Finite-element analysis of acoustic streaming generated between a bending transducer and a reflector through second-order approximated forces

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Abstract: The simulation of acoustic streaming between a bending transducer and a reflector is discussed. Instead of full fluid analysis, the streaming is calculated from second-order approximated forces of acoustic streaming and static pressure originated by the nonlinear sound field. Sound field and fluid dynamics are simulated separately under finite-element harmonic and static analyses, respectively. Through two examples of streaming, the validity of the simulation method is verified. One is streaming excited between a disk vibrator and a reflector, and the other is streaming in an ultrasonic air pump. By comparing the calculated results with the measured ones in terms of the distribution of sound pressure and streaming, it is found that the present method can well simulate the streaming in the air layer.

Keywords: Acoustic streaming, Air pump, Bending vibration, Finite-element analysis, Numerical analysis

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1. INTRODUCTION

Acoustic streaming, which is medium fluid flow in accordance with the gradient of the sound field energy density, has been attracting theoretical and experimental interest [1–4]. In particular, streaming fields of air in an acoustic resonant domain have been a target of study from the 19th century [1,5]. Many theoretical [2,6–8] and numerical approaches [9–12] have been reported up to now in efforts to understand the phenomena. At the same time, acoustic streaming plays an important role in several applications of high-power ultrasound [13–17].

We have developed an ultrasonic air pump utilizing acoustic streaming [18–23]. This device can be utilized as a low-profile air-supplying device, that induces gas flows into narrow spaces in which conventional fans or pumps cannot be embedded. A bending transducer is placed facing a reflector across a thin air layer, and excites an intense sound field and thus induces acoustic streaming. Asymmetry of standing waves or excitation of a traveling wave sound field in the air layer is one of the essential elements in producing directional streaming. To optimize the structure of the device, an appropriate method of predicting acoustic streaming is required.

Prediction by numerical transient simulation using compressible three-dimensional fluid equations often suffers from a heavy calculation cost, in spite of the recent increase in computer calculation speed. This is because it requires (1) a large volume of space of at least twice as much as the calculation target, (2) a very large number of calculation steps equal to thousands of cycles of sound, and (3) fine division of space and time of at least 1/20 of the wavelength and the period of ultrasound, respectively. We have conducted such numerical calculations based on finite-element analysis (FEA), and faced the fact that calculation time as long as 4.7 days is required even when using a computer with a 2.0GHz quad-core processor [21,22]. To reduce the numerical calculation cost, the adoption of harmonic and static analyses instead of transient analyses is effective because only one time step of equations need be solved in such “static” analysis.

On the other hand, the driving force of streaming, introduced by Nyborg [6], and derived from the time average and the conservation of the second-order static term, has been used for the theoretical approach. Although it is still difficult to solve fluid equations analytically...
using the driving force, the calculation cost of simulating streaming with the driving force is far lighter than that of simulating all phenomena numerically. Numerical simulations of acoustic streaming can be generally categorized into two types according to the principle of attenuation, since the sound field gradient causes the acoustic streaming. One is categorized by volume attenuation, which often appears in water with MHz order ultrasound. This is referred to as “Eckart Streaming,” and several simulations of acoustic streaming using this driving force have been reported [24]. However, because of the differences in the wavelength and attenuation rate, the simulation of Eckart streaming cannot be applied to the case of an ultrasonic air pump. The other type is categorized by the frictional attenuation, which often appears near the boundary between air and the structure in the Hz to kHz range. This is called “Rayleigh Streaming,” and the simulation of two-dimensional streaming in closed cylindrical coordinates is often carried out in this category [9–12, 25]. However these simulations were often based on theoretical pressure distributions, and had to be done in a closed and simple space domain. There are few reports on the three-dimensional simulation of acoustic streaming due to frictional attenuation in the thin air layer connected with the open domain by transient analysis [22, 23]. No report can be found on three-dimensional simulation of the driving force by FEA without any transient analysis.

In this paper, we suggest a method of simulating acoustic streaming generated in a gap between a transducer and a reflector by a streaming driving force, using FEA. We discussed the validity of the present simulation method by comparing the simulation and the measurement results through two examples of streaming: one is the case of a disk vibrator and a reflector and the other is an ultrasonic air pump.

