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Simulation of distribution of acoustic radiation force to microbubbles in traveling sound field
進行波音場内の微小気泡に作用する音響放射力分布のシミュレーション

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1. Introduction

Microbubbles used as an ultrasound contrast agents are applied to human body treatments. These treatments consist of several technologies, such as the induction and trap by primary Bjerknes force (PBF) [1-3], and aggregation of bubbles by secondary Bjerknes force (SBF) [4] from the ultrasound.

About the PBF, measurement of the distribution of PBF in standing wave along perpendicular to the sound axis is reported, and the PBF increased as the sound pressure of transducer [5]. In addition, measurement the PBF against microbubbles in the plane traveling sound field is reported, and the phenomenon that the direction of PBF is reversed according to the bubble diameter is showed [6].

Here, in the previous works, the sound field condition is a low frequency and low pressure, and sound wave is plane type, and a single bubble is used. On the other hand, in treatments, large amount of bubbles are used in traveling sound field with high frequency and high pressure. In this case, microbubbles are not only acted from PBF, but also affected interaction from SBF. As a result, aggregation of microbubbles is formed.

In this study, we simulated the distribution of PBF to microbubbles in traveling sound field with high frequency and high pressure, at focused wave condition. Moreover, we simulated the PBF considering aggregation of microbubbles formed by SBF, because the PBF increases as bubbles aggregate.

2. Theory

The simulation model of the sound field is based on Huygens principle. Assuming spherical bubbles, PBF in travelling sound field $\vec{F}$ acts to propel the bubbles in the direction of acoustic propagation as per the following equation,

$$\vec{F} = \pi a(x)^2 \left(\frac{\vec{I}}{c_s}\right) Y_p \quad , \qquad (1)$$

where $a(x)$ is the radius of the bubble depending on x which is distance from sound oscillator, because bubbles aggregate by SBF at the exposure time of the sound wave. That is, $a(x)$ becomes large while moving. Moreover, c_s is speed of sound, Y_p is a dimensionless factor called the radiation force function that depends on the scattering and absorption properties of the bubble, and $\vec{I}$ is acoustic intensity, respectively.

3. Experiment method

In order to observe the distribution of PBF acting on the microbubbles in travelling sound field, the experiment system shown in Fig.1 is prepared. Fig. 1(a) is overall view and Fig. 1(b) is closeup view as x-y plane.

In this experiment, F-04E microbubbles (Matsumoto Oil, Co. Ltd), an average radius of 2 μm are used. The central frequency and the maximum sound pressure of the transducer are 3 MHz and 250 kPa, respectively.

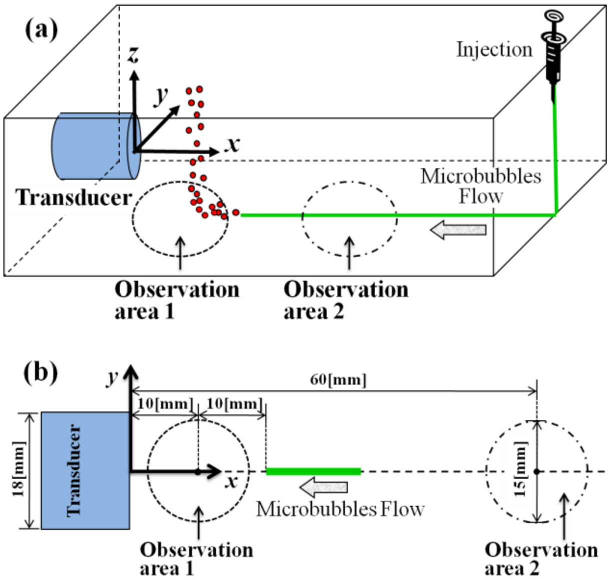

Fig.1 Experimental setup

As a procedure of experiment, microbubbles are injected at 20 mm on the sound axis from the oscillator of transducer. In order to make the flow

