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Effect of Acoustic Radiation Force to Microbubbles in Flow and Its Simulation in Bifurcation

流体中の微小気泡に対する音響放射力の影響と流路分岐部でのシミュレーション

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1. Introduction

Recently, application of microbubbles to medical treatments, such as drug delivery system, sonoporation, and HIFU, are researched and investigated[1]. In these treatments, induction of microbubbles to affected area is important since mircobubbles are difused by blood flow. From this reason, we focused on acoustic radiation force and have researched induction of microbubbles flowing in bifurcation by the acoustic radiation force[2,3]. However, behavior of microbubbles under the ultrasound emission is very complicated because of many kinds of parameters. Therefore, we analyze the bihavior by numerical simulation. In this paper, we simulated the bihavior of microbubbles in flow under the ultrasound emission, and compared simulated induction ratio of microbubbles by the acoustic radiation force with actual experiments.

2. Theory

Figure 1(a) shows the trajectory of a microbubble in blld flow without ultrasound exposure. In this case, the microbubble stream along the course of the flow, and receives the flow resistance. On the other hand, as shown in Fig. 1(b), traveling direction of the microbubble can be changed by the acoustic radiation force. Therefore, it becomes possible to induct microbubbles in any direction. The force acting on the microbubble ***F***, i.e, the flow resistance and the acoustic radiation force of traveling wave, is expressed as

$$\boldsymbol{F} = 6\pi r\mu(\boldsymbol{u} - \boldsymbol{v}) + \pi r^2 Y_\mathrm{p}\left(\frac{\boldsymbol{I}}{c}\right), \qquad (1)$$

where r is a radius of the microbubble, μ is viscosity of fluid, $\boldsymbol{u}$ is flow velocity at the location of the microbubble, $\boldsymbol{v}$ is the velocity of the microbubble, Y_p is acoustic radiation force function, $\boldsymbol{I}$ is acoustic intensity, and c is sound velocity of fluid, respectively. The acoustic radiation force function is complicated since this consists of several parameters.

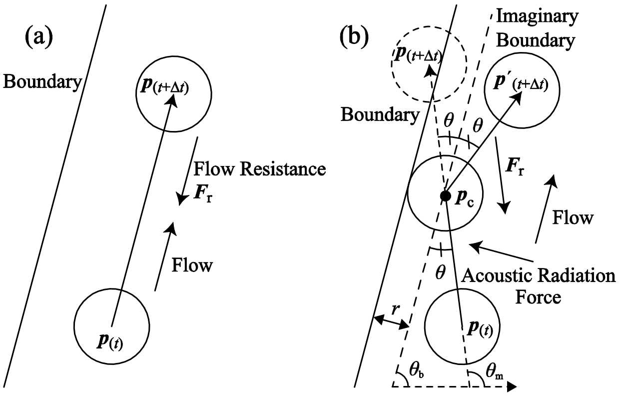

Fig. 1 Forces acting on the microbubble and boundary condition; (a) without acoustic radiation force, (b) with acoustic radiation force.

In this research, behavior of the microbubble in flow under the ultrasound emission is simulated by using verlet algorithm[4]. This algorithm iteratively updates location of the microbubble and its velocity from the force ***F***. Here, as shown in Fig. 1(b), the microbubble possibly transcends the boundary in calculation. In this paper, the microbubble transcended the boundary is reflexed. Here, $\boldsymbol{P}_{(t)}$ and $\boldsymbol{P}_{(t+\Delta t)}$ are location of the microbubbles at time t and $t+\Delta t$, respectively, and Δt is time step of the verlet algorithm. As shown in this figure, $\boldsymbol{P}_{(t+\Delta t)}$ is transcended the boundary. Thus, the imaginary boundary which is separate r from the boundary is considered. By using intersection of the imaginary boundary and the traveling direction $\boldsymbol{P}_\mathrm{c}$, the location of the reflected microbubble $\boldsymbol{P}'_{(t+\Delta t)}$ is obtained as

$$\boldsymbol{P}'_{(t+\Delta t)} = \boldsymbol{P}_\mathrm{c} + \boldsymbol{R}\cdot\left(\boldsymbol{P}_{(t+\Delta t)} - \boldsymbol{P}_\mathrm{c}\right) \qquad (2),$$

$$\boldsymbol{R} = \begin{bmatrix}\cos(-2\theta) & -\sin(-2\theta)\\ \sin(-2\theta) & \cos(-2\theta)\end{bmatrix}, \qquad (3)$$

$$\theta = \theta_\mathrm{b} - \theta_\mathrm{m}, \qquad (4)$$

where θ_b is angle of the boundary, and θ_m is that of velocity of the microbubble $\boldsymbol{P}_{(t)}$. Here, direction of velocity of $\boldsymbol{P}'_{(t+\Delta t)}$ is changed. The new velocity of $\boldsymbol{P}'_{(t+\Delta t)}$, $\boldsymbol{v}_{(t+\Delta t)}$, is defined as

$$\boldsymbol{v}_{(t+\Delta t)} = \frac{\left\|\boldsymbol{P}_{(t+\Delta t)} - \boldsymbol{P}_{(t)}\right\|}{\left\|\boldsymbol{P}'_{(t+\Delta t)} - \boldsymbol{P}_\mathrm{c}\right\|\cdot\Delta t}\left(\boldsymbol{P}'_{(t+\Delta t)} - \boldsymbol{P}_\mathrm{c}\right). \qquad (5)$$

