ddot{R}_b\left(1-2\frac{\dot{R}_b}{c}+\frac{\dot{m}}{\rho_l c}\right)+\frac{3}{2}\dot{R}_b^2\left(1+\frac{4}{3}\frac{\dot{m}}{\rho_l c}-\frac{4}{3}\frac{\dot{R}_b}{c}\right) - \frac{\ddot{m}R_b}{\rho_l}\left(1-2\frac{\dot{R}_b}{c}+\frac{\dot{m}}{\rho_l c}\right)-\frac{\dot{m}}{\rho_l}\left(\dot{R}_b+\frac{\dot{m}}{2\rho_l}\right)+\frac{p-p_r}{\rho_l}-\frac{R_b\dot{p}_r}{\rho_l c} \quad (1)$$

$$p_r = p_v + p_g - \frac{\dot{m}^2(\rho_{vr} + \rho_{gr} - \rho_l)}{\rho_l(\rho_{vr} + \rho_{gr})} - 2\frac{\sigma}{R_b} - 4\frac{\mu_l}{R_b}\left(\dot{R}_b - \frac{\dot{m}}{\rho_l}\right) \tag{2}$$

"c" is speed of sound here. And we solve energy equation in liquid phase, diffusion equation of noncondensable gas in liquid, energy conservation equation in gas phase with mist and nucleation rate equation of mist.

Results are shown in figure 1, 2, 3. We use Hamming window in FFT analysis and range of data is 10[μsec] $\leq t \leq$ 50.92[μsec]. Acoustic pressure emitted from a bubble, p_a is calculated by the following formula.

$$p_a = \frac{\rho_l}{4\pi r}\frac{d^2}{dt^2}\left(\frac{4}{3}\pi R_b^3\right) = \frac{\rho_l}{r}\left(\ddot{R}_b R_b^2 + 2\dot{R}_b^2 R_b\right) \tag{3}$$

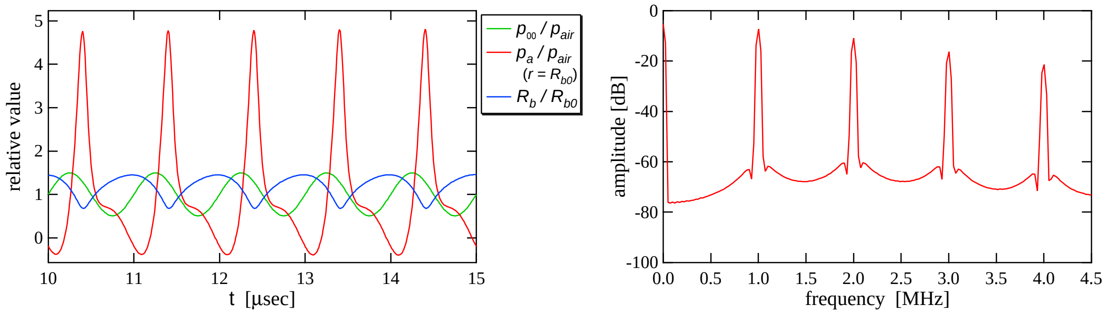

Figure 1: $R_{b0} = 3.0[\mu m]$ Left: acoustic pressure and radius. Right: FFT analysis of acoustic pressure.

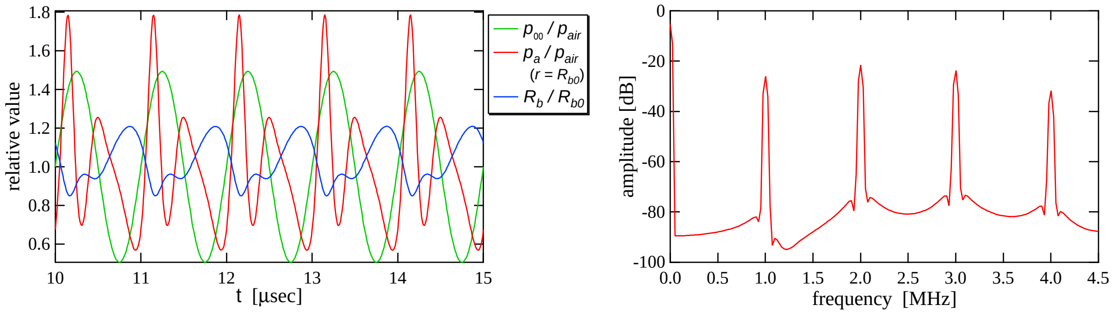

Figure 2: $R_{b0} = 1.7[\mu m]$ Left: acoustic pressure and radius. Right: FFT analysis of acoustic pressure.

