Control of acoustic streaming by a focusing source with two coaxially arranged transducers

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Control of acoustic streaming is expected to provide a promising method in microfluidic technologies. However, there are less research reports on such acoustic systems to control the streaming velocity. To make sure that the velocity depends strongly on sound field distribution, we carried out some experiments using a focusing ultrasound transducer that consists of two coaxially arranged concentric piezoelectric elements: i.e., one is an inner disc element and the other an outer ring one. Both the elements can be driven by electric signals at the same frequency of 3.45 MHz but different phase angles. A sound beam model equation, SBE [T. Kamakura et al., J. Acoust. Soc. Am. 107, 3035-3046 (2000).], is successfully used to predict the focused sound pressure distribution. The external driving force to act on the fluid is readily calculated by the pressure, and then the streaming speed can be theoretically predicted by the continuity equation and the Navier-Stokes equation with the term of the force [T. Kamakura et al., J. Acoust. Soc. Am. 97, 2740-2746 (1995).]. The profiles of the speed along and across the beam axis are measured using a Laser Doppler Velocimeter. It has been confirmed that experimental data and theoretical predictions are in pretty good agreement. The control feasibility of the streaming is discussed by changing the phase difference between the two signals.

1 Introduction

The propagation of an ultrasound wave in a viscous fluid induces globally mass flow in the beam. This macroscopic flow is known as acoustic streaming [1].

Acoustic streaming occurs because of momentum being transferred from the wave to fluid through energy dissipation in the wave caused by sound absorption. The magnitude or speed of the streaming, therefore, can be theoretically predicted by the properties of the fluid such as shear viscosity and of the sound such as absorption. Actually, by measurements of streaming, determination of the absorption, hence of bulk viscosity, which is usually measured otherwise with difficulty, were made for various liquids by Liebermann [2]. Additionally, the streaming is greatly dependent on sound intensity. From this respect, Starritt et al. reported that when the amplitude of a sound beam is finite and consequent generation of the waveform distortion becomes active the speed is apparently increased than expected [3].

Incidentally, there are plenty of reports concerning acoustic streaming induced in ultrasound waves from theoretical and experimental points of view [4]. The streaming is basically governed by the continuity equation and the Navier-Stokes equation in a viscous fluid with incompressibility [1, 5]. Besides, the driving force acting on the fluid that generates intrinsically the streaming is externally supplied from sound energy. Then, the movement of the streaming can be predicted in advance by knowing the driving force distribution in the beam and by solving such governing equations associated with appropriate boundary conditions. Computational fluid dynamics(CFD) that has been recently developed might be helpful for solving highly complicated flow problems conveniently and successfully. As for measurements of the velocity of acoustic streaming, five methods have been utilized so far: hot-wire anemometry [3], laser Doppler velocimetry [6], magnetic resonance imaging [7], particle image velocimetry [8], and ultrasound Doppler technique [9]. Each method has advantages and disadvantages. For example, it is easy to use and handle a hot-wire anemometer. However, appropriate correction is required for the probe to measure precisely absolute streaming speed on account of its nonlinear response to the fluid temperature.

As described above, it is evident that the characteristics of acoustic streaming depend temporally and spatially on the characteristics of sound field. This means that it is possible, for example, to control the streaming by changing sound fields appropriately. The present report, therefore, is primarily concerned with some experimental demonstrations on a simple control method of the streaming by varying the phase difference of two initial ultrasound waves emitted from a focused transducer. The transducer consists of two concentric piezoelectric ele-
ments arranged coaxially: i.e., one is an inner disc element and the other an outer ring one. Both the elements can be driven by sinusoidal signals at the same frequency of 3.45 MHz but different phase angles. From precise measurements of sound pressure distributions using a card-type hydrophone with a small sensitive area, the theoretical prediction of streaming speed along and across the beam axis is made to compare with the speed data measured by means of a laser Doppler velocimeter. Some intriguing findings are given for streaming distributions around the sound focus.