2. DERIVATION OF ACOUSTIC STREAMING

First of all, in the nonlinear acoustic field, acoustic-related variables, density \( \rho \), pressure \( p \) and velocity \( u \), can be expanded in series as [6, 8]

\[
\begin{align*}
\rho &= \rho_0 + \rho_1 + \rho_2, \\
p &= p_0 + p_1 + p_2, \\
u &= u_1 + u_2.
\end{align*}
\]

(1)

\( \rho_0 \) and \( p_0 \) are the material constants of air, that is, density and atmospheric pressure, respectively. \( \rho_1, p_1 \) and \( u_1 \) are for the vibrating part and can be eliminated in the time-averaging process over time \( T \), which is far longer than the period of ultrasound and far shorter than the characteristic time of the flow change \( \tau \). This process is indicated by brackets \( \langle \cdot \rangle \) in the following equations. \( \rho_2, p_2 \) and \( u_2 \) are the static or less-changing components for which change takes place on the time scale of \( \tau \), therefore,

\[
\langle \rho \rangle = \rho_0 + \rho_2, \quad \langle p \rangle = p_0 + p_2, \quad \langle u \rangle = u_2.
\]

(2)

Secondly, by substituting Eq. (1) into the compressible fluid equations of continuity and Navier-Stokes, we obtain the incompressible fluid equations of acoustic streaming \( U \) as

\[
U = u_2 + \frac{\langle \rho_1 u_1 \rangle}{\rho_0}, \quad \text{div} U = 0,
\]

(3)

\[
\frac{\partial U}{\partial t} + (U \cdot \nabla)U = -\frac{\nabla p_2}{\rho_0} + \frac{\eta}{\rho_0} \nabla^2 U + F,
\]

(4)

where \( \eta \) is the viscosity coefficient. \( F \) is the driving force that remains as a result of time-averaging of the Navier–Stokes equation:

\[
F = -\langle (u_1 \cdot \nabla)u_1 \rangle - \langle u_1 \text{div} u_1 \rangle.
\]

(5)

This driving force consists mainly of the conservation force, which is canceled out through space and naturally induces no streaming. What is worse, it affects the streaming field when calculated in a rather coarse finite-element mesh. One effective way of removing this conservation component is to consider the effect of another conservation force of \(-\nabla p_2/\rho_0\). The second-order approximated value of static pressure \( \bar{p}_2 \) is derived using Euler equations [26, 27] and is suggested to be the difference between the potential energy of sound \( \langle e_p \rangle \) and the kinetic energy of sound \( \langle e_k \rangle \):

\[
\bar{p}_2 = \langle e_p \rangle - \langle e_k \rangle = \frac{\langle p_1^2 \rangle}{2\rho_0 c^2} - \frac{\rho_0 \langle u_1^2 \rangle}{2}.
\]

(6)

Therefore, using the following force \( F_e \) is considered to be effective in retaining precision:

\[
F_e = -\langle (u_1 \cdot \nabla)u_1 \rangle - \langle u_1 \text{div} u_1 \rangle - \frac{\nabla \bar{p}_2}{\rho_0}.
\]

(7)

Then, the Navier–Stokes equation (5) is

\[
\frac{\partial U}{\partial t} + (U \cdot \nabla)U + \frac{\eta}{\rho_0} \nabla^2 U = -\frac{\nabla (p_2 - \bar{p}_2)}{\rho_0} + F_e.
\]

(8)

The importance of Eq. (8) is that acoustic streaming \( U \) can be predicted from the sound field because \( F \) and \( \bar{p}_2 \) are made up of sound variables \( p_1 \) and \( u_1 \). This fact enables us to divide the calculation of sound and streaming, neither of which requires transient analysis. The sound field can be simulated from harmonic analysis, and \( F \) and \( \bar{p}_2 \) calculated from the sound field. Then the acoustic streaming can be predicted by static fluid analysis.