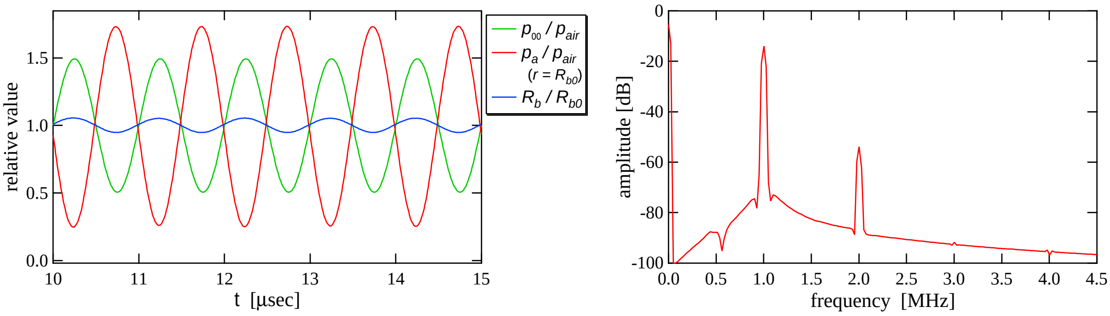

Figure 3: $R_{b0} = 6.0[\mu m]$ Left: acoustic pressure and radius. Right: FFT analysis of acoustic pressure.

In the acoustic pressure of a bubble whose initial radius is 3.0[μm], the amplitude of 1[MHz] is -7[dB]. At the same time the amplitude of 2[MHz], second harmonics, is -11[dB]. It is only 4[dB] smaller than that of 1[MHz]. In the acoustic pressure of a bubble whose initial radius is 1.7[μm], the amplitude of 1[MHz] is -26[dB]. At the same time the amplitude of second harmonics is -22[dB]. In contrast it is 4[dB] larger than that of 1[MHz]. In the acoustic pressure of a bubble whose initial radius is 6.0[μm], though the value is only -88[dB], we can see peak amplitude at 0.5[MHz].

3 Simulation of Bubble Cloud

In this simulation, ultrasound is irradiated to bubble cloud by four cycles. Bubble cloud consists of micro bubbles whose initial radius is 1.7[μm]. Void fraction of bubble cloud is 0.1[%] and its initial radius is 0.5[mm]. Amplitude of ultrasound is 50[kPa] and its frequency is 200[kHz] or 2[MHz]. Natural frequency of bubble cloud is about 200[kHz] and that of a single bubble is 2[MHz].

We use model of bubble cloud and numerical algorithm which Shimada et al. (1999) showed. The following assumptions are employed: (1)Bubble cloud moves maintaining spherical symmetry. (2)Bubbly liquid inside the cloud is treated as a continuum fluid. (3)Bubbles are small enough. (4)Coalescence and fragmentation of bubbles are ignored.

We solve following Keller equation for dynamic equation of bubble cloud by using Runge-Kutta method.

$$R_c\left(1-\frac{\dot{R}_c}{c}\right)\ddot{R}_c+\frac{3}{2}\left(1-\frac{\dot{R}_c}{3c}\right)\dot{R}_c^2=\frac{1}{\rho_l}\left(1+\frac{\dot{R}_c}{c}+\frac{R_c}{c}\frac{d}{dt}\right)\left(p_w-p_\infty-4\frac{\mu_l}{R_c}\dot{R}_c\right) \tag{4}$$

And we solve mass and momentum conservation equation of bubbly liquid in cloud and equation for each bubbles. A part of forementioned model of a single bubble is modified to apply to bubble cloud. That is, gases inside a bubble obey the van der Waals gas law and mass transfer of noncondensable gas on the bubble wall is ignored.