2 Experiments and discussion

2.1 Sound-field measurements

An ultrasound transducer as a source consists of two coaxially arranged confocal piezoelectric elements of an inner disc and an outer ring, as shown in Fig. 1. Their active surfaces are almost the same: the diameter of the disc element is 27.2 mm, and the inner and outer diameters of the ring element are 29.2 mm and 40 mm, respectively. Both the elements have the same resonance frequencies of 3.45 MHz and the same focal lengths of 60 mm. The transducer is flush-mounted on a side wall of a tank filled with fresh water. The tank dimensions are 150 mm in width, 300 mm in length, and 150 mm in height.

![Figure 1: Ultrasound focusing source.](image)

The block diagram of the experimental set-up for ultrasound field measurements is depicted in Fig. 2. Two electric tone-burst signals of 3.45 MHz and of about 50 cycles duration fed from a function generator are power-amplified individually and are applied to the transducer. The amplitudes and phases of the signals can be varied precisely. Let the phase difference between the two signals be \( \theta \). When the phase angles are equal: i.e., \( \theta = 0 \), the signals are in-phase. The signals are out of phase when \( \theta = 180^\circ \). A needle-type hydrophone with an active diameter of 0.5 mm that picks up local sound pressure is mounted on a translation stage driven by stepping motors. The motors enable the stage to move precisely along and across the beam axis in steps as small as 1 \( \mu \)m. Even if the initial sound pressure amplitude of a wave is low enough, the wave undergoes distortion during propagation due to the inherent nonlinearity of a medium. Especially, the distortion becomes significant near the focus.

![Figure 2: Experimental set-up for sound field measurements.](image)

Figure 3(a) shows on-axis sound pressure amplitudes of

![Figure 3: Fundamental and second harmonic sound pressure levels on the beam axis. Above: in-phase case (\( \theta = 0 \)), bellow: out of phase case (\( \theta = 180^\circ \)). Circles in black and in white are all measured data, and solid curves the theoretical prediction.](image)
fundamental frequency 3.45 MHz and second harmonic frequency 6.9 MHz for the case where the two electric signals are in-phase ($\theta = 0$). Circle symbols in the figure are all measured data, and solid curves the theoretical prediction based on the spheroidal beam equation (SBE) that has been recently proposed by the present authors to successfully describe a strongly focused beam of finite amplitude [10]. The pressure amplitude $p_0$ at the source face, which is initially needed for starting numerical calculation of the SBE model, was determined by a best fit of on-axis first harmonic pressure curve between the measured data and the theory, and was estimated to be 40 kPa, which corresponds to 209 dB in sound pressure level. The source pressure is assumed to be uniformly distributed over the face. Except for the regions less 50 mm and away from 80 mm, the present theory agrees excellently with the experimental data. Especially, the spatially oscillating structures of the field are adequately described by the SBE numerical simulation. The pressure amplitude of the fundamental frequency increases abruptly just the focus and attains a maximum of 242 dB at the focus $z = 60$ mm, which is 33 dB higher than the initial source level. The second harmonic amplitude increases more drastically near the focus. However, the maximum level of the second harmonic pressure is about 17 dB lower than that of the fundamental, then it is expected that the waveform at the focus does not distort so much.

In addition to the case of $\theta = 0$ mentioned above, experimental and theoretical results are given in Fig. 3 for the case where the phases are out of phase ($\theta = 180^\circ$). It is obviously observed that the pressure almost vanishes at the focus and takes two big peaks at 55 mm and 66 mm from the source. The pressure level at 55 mm is about 2 dB higher than that at 66 mm. However, the amplitude of the second harmonic does not take a dip at the focus but at about 3 mm behind the focus. This may be attributed to the fact that the virtual sources of the harmonic generated in the pre-focal region do not concentrate at the focus. It should be apparent that theory and experiment are in good agreement for both the different phase conditions of $\theta = 0$ and $180^\circ$.