3. CALCULATION PROCEDURE

Figure 1 shows the block diagram of the analysis,
which is based on the equations explained in the previous section.

### 3.1. Sound Field Analysis

Vibrations of the air and the transducer are simulated through the piezoelectric-structure-acoustic interaction analysis model using the commercial FEA software ANSYS 11.0 (ANSYS, Inc.).

The calculation model is made up of the elastic and piezoelectric elements of the transducer and the reflector, and the acoustic fluid elements of air, which surround the transducer and the reflector. By setting the boundary condition of voltage or force to the transducer, the vibration of the transducer is simulated, and then the vibration of the air is induced via fluid-surface interaction (FSI). The outer end of the air block is set to be the absorption boundary to express the open domain.

The effect of viscosity is considered by setting the attenuation from the friction at the boundary between the fluid and solids. This rate of attenuation \( b \), which is a nondimensional value and is input in the format of the absorption coefficient, is derived from the theory of sound in a thin air gap [28],

\[
b = \sqrt{\frac{\eta_0}{\rho_0 c^2}},
\]

where \( \eta_0 \) is the viscosity of the air. When the frequency is 20 kHz, the value of attenuation \( b \) is 0.02%.

The calculation space is divided in hexahedral elements whose mesh size is around one-tenth of the wavelength. Since the streaming in the considering thickness direction negligibly influences the pump capability, and the viscous effects are taken into account by considering attenuation from the friction, this mesh size is acceptable even though it is larger than the boundary layer.

### 3.2. Calculation of Driving Force and Gradient of Static Pressure

The driving force \( F \) and the static pressure \( p_2 \) are calculated from the sound pressure \( p_1 \) and the particle velocity \( u_1 \) in complex numbers. Using the complex numbers, Eq. (8) yields the following form:

\[
F_c = -\frac{\text{Re}[(u_1 \cdot \nabla)u_1^*] - \text{Re}[u_1 \cdot \nabla u_1^*]}{2} \left( \frac{\nabla|p_1|^2}{(2\rho_0 c)^2} + \frac{|\nabla u_1|^2}{4} \right),
\]

where \( \ast \) and \( \text{Re} \) indicate the complex conjugate and the real part of the complex number, respectively. Spatial differentials in the equation are calculated numerically through the linear regression analysis on the FEA mesh. The differentiation on a node in the FEA mesh is calculated from the values of the surrounding nodes, which belong to the same element with the target node and whose number is often 26 if the mesh around the target node is composed of a rectangular grid. For example, to calculate the spatial differentials of \( \phi \) and obtain \( \frac{\partial \phi}{\partial x} \cdot \frac{\partial \phi}{\partial y} \cdot \frac{\partial \phi}{\partial z} \), the regression analysis in an overdetermined linear system will be carried out in the form

\[
\phi_0 + \frac{\partial \phi}{\partial x} x + \frac{\partial \phi}{\partial y} y + \frac{\partial \phi}{\partial z} z = \phi,
\]

where the vectors \( x = [x_1 \cdots x_{26}] \), \( y \) and \( z \) are the coordinate of the nodes, and the vector \( \phi = [\phi_1 \cdots \phi_{26}] \) is the value for each surrounding node. The differentials and a constant, \( \frac{\partial \phi}{\partial x} \cdot \frac{\partial \phi}{\partial y} \cdot \frac{\partial \phi}{\partial z} \) and \( \phi_0 \), respectively, will be calculated by the least-squares method.

### 3.3. Streaming Analysis

The streaming of air \( U \) is simulated by the following equation:

\[
(U \cdot \nabla)U + \frac{\eta}{\rho_0} \nabla U = -\nabla(p_2 - \bar{p}_2) + F_c, \tag{13}
\]

where \( \partial U/\partial t = 0 \), since the acoustic streaming is regarded as a static flow. This static flow analysis is carried out using the commercial FEA software ANSYS 11.0 (ANSYS Inc.). The Reynolds number of the streaming is expected to be in the range of 10–100, therefore, the laminar simulation is adopted.

