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Effects of cavity disks on the generation of underwater acoustic streaming

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1. Introduction

Underwater acoustic streaming and cavitation are essential in many applications, especially ultrasonic cleaning machines and homogenizers. To improve working efficiency with less consumption, creating a “booster” with a particular structure and placing it near the vibrating surface is one of the methods to enhance acoustic streaming. Through conducting particle image velocimetry (PIV) experiments, it has been observed that acoustic streaming in the air can be enhanced significantly by a disk with a small hole placed at a certain distance from the vibrating surface.1) Inspired by this phenomenon, this study investigates a booster configuration based on the disk with a cavity and utilizes finite element analysis (FEA) to examine the impact of the disk material and the cavity on underwater acoustic streaming.

2. Calculation method for simulation

The phenomenon of acoustic streaming enhancement by the disk with a cavity in the air might be related to the resonance frequency of the disk with a cavity, which is the driving frequency that results in the maximum sound pressure generated inside the cavity under unchanged conditions1). If the resonance frequency does not match the driving frequency, the sound pressure in the cavity will be low. This may cause some of the acoustic streaming generated by the transducer will pass through the cavity and jet out, while the other portion will be reflected by the disk, resulting in energy loss. To validate this hypothesis, simulations were conducted using the FEA software (COMSOL Multiphysics 6.1).

The sound pressure p can be calculated by the Helmholtz equation:

$$\nabla^2 p + k^2 p = 0. \qquad (1)$$

where k is the wave number and obtained by angular frequency ω and acoustic velocity c: $k = \omega/c$. Acoustic radiation pressure p_{rad} and acoustic driving force $\boldsymbol{F}_D$ can be obtained by2)

$$\boldsymbol{u} = \frac{i}{\omega\rho}\nabla p, \qquad (2)$$

$$p_{rad} = \frac{\langle p^2 \rangle}{2\rho c^2} - \frac{\rho}{2}\langle \boldsymbol{u}\cdot\boldsymbol{u}\rangle, \qquad (3)$$

$$\boldsymbol{F}_D = -\rho(\langle(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}\rangle + \langle\boldsymbol{u}(\nabla\cdot\boldsymbol{u})\rangle), \qquad (4)$$

where $\boldsymbol{u}$ is the particle velocity and ρ is the density of the medium. Acoustic streaming $\boldsymbol{U}$ can be calculated by2)

$$\boldsymbol{F}_{eff} = \boldsymbol{F}_D - \nabla p_{rad}, \qquad (5)$$

$$\rho(\boldsymbol{U}\cdot\nabla)\boldsymbol{U} = -\nabla p + \mu\nabla^2\boldsymbol{U} + \boldsymbol{F}_{eff}, \qquad (6)$$

$$\nabla\cdot\boldsymbol{U} = 0, \qquad (7)$$

where $\boldsymbol{F}_{eff}$ is the volume force and μ is the viscosity coefficient of the medium. Even in the air, the viscosity can not be ignored because it affects fluid flow within the narrow gap and interactions with solid surfaces.

3. Simulation model and results in water

3.1 Simulation model

In Ref. 1, results showed that at 28 kHz and 40 μm vibration amplitude, the maximum velocity of the acoustic streaming jet can be enhanced to approximately 20 m/s by the duralumin disk with a cavity. The simulation model was the same as in Ref. 1 in order to figure out the effect of the same disk on underwater acoustic streaming, apart from changing the medium from air to water and decreasing the vibration amplitude from 40 to 1 μm. The simulation model is shown in Fig. 1.

3.2 Simulation results

Simulations in water were conducted under conditions of frequency up to 200 kHz of the same vibration source without disk first. Results show that the maximum sound pressure increased with increasing frequency and reached 3.5 MPa at 200 kHz. However, the maximum velocity of acoustic streaming remained below 0.1 mm/s.

When using the same duralumin disk, the peak of maximum sound pressure in the cavity in water did not appear along the increase of frequency until 128 kHz, so the resonance frequency of this duralumin disk in water was 128 kHz. Distributions of sound pressure and acoustic streaming at 128 kHz are shown in Fig. 1 and Fig. 2, respectively. The entire cavity was indicated as a region of high pressure with a maximum value of 81.4 MPa. At the same time, streaming jetted out from the cavity outlet at a velocity of approximately 3 m/s, and streamlines indicated that the majority of streaming was converged from around the disk towards the cavity outlet, rather than passing through the cavity.