Results are shown in figure 4, 5, 6. Results of a single bubble whose initial radius is 1.7[μm] are shown in figure7 to compare with bubble cloud.

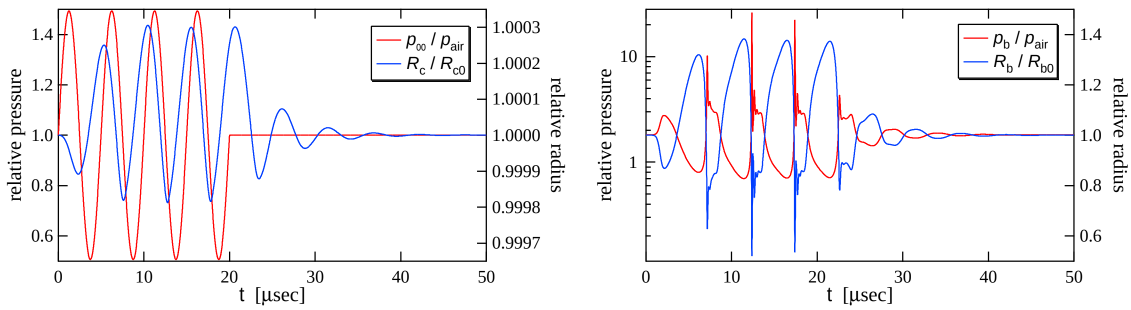

Figure 4: frequency is 200[kHz]. Left: radius of cloud. Right: internal pressure and radius of a bubble at the center of cloud.

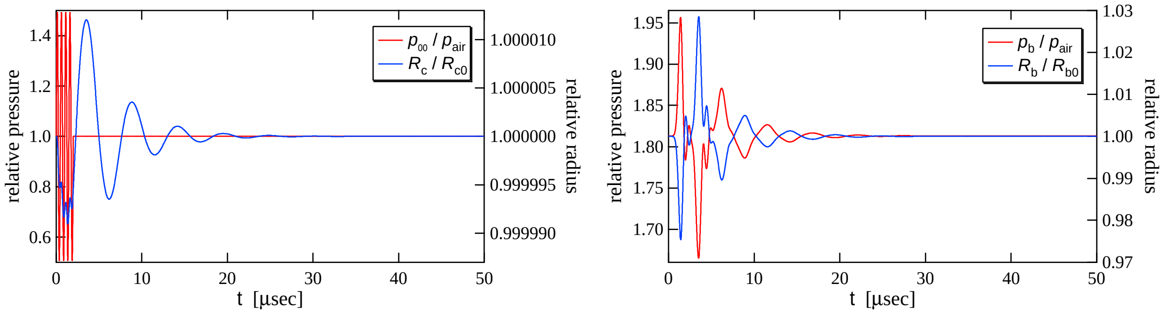

Figure 5: frequency is 2[MHz]. Left: radius of cloud. Right: internal pressure and radius of a bubble at the center of cloud.

