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Finite element analysis of acoustic streaming in an ultrasonic air pump.

超音波ポンプにおける音響流の有限要素解析

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1. Introduction

Recently, there is a demand for a low-profile air supplying device which supplies gas flows into narrow space in which conventional fans or pumps cannot be embedded. We have studied an application of acoustic streaming to an ultrasonic air pump which consists of a bending transducer and a reflector and can be easily downsized and lower-profiled [1]. An approximate method to calculate the acoustic streaming in attenuated plane waves has been reported [2]. However, numerical calculation which directly derive the acoustic streaming from the sound field by solving Navier-Stokes equations has not been reported.

In this paper, we carried out the full-fluid dynamics calculation of acoustic streaming in a small gap between a bending vibrator and a reflector. The calculation accuracy is verified by comparing the result of the finite element analysis (FEA) and the measurement with regard to sound pressure distribution and flow distribution in absolute figures.

2. Structures and calculation method

The basic structure of the device is shown in Fig. 1. The bending transducer consists of an aluminum plate (20x30 mm^2, 1 mm thickness) and a PZT element (7x30mm^2, 0.4 mm thickness) bonded on the back of the aluminum plate. An acrylic resin plate in the same dimension of the aluminum plate is located parallel over the transducer with a gap of 1 mm and displaced 5 mm towards x-direction to act as a reflector and induce the directional flow. Maximum vibration velocity of the transducer is adjusted to 0.5 m/s by changing the input voltage both for measurement and analysis.

When the fundamental bending vibration mode at the resonant frequency of 12.9 kHz shown in Fig. 2 is excited on the transducer, the intense sound field is excited in the gap. And then the acoustic streaming is induced.

To calculate the sound field and flow field using FEA, we adopted piezoelectric-structure-fluid interaction analysis model by ANSYS 11.0 MFX-ANSYS/CFX (ANSYS Inc.) where the viscosity of air is taken into account. The analysis model is shown in Fig. 3 where the mesh size is 1 mm. The device is surrounded by the spherical air block where the absorption boundary condition of sound wave is set on outer surface. Setting the symmetric boundary condition at y=0 plane, we can spare the half of model to save the amount of calculation. The calculation time step is 2 μs (38.2 times per 1 cycle of the driving ultrasound). Total simulation time is 8 ms (103.2 cycles, 4000 steps).

The FEA outputs the pressure and particle velocity temporal waveform. We obtain the amplitude and phase of sound pressure from the waveform through the simulated lock-in detection. Then we obtained the flow velocity by applying a fifth butterworth low-pass filter to the waveform, assuming that the time average of the waveform gives acoustic streaming flow velocity. The cutoff frequency is 2.6 kHz, which is 1/5 of the driving frequency.

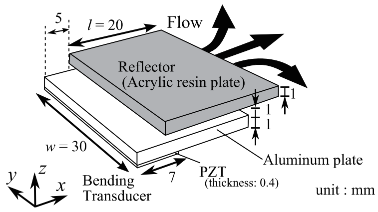

Fig.1. Basic structure of the device.

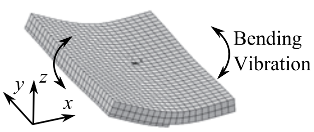

Fig.2. Bending vibration mode on the transducer at the resonant frequency of 12.9 kHz.

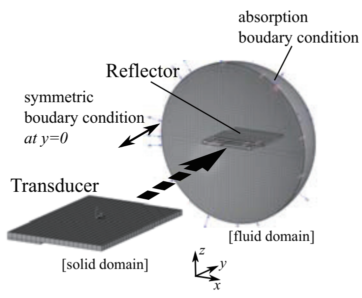

Fig.3. Simulation model for the FEA.

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3. Measurement setup

The sound pressure distribution in the gap was measured using an optical fiber probe with the diameter of 125 um [3] and the absolute flow velocity at the right edge (x, y) = (+10, 0) mm is measured by a hot-wire airflow meter (KANOMAX Model 6543). The flow velocity trend is observed from the motion of powder (lycopodium spores).

4. Analysis and experimental result

The results of calculated and measured pressure amplitude distributions within the air pump on xy-plane are shown in Fig.4. Both results showed a good agreement in their shapes of the sound field.