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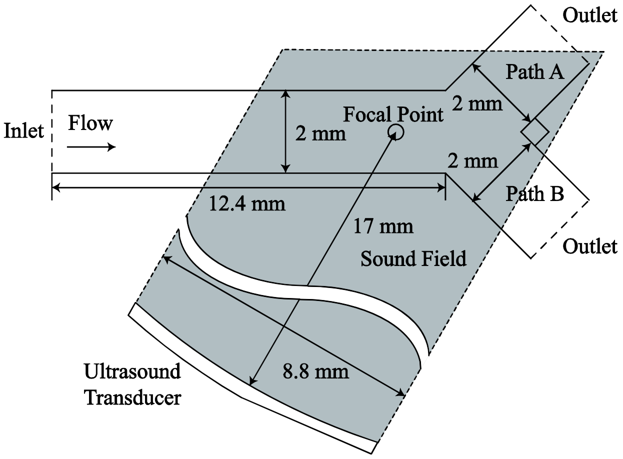

Fig. 2 Analytical model of fluid flow and sound field.

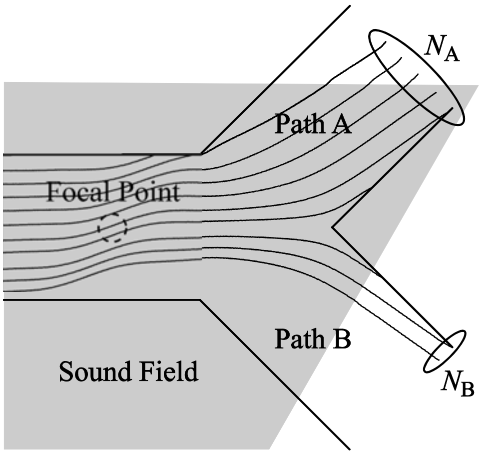

Fig. 3 An example of simulation result at bifurcation where thin lines denote behavior of microbubbles.

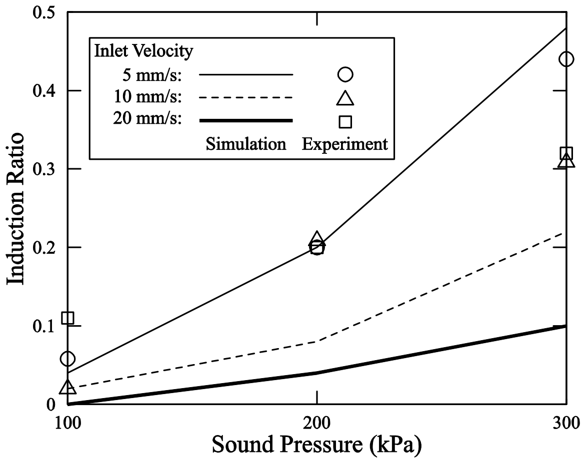

Fig. 4 Induction ratio by changing sound pressure at the focal point and inlet velocity.

3. Numerical Simulations and Discussion

Figure 2 illustrates analytical model of fluid flow and sound field where path A is target to induct microbubbles. Based on incompressible Navier-Stokes equations and Huygens' principle, flow velocity and sound field are simulated by finite element method (COMSOL Multiphysics), and the verlet algorithm is calculated by use of Matlab. **Figure 3** shows an example of simulation result at bifurcation where $r = 3$ (μm), $\mu = 1$ (mPa· s), $c = 1500$ (m/s), $Y_p = 0.2$, $\Delta t = 1$ (ms), and mass of a microbubble, inlet velocity, and sound pressure at the focal point are $1.2*10^{-10}$ kg, 5 mm/s, 300 kPa, respectiely. Initial microbubbles are set at the inlet at equal intervals. As shown in this figure, traveling directions of microbubbles are effected from the acoustic radiation force. Moreover, microbubbles flow in the case that microbubbles contact the boundary. Here, the number of microbubbles reached to path A and path B are defined as N_A, N_B, respectively. Use of these parameters, induction ratio ξ is defined as

$$\xi = (N_A - N_B)/(N_A + N_B). \tag{6}$$

Figure 4 shows induction ratio of the simulation and actual experiment. In these results, sound pressure at the focal point and inlet velocity are changed. In this simulation, parameters except for the sound pressure and inlet velocity are same as the case of the result shown in Fig. 3, and the number of microbubbles is 100. By increasing the inlet velocity, error between the ratio of the simulation and that of the experiment increases. Moreover, the induction ratio of the simulation is lower than that of the experiment. This is owing to the time step. The time step is considered to be rough. Therefore, by shortening the time step, the ratio of the simulation is considered to approach that of the experiment.

4. Conclusions

By numerical simulations, behavior of microbubbles in flow under the ultrasound emission was verified. In addition, simulated induction ratio of microbubbles by the acoustic radiation force was compared with actual experiments.

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