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Study for trapping of microbubbles in flow by forming two focal points with opposite phase

逆位相 2 焦点同時形成による微小気泡の流路内捕捉法の検討

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1. Introduction

We have ever researched microbubble manipulation techniques using ultrasound. For instance, active path selection at bifurcations [1,2], and trapping of microbubbles in blood flow [3] using artificial blood vessels. Those results provide us at least two valuable information. First, aggregated microbubbles were easily manipulated than non-aggregated microbubbles. Second, the size of the aggregated microbubbles depended on the strength of secondary Bjerknes Force (BF), which is proportional to the gradient of the sound pressure. Also forming two focal points with opposite phase was previously examined to trap microbubbles by creating the high spacial gradient of the sound pressure [4].

However, in the previous experiments single element transducers were applied to produce focused or plane wave of acoustic fields, by using concave or flat surface transducers, respectively. There are constraints in using single element transducers, focal area of acoustic fields is fixed with the shape of the transducer's surface. And it is difficult to change acoustic field dynamically. Moreover, there is a spatial limitation in the number of transducers for controlling microbubbles. Thus by applying a 2D-array transducer to control the behavior of microbubbles, not only the shape of acoustic fields is changed actively, but also multiple focal areas are produced simultaneously [5].

In this paper, we aim to enhance trapping efficiency of microbubbles in terms of the acoustic power. We design acoustic field by using 2D-array tranducer and forming two focal points in target area with opposite phase.

2. Method

We have used a square flat 2D-array transducer, which has air-backed 64 PZT elements with the aperture of 23.9 x 23.9 mm^2, the size of each element of 2.9 x 2.9 mm^2, and the pitch of the elements of 3.0 mm, respectively. The resonance frequency of the transducer is 1 MHz, where the drive unit was required to produce continuous square wave with minimum delay pitch of 5 ns.

Fig.1 shows the experimental setup. A straight path, which was made of PolyEthylene Glycol MonomethAcrylate (PEGMA) with the inner diameter of 2 mm, was fixedly floated from the bottom of a water tank with filled water. The observation area was focused and adjusted in the center of the path by an optical microscope (Omron KH-7700) from the bottom of the tank. The axis of 2D-array transducer was set to cross the center of the observation area with the angle θ = 40 deg and the distance d = 80 mm, where the array surface was entirely soaked below water. Also we prepared the suspension of microbubbles, which are F-04E microcapsules (Matsumoto Oil) [2] with a shell made of PolyVinyl Chloride (PVC), a specific gravity of 0.0225, and an average diameter of 4 μm.

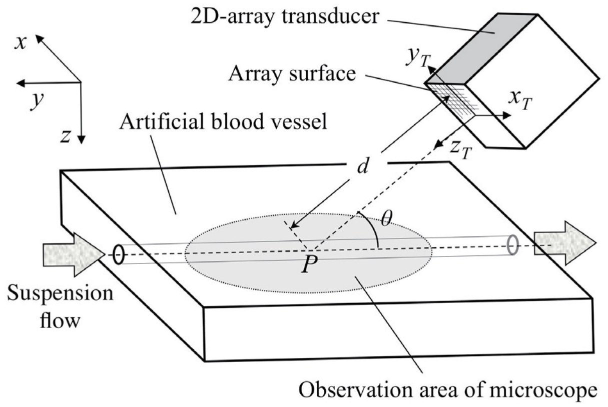

Fig.1 Experimental setup to trap microbubbles by using a 2D-array transducer.

Then we prepared totally seven types of acoustic patterns, which were produced by setting delay times in 64 elements individually. The "1 spot" acoustic pattern was produced to make a focal point P, which is the intersection of the axis of the path and the axis of the transducer as shown in **Fig.1**. Also six acoustic patterns have two focal points, which include the three patterns with same phase, and others with opposite phase, respectively. By centering the point P, two focal points were produced on the path (along y-axis) symmetrically, which distances (ΔY) were 6, 12 and 18 mm, in each pahse condition.

