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Analysis of acoustic radiation force to estimate behavior of thin catheter in acoustic field

音場中の極細カテーテルの挙動推定のための音響放射力の解析

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1. Introduction

In a conventional catheter therapy, because the diameter of a guide wire is at least 500 µm, it is difficult to apply to blood vessels smaller than 1 mm. To develop new possibilities of more precise therapies using a thin catheter, which diameter is expected to be less than 200 µm, we have proposed to utilize acoustic force to bend a thin catheter. Despite we have already confirmed in several experiments that acoustic radiation force can be used to move thin catheters[1-2], we have not found the theoretical optimum in parameters such as ultrasound frequency, direction of irradiation, or catheter size. Hence, it is necessary to find effective parameters to bend the catheter to adopt to various simulations. In order to estimate the displacement of the catheter, we calculated the acoustic radiation force by referring to conventional studies considering a cylinder placed in a plane wave. In this paper we introduce our simulation to estimate displacement of the catheter compared with the actual experimental results.

2.Theory

According to the conventional Langevin theory, acoustic radiation force F_p applied on a cylinder, representing the shape of a thin catheter, which axis was set in the perpendicular direction of ultrasound propagation, is expressed as eq. (1) with acoustic radiation function Y_p:

$$F_p = ES_pY_p \qquad (1)$$

where E and S_p indicate acoustic energy density and the effective area on the cylinder, respectively. Fig. 1 shows a schematic when a plane wave penetrates perpendicularly across a cylinder. In this case, S_p is $2r_o$. According to the preceding research[3], acoustic radiation force function Y_p can be expressed as eq. (2):

$$Y_p = -\frac{2}{kr_o}\sum_{n=0}^{\infty}[\alpha_n + \alpha_{n+1} + 2(\alpha_n\alpha_{n+1} + \beta_n\beta_{n+1})] \qquad (2)$$

where k is the wavenumber, r_o is the outer radius of the cylinder, and α and β are the real and imaginary parts of the scattering coefficient calculated from sound velocity and density of the cylinder material, surrounding and inner medium.

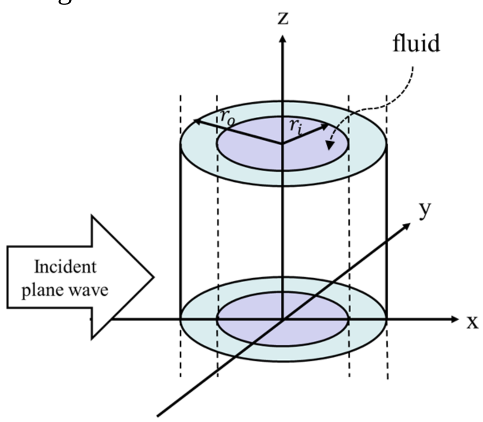

Fig. 1 A cylinder placed in a plane wave

3. Methods

In order to determine the acoustic energy density E, a three-dimensional acoustic field was calculated, which was based on the mathematical model of k-Wave.[4] The mechanical parameters of the transducer, such as the delay time setting, are the same as those used in the experiment. From the calculated sound field results, we calculated the average acoustic energy density in the x-axis direction of the catheter shown in Fig. 1. The acoustic radiation force function Y_p was calculated for PTFE (polytetrafluoroethylene), which is similar to the PFA (perfluoroalkoxy alkane) catheter used in an actual experiment. The external and internal medium of the cylinder were water and air, respectively. The density and sound velocity of each are shown in Table 1.

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Table 1 Parameters of the materials

Material	PTFE	Water	Air
mass density [kg/m^3]	2170	1000	1.2
longitudinal wave velocity [m/s]	1372	1480	344
transverse wave velocity [m/s]	635	-	-

Fig. 2 shows the flowchart to determine the displacement of the catheter. The acoustic radiation force F_p was calculated using E and Y_p to derive the catheter displacement using the cantilever theory. When an expected displacement exceeds a threshold, catheter position and its surrounding acoustic energy density E were updated to find the expected displacement. Otherwise, the calculated position was determined as the final position of the catheter.