The same calculation model as the sound field analysis is adopted for the streaming analysis, except that the acoustic fluid and the solid element in the model are replaced by the static flow fluid element and voids of the fluid elements, respectively. Considering the viscous effect, the no-slip condition is applied at the boundary between the air and the voids, which remains after the solid part is removed. The body force \( F_c \) is loaded on every node of the fluid element. To express the open region, the static pressure \( (p_2 - \bar{p}_2) \) is set to zero at the outer surface of the surrounding air.

Table 1 summarizes the material properties used in the calculations.
4. EXAMPLE 1: STREAMING FROM A DISK VIBRATOR AND A REFLECTOR

4.1. Configurations of the Experiment

Figure 2 shows the experimental setup for the first example. An aluminum disk vibrator, whose radius and thickness are 65.8 mm and 2.4 mm, is driven by a bolt-clamped Langevin transducer (BLT) with a horn at the resonance frequency of 19.2 kHz. The disk vibrates in a bending mode, which has two nodal circles and no nodal line, as shown in Fig. 3. A square reflector made of acrylic resin, whose thickness and length are 5 mm and 200 mm, is placed just above the disk vibrator, as shown in Fig. 2. The following two cases of streaming are analyzed: (a) the reflector is parallel to the vibrator and (b) the reflector is tilted by 5 degrees. We set the $x$-axis along the radial direction from which the reflector is tilted, and the $z$-axis normal to the plate. Moreover, we set the origin at 2 mm above the center of the disk, as shown in Fig. 2. In both cases, the distance between the center of the vibrator and the reflector is 9.5 mm. The peak-to-peak vibration amplitude at the center of the vibrator is adjusted to 50 $\mu$m in both the experiment and the calculation.

4.2. Calculation Model

Figure 4 shows the calculation model for FEA. Vibration force is input to the central region, $r < 2.5$ mm, at the bottom of the disk to simulate excitation by the end of the horn. The vibration disk is surrounded by an air block whose length and width are both 85.8 mm, and height is 13.9 mm. Top side of the outer boundary is represented by a rigid wall to express the reflector, while the rest of the boundaries are represented by absorption boundaries. The mesh size of the model is set to 2 mm, which is approximately 1/9 of the wavelength in air.

Table 2 shows the specifications of the computer, the FEA, and the resources spent for the calculations.

4.3. Measurement Setup

The sound pressure distribution on the plane just 2 mm above the disk vibrator was measured using the probe microphone (B&K type 4182, 3.1 mV/Pa) of 1.24 mm diameter. The microphone was scanned using a two-axis...
stage with one-millimeter steps. Amplitude and phase were recorded via a lock-in amplifier. To obtain a stable result, the measurement was carried out at a smaller amplitude than one in which streaming actually takes place.

The distribution of streaming was measured through particle image velocimetry (PIV). Ethanol mist was used as the tracer for PIV. The ethanol was continuously dropped on the surface of the vibrator to be atomized by the vibration, and then the ethanol mist was made to flow along the acoustic streaming. The motion of the mist was recorded with a high-speed camera filming at the rate of 500 frames per second. Using the PIV results, the instantaneous streaming velocity was calculated from the shift of the mist pattern with the time step of 1/500 seconds in these experiments. Then, the static streaming velocity field was calculated from all frames using the weighted mean of instantaneous vectors with the correlation of two patterns. However, because the PIV is based on the pattern of mist, in some areas, the density of the mist is insufficient to correctly calculate the velocity vector.

4.4. Results and Discussion

Figure 5 shows the measured and calculated sound pressure distributions on the y = 0 plane and z = 0 mm plane. In the case of the parallel reflector, the axisymmetric standing wave distribution was observed, which has one nodal circle at r = 16 mm and one nodal plane at z = 4.8 mm. In contrast, in the case of the tilted reflector, the sound pressure distribution became asymmetric, where a very vague nodal plane and half-nodal circle could be observed in the zx-distribution and the xy-distribution, respectively. The amplitude of the right part was four times larger than that of the left part.