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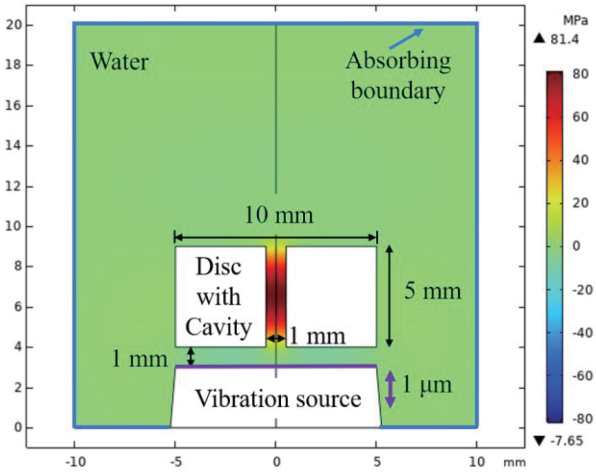

Fig. 1 Sound pressure distribution around the duralumin disk at 128 kHz and 1 μm vibration amplitude in water.

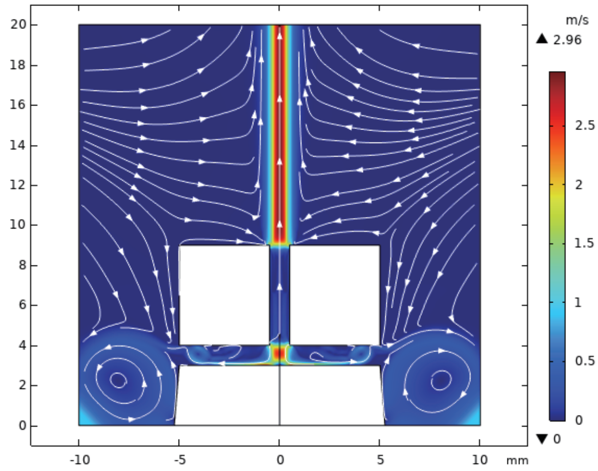

Fig. 2 Acoustic streaming distribution around the duralumin disk at 128 kHz and 1 μm vibration amplitude in water.

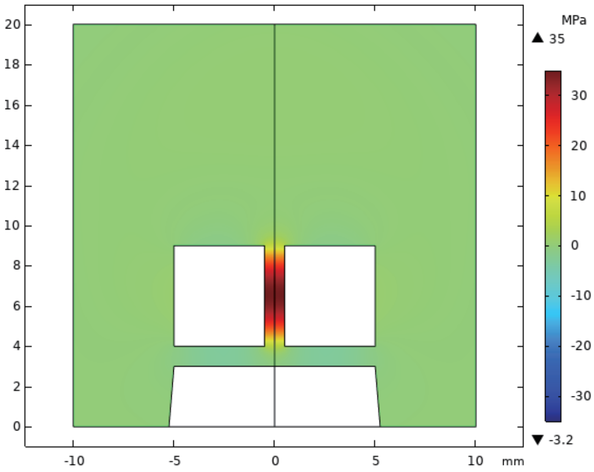

Fig. 3 Sound pressure distribution around the acrylic disk at 80 kHz and 1 μm vibration amplitude in water.

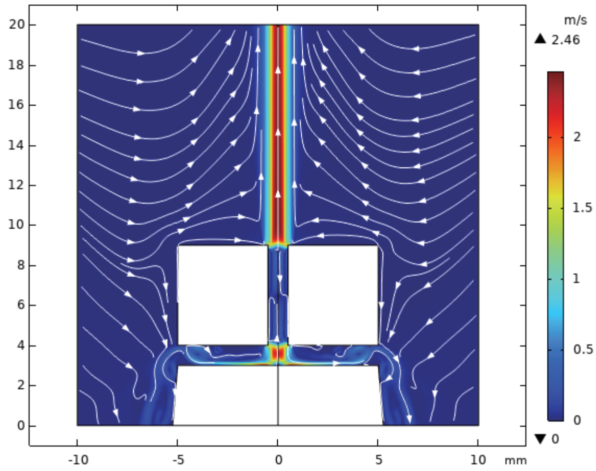

Fig. 4 Acoustic streaming distribution around the acrylic disk at 80 kHz and 1 μm vibration amplitude in water.

In addition to altering the dimensions of the disk and cavity, it was found in this study that changing the material can also affect the frequency at which the maximum value of sound pressure occurred. The resonance frequency of a disk in the same dimension but made of acrylic was 80 kHz. Distributions of sound pressure and acoustic streaming at 80 kHz are shown in Fig. 3 and Fig. 4, respectively. The sound pressure distribution was similar to that of Fig. 1, and the maximum value was 35 MPa, lower than that of the duralumin disk at 128 kHz. The maximum streaming velocity was also lower than that in Fig. 2, which was about 2.5 m/s.

4. Conclusion

Simulations of sound pressure and acoustic streaming generated around the disk with a cavity in water were conducted in this study, and the results showed that when driving the vibration source at the resonance frequency of the disk with a cavity, the velocity of the underwater acoustic streaming was improved. Moreover, the resonance frequency not only depended on the dimension of the cavity but also on the material of the disk. In the upcoming research, factors influencing the resonance frequency of the disk with a cavity will be studied and validated by PIV experiments.

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