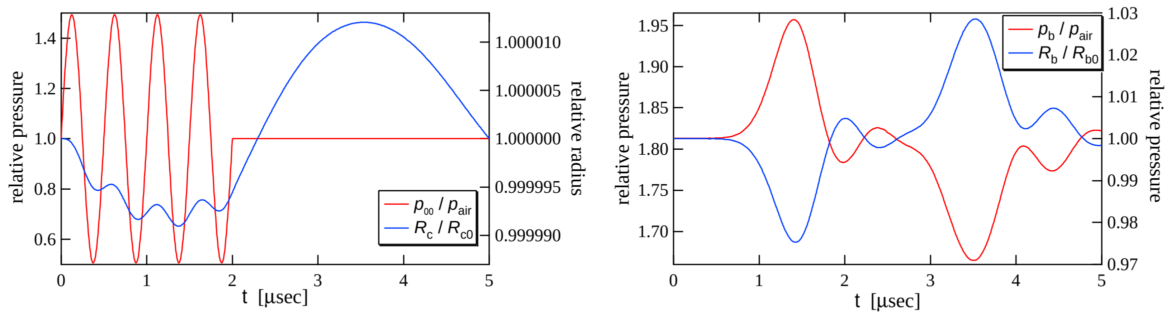

Figure 6: frequency is 2[MHz]. Left: radius of cloud (magnified figure). Right: internal pressure and radius of a bubble at the center of cloud (magnified figure).

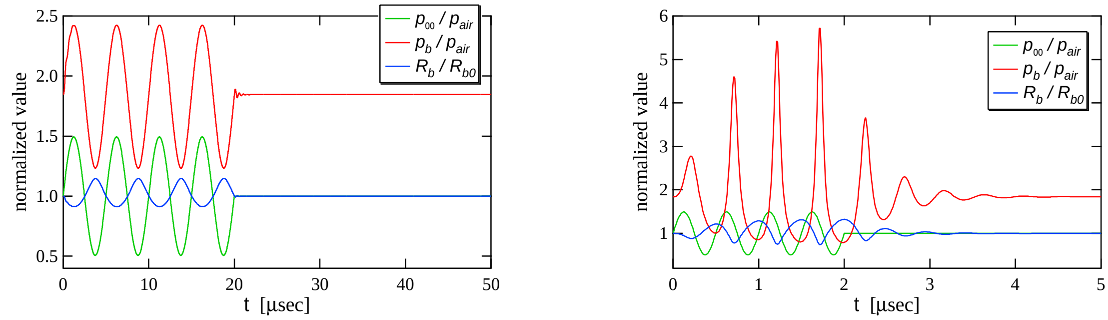

Figure 7: Left: frequency is 200[kHz]. internal pressure and radius of a single bubble. Right: frequency is 2[MHz]. internal pressure and radius of a single bubble.

Internal pressure of a bubble at the center of cloud reaches 2.6[MPa] in the case of 200[kHz]. When the same ultrasound is irradiated to a single bubble, maximum internal pressure is only 0.24[MPa]. When the irradiated ultrasound frequency is the natural frequency of it, 2[MHz], maximum internal pressure is 0.6[MPa]. So the pressure of cloud reaches much higher than that of a single bubble with natural frequency. Internal pressure of a bubble at the center of cloud reaches only 0.2[MPa] in the case of 2[MHz]. When the same ultrasound is irradiated to a single bubble, maximum internal pressure is 0.6[MPa]. So the pressure of cloud reaches only 1/3 of that of a single bubble in this case.

4 Conclusions

We conducted FFT analysis of acoustic pressure emitted from a single micro bubble and we investigated its radius and power spectrum. When natural frequency is almost the same or higher than that of ultrasound, the amplitude of second-harmonics is almost the same or larger than that of ultrasound. When the frequency is lower than natural frequency, we can find sub-harmonics.

We investigated maximum pressure at the center of bubble cloud which consists of micro bubbles. Maximum pressure of cloud is much lower than that of a single bubble when the irradiated ultrasound frequency is the natural frequency of a single bubble. However it is much higher than that of a single bubble when the irradiate ultrasound frequency is the natural frequency of bubble cloud.

References

Fujikawa, S. and Akamatsu, T. (1980). *J. Fluid Mech.*, **97**, 481-512.

Keller, J. B. and Kolodner, I. I. (1956). *J. Appl. Phys.*, **27**, 1152-1161.

Matsumoto, Y. and Takemura, F. (1994). *JSME Int. J.*, **B-37 2**, 288-296.

Takemura, F. and Matsumoto, Y. (1994). *JSME Int. J.*, **B-37 4**, 736-745.

Kameda, M. and Matsumoto, Y. (1996). *Phys. Fluids*, **8**, 322-335.

Shimada, M., Kobayashi T. and Matsumoto, Y. (1999). *FEDSM*, **99**, 6775.