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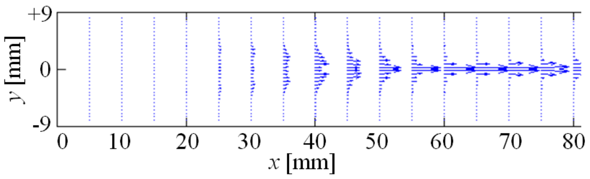
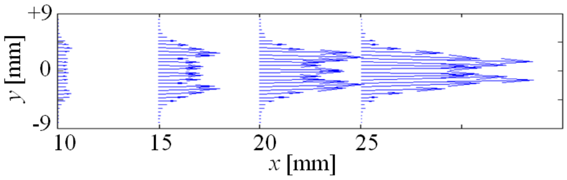
of microbubbles constant, they are injected by the pump, and the flow speed is about 10 mm/s in the tube. When microbubbles begin to cover forward of the transducer by the buoyancy and diffusion as Fig. 1(a), the sound wave is irradiated. Here, observation area 1 is near the oscillator of transducer, and observation area 2 is at the focus position in the sound field. They are taken from a bottom of water tank in the direction of *z* axis.

4. Results

Figure 2 shows the simulated distribution of PBF where vector denotes direction and intensity of PBF in each sound field at intervals of the *x*=5[mm]. The length of the vector, i.e., the intensity, is regularized by the maximum value of PBF in each figure.



(a) Overall view



(b) Closeup view

Fig.2 Simulation of the distribution of PBF

Radius of the microbubbles aggregation *a*(*x*) is defined as Table 1 since the saturation time of *a*(*x*) is about 1 second [7], and the passing speed of the microbubble is 15 mm/s on average by the experiment. In Table 1, *x*=10[mm] is at beginning aggregation, and *x* > 25[mm] is at saturating the radius of microbubbles.

Table 1 Radius of microbubble *a*(*x*)

x [mm]	*x* = 10	*x* = 15	*x* = 20	*x* = 25	*x* > 25
a(*x*) [μm]	2	8	10	12	15

Figure 2(a) shows all calculated areas, and Fig. 2(b) shows the transition of PBF from beginning of the microbubble aggregation to saturation. At Fig. 2(a), the vector is hardly seen near the oscillator because there are about 200 times the difference in the maximum and the minimum value of PBF. At Fig. 2(b), it is seen that the PBF increases as microbubbles aggregate. Furthermore, Fig.2 shows that the direction of PBF is toward the sound axis. This result is corresponding to the experiment, as shown in Fig.3.

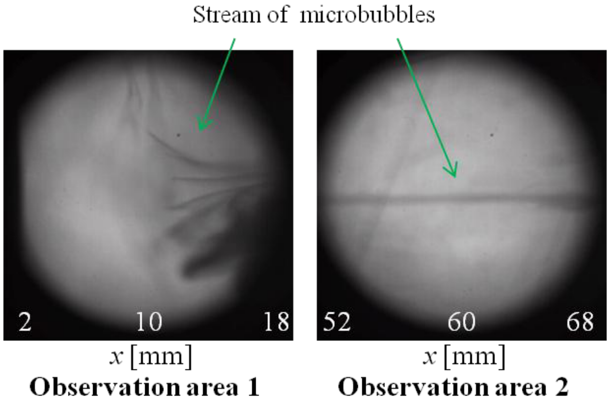


Fig.3 Microscope images on the experiment

At Fig.3, both observation area 1 and 2 shows that the microbubbles advance toward the sound axis. Strength of PBF has not been measured yet by experiment, but the direction of PBF is similar to the simulation result.

5. Conclusions

In this study, we realized simulation of distribution of PBF to microbubbles aggregation in traveling sound field with frequency 3 MHz and sound pressure 250 kPa, at focused wave condition. We confirmed that the direction of PBF depends on the traveling sound direction. For further analysis, strength of PBF is measured from the passing speed of the microbubbles by the experiment. Also to be suitable for the experiment result, the parameter that should be considered is added to the simulation.

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