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Bending control of thin catheter using tempo-spatial variations of acoustic interference

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1. Introduction

We have been attempting to use the acoustic radiation force to bend a thin catheter, which is supposed to be inserted into a blood vessel [1-6]. Using a 2D array transducer [2-6] (hereinafter, 2D array), which can produce an arbitrary shape of acoustic field and bring about dynamic changes in an acoustic field, we succeeded to bend it in the direction perpendicular to ultrasound propagation[3] in water or viscous liquids. In addition, we succeeded to bend the catheter in any direction by forming an interference acoustic field using multiple 2D arrays[6]. However, in previous studies, priority has been given to advancing the catheter by directing the sound waves in a forward manner, which has limited the ability to precisely control the tip position from free irradiation directions. In this research, we report our attempt to bend a thin catheter by forming standing waves through the interference of ultrasonic sound fields and spatially controlling the node positions.

2. Methods

Fig.1 shows the experimental setup including two 2D arrays, which have 128 elements with a central frequency of 3 MHz and placed in a water tank as well as our preceding researches[4,5]. Also, a thin catheter, which was made of a perfluoro alkoxy (PFA) copolymer, was placed along the *x*-axis, where the 2D arrays rotate with the azimuth angle θ and the elevation angle φ.

When two focused waves form a focal point on the origin of the coordinate, an interference acoustic field is generated. Defining the incident waves are sinusoidal waves f_1 and f_2 as shown in eqs. (1) and (2), they form a standing wave, which has a periodical variation in the *z*-direction formed by the summation of f_1 and f_2 as eq. (3):

$$f_1(z,t) = A\sin[\omega t - (k\cos\theta\cos\varphi)z + \delta_1(t)], \quad (1)$$

$$f_2(z,t) = A\sin[\omega t + (k\cos\theta\cos\varphi)z + \delta_2(t)], \quad (2)$$

$$f(z,t) = 2A\sin[\omega t + (\delta_1(t) + \delta_2(t))/2] \cos[(k\cos\theta\cos\varphi)z - (\delta_1(t) - \delta_2(t))/2], \quad (3)$$

where A is the amplitudes of f_1 and f_2; ω is the angular frequency; k is the wave number. Further, $\delta_1(t)$ and $\delta_2(t)$ indicate phase shifts in the incident waves of f_1 and f_2, respectively, which contribute to the movement of nodes and antinodes in the interference acoustic field. Normally, a standing wave is generated by the overlapping of ultrasound waves with the same amplitudes and frequencies, where the nodes in the sound pressure distribution do not move. In this study, by shifting the position of the nodes using phase sweeping, we tried to bend the catheter. To create a sweeping motion of the standing wave field, the phase shifts can be varied. If either of the phase shift simply increased from 0 to 2π in sweep time T_{sw} repeatedly, the sweep velocity v_{sw} is expressed as

$$v_{sw} = \{2T_{sw}k\cos\theta\cos\varphi\}^{-1}. \quad (4)$$

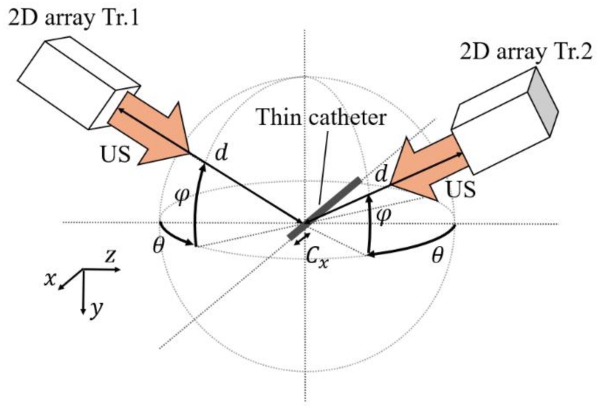

Fig.1 Experimental setup to bend thin catheter with two 2D array transducers.

The catheter, which has the outer and inner diameters of 0.2 and 0.05 mm, respectively, was fixed on a rigid body with the length of 60 mm. The distance between the tip of the catheter and the origin of the coordinate was set to C_x = 4 mm. The positions of 2D arrays were set to d = 60 mm.

As the ultrasound wave to be irradiated, a burst wave with a pulse repetition time (PRT) of 100 µs and a duty ratio of 60% was generated by a driving equipment (Microsonic, ES1144-1). We recorded the trajectory of the tip of the catheter to measure displacement D_z [mm] using a high-speed camera (Photoron, PCI-1024), which located on the *x*-axis to observe the catheter in the *y*-*z* plane. In the following experiments, we set the phase shift of $\delta_2(t) = 0$ to verify the effect of single phase variation of $\delta_1(t)$.