Figure 6 shows the measured and calculated streaming field distributions. For the measurement result, one of the frame pictures in the captured video for the motion of the ethanol mist is displayed. The ethanol is continuously dropped onto the disk vibrator, and atomized mist can be seen as a white cloud in the captured video. Flow velocity vectors calculated by PIV are plotted in the figure. Note that a blank vector plot in the measurement results does not indicate zero velocity, merely the arrows are not displayed since the reliability of the streaming vectors was low.

In the case of the parallel reflector, the ethanol mists remain in the air layer in the experiment, as a result of the opposing circular streaming just above the vibrator disk. A symmetric flow distribution was obtained in the simulation

| CPU | AMD Phenom 9550 Quad-Core Processor 2.20 GHz |
|-----|---------------------------------------------|
| Memory | 8.0 Gbyte |
| Operation System | CentOS Linux 5.4 |
| Shared-Memory Parallel | 2 process |

| Example 1 | Example 2 |
|-----------|-----------|
| Nodes | 25,368 | 25,662 |
| Elements | 22,253 | 23,142 |
| Memory used [MByte] | 510.9 | 510.8 |
| Sound calculation time [s] | 243.0 | 357.4 |
| Fluid calculation time [s] | 225.8 | 198.3 |

Fig. 5 Simulation (top and middle) and measurement (bottom) results of pressure distribution.

Fig. 6 Simulation (top) and measurement (bottom) results of streaming distribution.
and the PIV measurement. In the case of the tilted reflector, the ethanol mist flows to the open side, and directional flow distribution was obtained from both the simulation and the PIV measurement. The directional flow velocity at the left edge is 0.11 m/s, where the flow rate from the left side of the vibrator is approximately 110 ml/s.

Figure 7 shows the measured and calculated $x$-component streaming field distributions on the $x$-axis. In the case of the parallel reflector, the FEA result is symmetric to $x = 0$ and shows sinusoidal distribution. In the case of the tilted reflector, streaming distributions are no longer symmetric, and streaming flows toward the negative-$x$ direction in most of the region. The peak positions of the calculation result and the measurement result agree in most parts except the range between $x = +10$ mm and $x = +20$ mm. Also, the calculated absolute value of streaming agrees with the measurement value. For the area of $+10 \leq x \leq 20$ mm, the calculation result shows distribution in the $z = 0$ plane, the plane 2 mm above the disk vibrator, whereas the measurement result was calculated from the images captured above the reflector. Therefore, the measurement result includes the streaming on planes other than $z = 0$, especially a liquid drop just on the vibrator. In addition to that, the injection point of ethanol is rather close to the area of $+10 \leq x \leq 20$ mm; and then several atomized ethanol drops have velocity toward the negative-$x$ direction.

5. EXAMPLE 2: STREAMING FROM AN ULTRASONIC AIR PUMP

5.1. Configurations of Device

Figure 8 shows the configuration of the pump. The bending transducer consists of an aluminum plate and a lead zirconate titanate (PZT; Fuji Ceramics C-203) element bonded on the back of the aluminum plate. The aluminum plate is 30 mm in width, 20 mm in length, and 2 mm in thickness, and the PZT element is 30 mm in width, 10 mm in length, and 0.4 mm in thickness. By driving the PZT element at the resonant frequency of 26.2 kHz, the fundamental bending vibration along the length direction is excited on the transducer, as shown in Fig. 9. We set the $x$-axis along the length direction, the $y$-axis along the width direction, and the $z$-axis normal to the plate; moreover, we set the origin at the center of the plate in the middle of the air gap, as shown in Fig. 8. The maximum vibration speed at the edge of the transducer ($x = 10$ mm, $y = 15$ mm) is adjusted to 0.5 m/s (6.1 μm in peak-to-peak vibration amplitude) in both the experiment and the calculation.

An acrylic resin plate with the same dimensions as the aluminum plate is first positioned parallel to the transducer with a gap of 1 mm and acts as a reflector. Then, as shown in Fig. 8, the reflector is tilted in the range of 0–10 degrees along the length direction to obtain directional flow.

5.2. Calculation Model

The models of the transducer and the reflector are surrounded by an air block ($32 \times 38 \times 13$ mm$^3$), as shown in Fig. 10. The outer surface of the air block is set to be
The absorption boundary. The mesh size of the model is set to 1 mm, which is approximately 1/13 the wavelength in air.