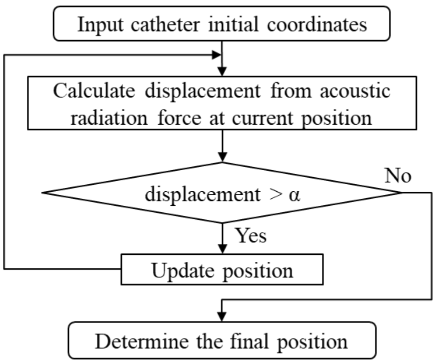


Fig.2 Flowchart to determine the displacement of the catheter

Table 2 Three types of catheter

catheter	A	B	C
outer radius r_o [mm]	0.2	0.225	0.475
inner radius r_i [mm]	0.025	0.175	0.425

4. Results

We prepared three types of thin catheter used in the experiments, which sizes are shown in Table 2. The transducer has 64 elements in the surface with the central frequency of 3 MHz. In the distance 60 mm from the surface of the trandsucer, the maximum sound pressure was set to 300 kPa-pp of continuous sinusoidal wave. Fig. 3 shows the comparison between the simulated displacements versus the experimental ones. The slope of the approximated line was 0.7481, which was caused by the difficulty in reproduction using the catheter A.

Fig. 4 shows the displacement of the catheter versus the ratio of the inner radius r_i to the outer radius r_o. Although the number of the experimental results were insufficient, it can be mentioned that the displacement of the catheter would be expected using the ratio of inner to outer radius.

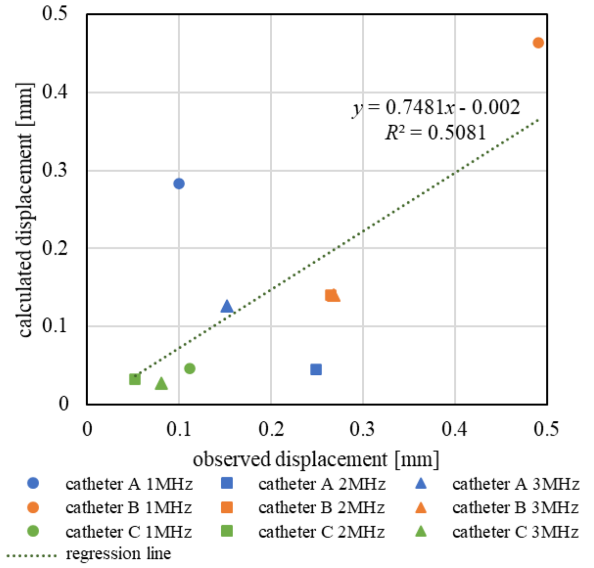
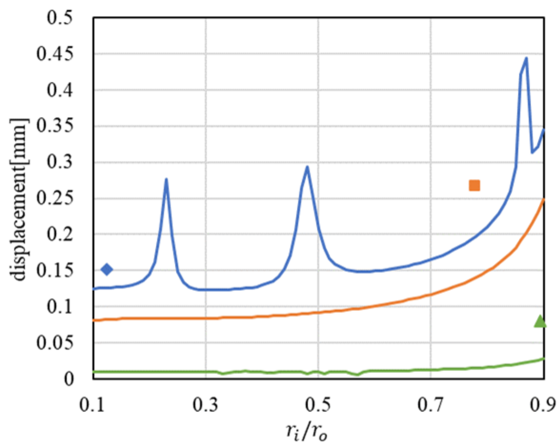


Fig. 3 Comparison of displacement of the catheter



blue→A, orange→B, green→C

Fig. 4 Comparison of displacement of the catheter versus ratio of r_i to r_o (lines: simulation, dots: experiment)

5. Conclusions

We calculated the displacement of an thin catheter using the acoustic radiation force of a plane wave incident perpendicularly on a cylinder, and compared it with the experimental displacement. Although the simulated displacements were lower than the experimental results, we consider that this simulation might be a clue to derive optimal parameters including ultrasound frequency or the ratio of the inner to outer radius of the catheter. We are going to examine further experimental results to update the simulation.

References

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