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3. Results

Before the experiments, we confirmed spatial distribution of sound intensity, which related to the acoustic radiation force, using MATLAB. The method of calculating the sound field was based on the mathematical model of k-Wave[7]. The electrical parameters of the 2D array, such as the delay time setting, were the same as our preceding researches[2-6]. **Fig.2** shows the spatial distribution of sound pressure when the azimuth angle θ = 40 deg and the elevation angle φ = 0 deg. It was confirmed that the interference acoustic field was maintained in -4 ≤ z ≤ 4 mm. **Fig.3** shows the superimposed tips of the catheter before and after the ultrasound irradiation of T_{sw} = 0.7 s.

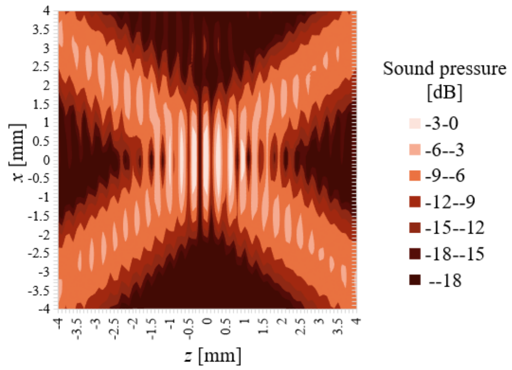

Fig.2 Distribution of sound pressure in the interference field with the angles of θ = 40 deg and φ = 0 deg.

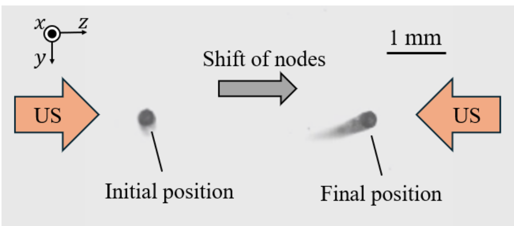

Fig.3 Observation of the tip of the catheter before and after the ultrasound irradiation.

Fig.4 shows the displacement of the tip of the catheter versus the sweep time T_{sw}, where the maximum sound pressure of each source was set to 600 kPa-pp and the elevation angle was set to φ = 0 deg. When the sweep time was 0.4 ≤ T_{sw} ≤ 0.5 s and T_{sw} = 1.0 s, the catheter was bent in the opposite direction to the phase sift. Under other conditions, since the catheter was bent in the same direction to the phase shift, the condition of the sweep time for precise control was determined.

Fig.5 shows the catheter velocity of the tip versus the sweep velocity v_{sw} when the sweep time was T_{sw} = 0.1, 0.2 s (left) and T_{sw} = 0.7, 0.8 s (right). Although there were limitations in the catheter velocity, which were estimated around 1 mm/s, we confirmed the possibility to control the catheter velocity by varying the sweep velocity v_{sw}.

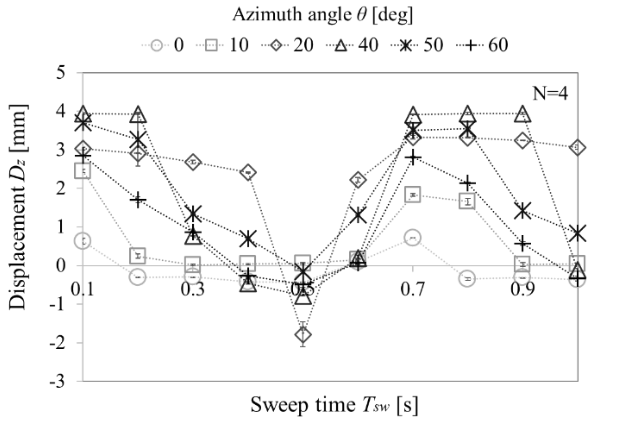

Fig.4 Relationship between the sweep time and the catheter displacement using phase sweeping.

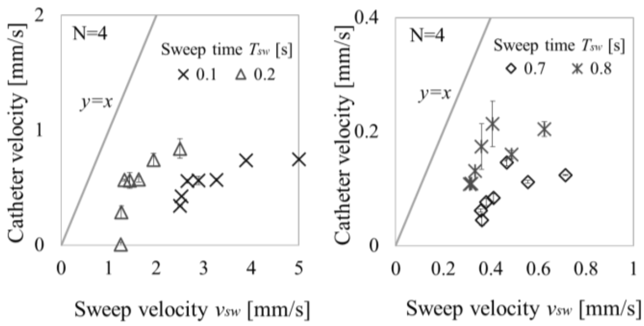

Fig.5 Relationships between the sweep velocity and the catheter velocity when the sweep time was T_{sw} = 0.1, 0.2 s (left) and T_{sw} = 0.7, 0.8 s (right).

4. Conclusion

In this research, we succeeded to bend the catheter using phase sweeping in an interference acoustic field produced by multiple 2D array. When the sweep time T_{sw} was 0.1 or 0.7 s, the bending direction of the catheter always aligned in the direction of node movement. As the results, using an appropriate sweep time realized a precise control of the catheter through phase sweeping. Additionally, controlling the sweep velocity enabled regulation of the catheter velocity of the tip. We will investigate the optimal irradiation conditions when the azimuthal and elevation angles were limited according to the position and the orientation of blood vessels and a shape of body surface.

References

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