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Forming two focal points was realized by the equation (1), which calculates the phase of delay in the j-th element of 2D-array transducer, where the subscripts of u and d indicate upstream and downstream, respectively, and $\Phi_{j,*}$ means the theoretical phase of delay in each focal point.

$$\Phi_j = \tan^{-1}\left(\frac{\sin\Phi_{j,u} + \sin\Phi_{j,d}}{\cos\Phi_{j,u} + \cos\Phi_{j,d}}\right) \tag{1}$$

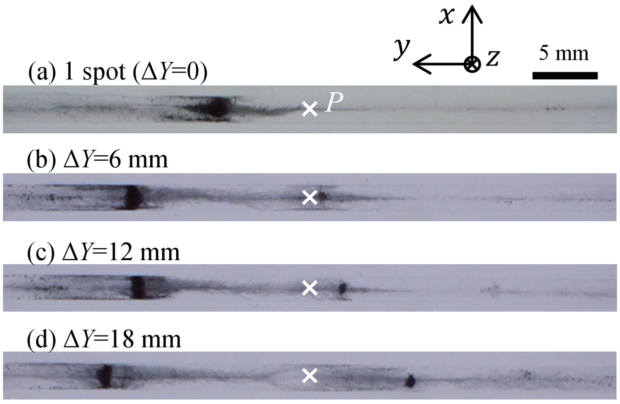
We have calculated the acoustic fields on the observation area to normalize the acoustic energy passing E through the straight path in all paterns of acoustic field above by introducing a finite element method with eq. (2), where $\boldsymbol{I}$ is the acoustic intensity, and $\boldsymbol{n}$ is the normal vector of the cross section of path, and ds is the element of the calculation, respecively.

$$E = \int I \cdot n \ ds \tag{2}$$

3. Results

We have observed the behavior of microbubbles when the suspension (volume density: 1.57 μl/ml, volume: 0.8 ml) was injected under radiation of the seven patterns of acoustic fields. Then total acoustic energies which pass through the path were fixed, where total acoustic power was limited to 32.8 mW. **Fig.2** shows the microscopic images under exposure of acoustic field of (a) 1 spot, and three patterns with oposite phase from (b) to (d), where the suspension flows from left to right with a flow velocity of 20 mm/s, In these results, microbubbles were seemed to be propelled by primary BF and aggregated by secondary BF in the path. In **Fig.2** (a), trapped microbubbles were confirmed in the upstream of the focal point. Similary, as shown in **Fig.2** (b) to (d), trapped microbubbles were confirmed in the upstream of both focal points, where more microbubbles aggregations were confirmed in the upper focal point than the lower one. Comparing these three patterns, trapped amount of microbubbles were decreased according to the distance of two focal points. Also comparing the patterns with same phases with oposite phases, more microbubbles were observed in the latter patterns.

Fig.3 shows the total trapped area of microbubbles, which was calculated from microscopic images 40 s after the emission of ultrasound, versus above acoustic patterns. From these results forming two focal points with opposite phase can trap more amount of microbubbles than "1 spot" pattern, where forming two focal points with same phase does not contribute to trapping. In addition, there is negative correlation between the distance of two focal points and trapped area of microbubbles in both phase patterns.


(a) 1 spot (ΔY=0)

(b) ΔY=6 mm

(c) ΔY=12 mm

(d) ΔY=18 mm

Fig.2 Microscopic images of trapped microbubbles in the straight path by forming acoustic field of (a) 1 spot, and three patterns with oposite phase from (b) to (d).

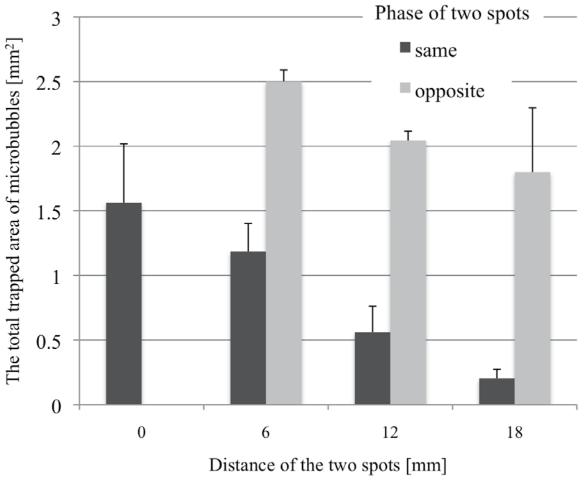


Fig.3 The trapped area of microbubbles versus acoustic patterns, which correspond to Fig.2.

4. Conclusions

We have observed the behavior of microbubbles under exposure of seven acoustic patterns in a straight path. Then we verified that forming two focal points with opposite phase was effective to trap more amount of microbubbles than those with same phase. Also determination of the distance of the two focal points seemed to be dominant for trapping performance, which we are going to investigate further.

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