To maintain the mesh quality and the square z-projection, a wedged-shaped reflector shape was chosen, unlike in Fig. 8. Because the shapes of the air layer are identical and the reflector behaves as a rigid wall, the changes in the upper-side shape or partial thickness of the reflector cause almost no effect on the sound field or acoustic streaming distribution.

5.3. Measurement Setup

Sound pressure measurement was done using a fiber optic probe [29] in this experiment because the air layer was too thin to use a conventional microphone. Figure 11 shows the setup of the fiber optic probe, which detects the intensity modulation of the reflected light at the end of the fiber. The absolute value of sound pressure was calculated from the fiber-end reflection modulation. Because the signal-to-noise ratio in the measurement setup is low, error from some tens to some hundred pascals can occur [30].

Streaming of air was measured by PIV. This time, the tracer was lycopodium spores scattered on the transducer before streaming. Because it is difficult to supply the tracer continuously, the moment of starting the drive was captured with a high-speed camera filming at 1310 frames per second. Because of the mass of lycopodium spores, the calculated absolute velocity of air is inaccurate, however, the traced pattern of powder motion is expected to indicate the streaming pattern of the air.

To determine the absolute streaming velocity at the open end of the air layer, a hot-wire airflow meter (KANOMAX Model 6543, nondirectional, measurement range 0.05–5.00 m/s) was applied. Figure 12 shows the measurement setup. The sensor head of the probe was placed just beside the air layer. Measurement was carried out for every degree in the range of 0–10 degrees and four times for each angle, and then the average, maximum, and minimum were plotted as an error bar in Fig. 15.

5.4. Results and Discussion

Figure 13(top) shows the calculated sound pressure distribution on the $z=0$ plane, and Figs. 13(center, bottom) show the measured and calculated sound pressure distributions on the $x$-axis, respectively. In both cases, the sound distribution was observed to have three antinodes along the $x$ direction and one antinode along the $y$ direction. In the case of the parallel reflector, the sound pressure distribution was almost symmetric to the $y$-axis and standing wave, whereas in the case of the tilted reflector, the sound field was asymmetric and the traveling wave could be identified from the phase. The calculation result well predicted the measurement result, the standard derivation was around 140 Pa (8.7%) and 68.5 Pa (8.6%) of the maximum for the parallel and the tilted reflector, respectively.

Figure 14 shows the measured and calculated streaming field distributions. For the measurement result, one of the frame pictures in the video of the motion of the lycopodium spore powder is displayed. The lycopodium spore powder was scattered uniformly in the $xy$-plane before inducing the vibration, and can be seen as a white cloud in the captured video. Flow velocity vectors calculated by PIV are plotted in the figure.
In the case of the parallel reflector, both simulation and measured results indicate that the streaming is almost symmetric to the $x$ and $y$ axes, and the main streaming flows toward both left and right side directions. Directional flows that transport air cannot be seen in the pump. In the case of a tilted reflector, both simulation and measurement show strong directional flow along the $x$-axis mainly around the region of $x < 0$. The directional flow velocity at the left edge is 0.25 m/s and the flow rate from the left side of the vibrator is approximately 7.5 ml/s.

The difference in the streaming field between measurement and calculation, especially in the case of the plane reflector, is the vortex flow along the $y$-axis, which cannot be considered in the calculation with a rather coarse mesh. However, as many reports state, this kind of vortex is circular flow \[6\], and hence produces little streaming toward the outside of the circulation path. As evidence, we can see that the average $x$-velocities along the $x$-axis in the calculation and measurement are 4.3\% and 9.3\% of the maximum, respectively. For the tilted reflector, average streaming is 15\% and 60\% of the maximum velocity in the calculation and the measurement, respectively. We can conclude that this vortex causes little effect on pump capability, and the mesh size is acceptable for this case. Still, further inquiry on this kind of phenomena in the case of a fine mesh may be needed.