The results of calculated and measured pressure amplitude distributions on the x-axis are shown in Fig.5. In each result, we can find an asymmetric standing wave with a maxima of 920 Pa near the x=+4 mm. This asymmetric sound field induces the unidirectional flow towards the right. The standard deviation of the errors between the result of analysis and the measurement is ±53 Pa (5.9% of the maximum).

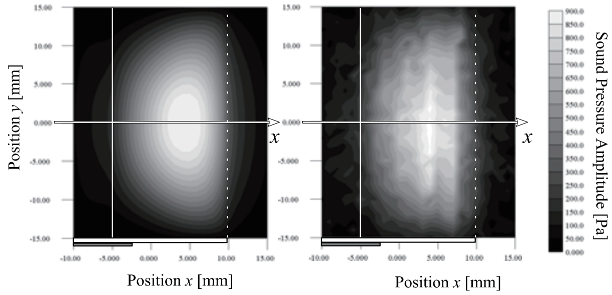
The result of calculated x-component of the particle velocity temporal waveform at the point of (x, y) = (5, 0) mm is shown in Fig.6 (a). We apply the low-pass filter to this waveform, and then we regard the final value of the applied waveform (17.4 cm/s in this case) as the flow velocity of this point.

The result of calculated x-component of the flow velocity distribution on the x-axis is shown in Fig.6 (b). We can see an steep peak (50 cm/s) and dip (-10 cm/s) at the right edge of the transducer, however we can estimate the value as around 16.5 cm/s from the context and this value shows an agreement with the measured result of 14.7 cm/s by hot-wire airflow meter.

The result of (a) calculated and (b) observed flow velocity distribution on the xy-plane is shown in Fig.7. From both result we can see the unidirectional flow towards the right.

5. Conclusion

In this report, we calculated the sound pressure and the acoustic streaming velocity with the accuracy of 5.9% in the proposed air pump. The calculation is based on the full analysis of piezoelectric-structure-fluid interaction through finite element analysis where the viscosity of air is taken into account.



(a) (b)

Fig.4. Sound pressure distributions of the (a) calculated and (b) measured results.

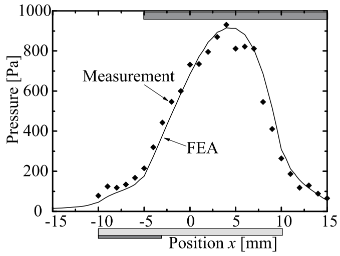
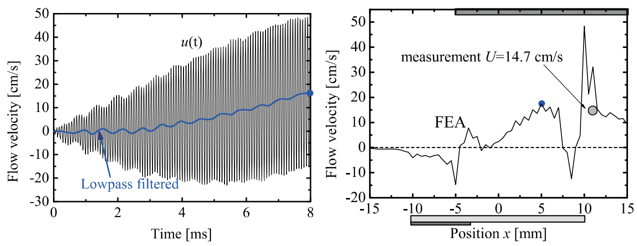
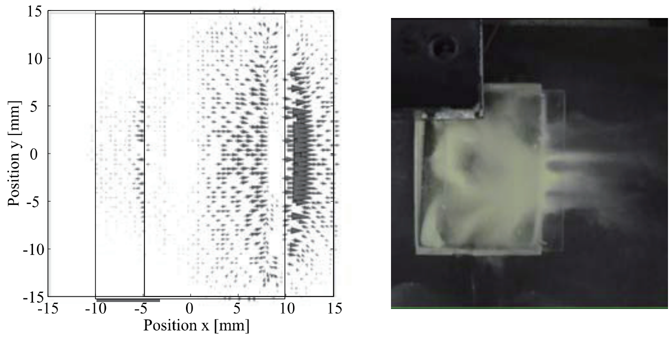


Fig.5. Pressure amplitude distributions of the simulation and measurement results on x-axis.



(a) (b)

Fig.6. Flow velocity (a) temporal waveform at (x, y) = (5, 0) and (b) distribution on x-axis.



(a) (b)

Fig.7. Flow velocity distribution of (a) calculated results and (b) actual flow on xy-plane.

References

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