Figure 15 shows the velocity characteristics at the left side of the air pump versus the tilt angle of the reflector. The result of the FEA is rough because the mesh formation in 1 millimeter affects the result. From both the simulation and the measurement, velocity tends to increase in small degrees owing to increases in sound pressure traveling waves, and there is soft peak at around 4 degrees, and then the velocity decreases by larger degrees because the sound pressure become smaller. As in Fig. 16, which is a plot of the measurement versus the FEA results, the rate of change corresponds well to a 0.98 proportional constant, though the measurement results showed a value just 0.1 m/s smaller than that of the FEA.

Two reasons can be considered for the above error. The first reason is the difference in the acoustic streaming $U$ and the static velocity $u_2$ in Eq. (3). There is a difference of
measured the velocity in the measurement can be partially explained by the to the case of the tilted reflector. Therefore, the difference in the case of an 800-Pa-amplitude traveling wave, similarly disturbed to some extent.

An air layer, whereby the sound and streaming field were flow meter probe, which is larger than the thickness of \( U \) smaller value than the calculation result of acoustic streaming \( U \). The second reason is the finite size of the flow meter probe, which is larger than the thickness of the air layer, whereby the sound and streaming field were disturbed to some extent.

6. CONCLUSION

In this paper, a simulation method, based on driving force, for acoustic streaming in a small space between a transducer and a reflector was suggested. The calculation cost was within 30 minutes for centimeter-order devices. The simulation and measurement results were compared with each other, and the results of sound pressure agreed well. The amplitudes of acoustic streaming in the results of both calculation and measurement showed identical trends and orders, though several percent bias was observed. The detailed streaming distribution was less precise owing to the mesh roughness, however, it was sufficiently informative to predict the capability of the ultrasonic air pump.

REFERENCES

[1] M. Faraday, “On a peculiar class of acoustical figures; and on certain forms assumed by groups of particles upon vibrating elastic surfaces,” *Philos. Trans. R. Soc. Lond.*, **121**, 299–340 (1831).

[2] J. W. S. Rayleigh, *Theory of Sound*, Vol. 2 (Dover, New York, 1945), pp. 312–342.

[3] J. W. S. Rayleigh, “On the circulation of air observed in Kundt’s tubes, and on some allied acoustical problems,” *Philos. Trans. R. Soc. Lond. Ser. A.*, **175**, 1–21 (1883).

[4] C. Eckart, “Vortices and streams caused by sound waves,” *Phys. Rev.*, **73**, 68–76 (1948).

[5] V. Dvorak, “Über die akustische Anziehung und Abstosung,” *Ann. Phys.*, **233**, 42–73 (1876).

[6] W. L. Nyborg, “Acoustic streaming due to attenuated plane waves,” *J. Acoust. Soc. Am.*, **25**, 68–75 (1953).

[7] W. L. Nyborg, “Acoustic streaming near a boundary,” *J. Acoust. Soc. Am.*, **30**, 329–339 (1958).

[8] O. V. Rudenko and S. I. Soluyan, *Theoretical Foundations of Nonlinear Acoustics* (Plenum, New York, 1977), pp. 187–211.

[9] M. Kawahashi and M. Arakawa, “Nonlinear phenomena induced by finite-amplitude oscillation of air column in closed duct: Analysis of acoustic streaming,” *JSM Int. J. Ser. B.*, **39**, 280–286 (1996).

[10] T. Yano, “Turbulent acoustic streaming excited by resonant gas oscillation with periodic shock waves in a closed tube,” *J. Acoust. Soc. Am.*, **106**, L7–L12 (1999).

[11] A. Alexeev and C. Gutfinger, “Resonance gas oscillations in closed tubes: Numerical study and experiments,” *Phys. Fluids*, **15**, 3397–3408 (2003).

[12] M. K. Aktas and B. Farouk, “Numerical simulation of acoustic streaming generated by finite-amplitude resonant oscillations in an enclosure,” *J. Acoust. Soc. Am.*, **116**, 2822–2831 (2004).

[13] T. Hasegawa, J. Friend, K. Nakamura and S. Ueha, “Characteristics of ultrasonic suction pump without moving parts,” *Jpn. J. Appl. Phys.*, **44**, 4658–4661 (2005).

[14] Y. Imamura, S. Sakamoto and Y. Watanabe, “Modulation of sound field in looped-tube thermoacoustic cooling system with membrane,” *Jpn. J. Appl. Phys.*, **46**, 4417–4420 (2007).

[15] R. Ozaki, T. Shinpo, M. Ozaki and H. Moritake, “Lasing in cholesteric liquid crystal oriented by acoustic streaming,” *Jpn. J. Appl. Phys.*, **47**, 1363–1366 (2008).

[16] D. Köster, “Numerical simulation of acoustic streaming on surface acoustic wave-driven biochips,” *SIAM J. Comput.*, **29**, 2352–2380 (2007).

[17] T. Frommelt, D. Gogel, M. Kostur, P. Talkner, P. Hanggi and A. Wixforth, “Flow patterns and transport in rayleigh surface acoustic wave streaming: Combined finite element method and raytracing numerics versus experiments,” *IEEE Trans. Ultrason. Ferroelec. Freq. Control*, **55**, 2298–2305 (2008).

[18] H. Takei, D. Koyama, K. Nakamura and S. Ueha, “Air flow in a small gap between a bending vibrator and a reflector,” *Jpn. J. Appl. Phys.*, **47**, 4276–4281 (2008).

[19] H. Takei, D. Koyama, K. Nakamura and S. Ueha, “Improvement of the air flow generation using a bending vibrator and a reflector,” *IEEE Trans. A.*, **91**, 1152–1155 (2008) (in Japanese).

[20] D. Koyama, Y. Wada, K. Nakamura, M. Nishikawa, T. Nakagawa and H. Kihara, “An ultrasonic air pump using an acoustic traveling wave along a small air gap,” *IEEE Trans. Ultrason. Ferroelec. Freq. Control*, **57**, 253–261 (2010).

[21] Y. Wada, D. Koyama, K. Nakamura, M. Nishikawa, T. Nakagawa and H. Kihara, “An ultrasonic air pump utilizing acoustic streaming,” *Phys. Procedia*, **3**, 943–952 (2010), *Int. Congr. Ultrasonics*, Santiago de Chile, January (2009).

[22] Y. Wada, D. Koyama and K. Nakamura, “Finite element analysis of acoustic streaming in an ultrasonic air pump,” *Jpn. J. Appl. Phys.*, **49**, p.07HE15 (2010).

[23] Y. Wada, D. Koyama and K. Nakamura, “Finite element analysis of acoustic streaming through the driving force in an ultrasonic air pump,” *Proc. 20th Int. Congr. Acoustics*, p. 267 (2010).
[24] T. Kamakura, K. Matsuda, Y. Kumamoto and M. A. Breazeale, “Acoustic streaming induced in focused gaussian beams,” J. Acoust. Soc. Am., 97, 2740–2746 (1995).

[25] L. P. Cheng and S. Y. Zhang, “Simulation of the flow induced by acoustic streaming in noncontact ultrasonic motors,” Appl. Phys. Lett., 90, p.244106 (2007).

[26] L. V. King, “On the acoustic radiation pressure on spheres,” Philos. Trans. R. Soc. Lond. Ser. A, 147, 212–240 (1934).

[27] W. L. Nyborg, “Radiation pressure on a small rigid sphere,” J. Acoust. Soc. Am., 42, 947–952 (1967).

[28] T. Hayasaka and S. Yoshikawa, Onkyo Shindo-ron (Theory of Acoustics and Vibrations) (Maruzen, Tokyo, 1974), pp. 696–670 (in Japanese).

[29] H. Takei, T. Hasegawa, K. Nakamura and S. Ueha, “Measurement of intense ultrasound field in air using fiber optic probe,” Jpn. J. Appl. Phys., 46, 4555–4557 (2007).

[30] B. Shen, Y. Wada, D. Koyama and K. Nakamura, “Sensitive study of fiber optic ultrasonic probe based on the modulation in the refractive index of air,” Proc. 20th Int. Congr. Acoustics, p. 252 (2010).