Under the same source conditions, beam patterns of the fundamental and second harmonic pressures in the focal plane of $z = 60$ mm were measured. The experimental results are shown in Fig. 4 with theoretical predictions. For $\theta = 0$, the source has a relatively large main-lobe and plenty of side lobes for the fundamental just like a conventional directive source. However, there is no side-lobe for the second harmonic within the framework of the present experimental conditions. The half beamwidth is about 1 mm for the fundamental. The beamwidth of the second harmonic is further narrower than that of the fundamental. These widths are comparative with the active diameter of the hydrophone. Then, it is of great importance to take into account of the spatial averageing effect of a hydrophone with finite aperture size that in general leads to an underestimate of the pressure when close examination with theory is needed. In contrast, there exists a deep dip around the axis for the fundamental pressure pattern when the signals are out of phase ($\theta = 180^\circ$). This means the pressure is spatially distributed just like a caldera. It should be noted again that the theory based on the SBE model agrees well with the experiment for both the two initial phases.

### 2.2 Flow-field measurements

Acoustic streaming was observed in the same water tank as used in the sound-field measurements. The temperature was held around 20°C. The set-up of the experiment is shown in Fig. 5. Two coherent laser beams penetrate through transparent tank plates intersect at 11.5° in water. The Doppler shift in frequency of light scattered by tiny particles suspended in the water contains information about the particle velocity. The Doppler signal is detected by a photomultiplier and a subsequent frequency tracker whose output voltage is directly proportional to the velocity. This velocity measurement system is so-called laser...
Doppler velocimetry.

The ultrasonic transducer with two piezoelectric elements in the preceding section was operated under the source conditions that remain unchanged except for cw mode excitation. As soon as two 3.45 MHz sinusoidal signals from the generator are simultaneously applied to the transducer, the streaming begins to be observed. Especially, the build-up of streaming is fast near the focus and is established to be steady-state within 10 sec. It takes only 60 sec to approach the steady-state velocity in other observation points.

Acoustics streaming is in principle governed by the continuity equation and the Navier-Stokes equation in a viscous, incompressible fluid. The driving force that induces the streaming is externally supplied by the dissipation process of ultrasound through viscosity. These basic equations are readily solved utilizing a classical concept of the stream-function vorticity method under the flow to be axisymmetric. The force per unit mass to act on the fluid is given for a progressive confined beam by

$$F = -\frac{1}{\rho_0 c_0^3} \left( \zeta + \frac{4}{3} \eta \right) \frac{\partial^2 p}{\partial t^2},$$  \hspace{1cm} (1)$$

where \(\rho_0\) is the medium density, \(c_0\) is the sound speed, \(p\) is the sound pressure. The symbol ‘overline’ denotes averaging over time. Moreover, \(\eta\) and \(\zeta\) are the coefficients of shear viscosity and bulk viscosity, respectively. The derivative with respect to time in eq. (1) says that ultrasound beams with higher frequencies increase the driving force and enhance acoustic streaming. Therefore a distorted wave with plenty of harmonics induces generally a fast flow in the beam than might be expected by linear theory. If the pressure waveform with the fundamental frequency \(f\) can be expanded into a Fourier series; i.e.,

$$p = \sum_{n=0}^{\infty} p_n \sin(2\pi ft + \varphi_n),$$  \hspace{1cm} (2)$$

the force is then given by eq. (1) as

$$F = \frac{\alpha}{(\rho_0 c_0)^2} \sum_{n=1}^{\infty} n^2 p_n^2,$$  \hspace{1cm} (3)$$

where \(p_n\) and \(\varphi_n\) are the amplitude and phase of the \(n\)-th harmonic pressure. \(\alpha\) in the equation is the absorption coefficient of the ultrasound at frequency \(f\). Incidentally, the second harmonic pressure level for the in-phase case was about 17 dB lower than the fundamental pressure level at the focus. Hence, the contribution of the harmonic on the force enhancement is at most 8\% in the present experimental situation.

Axial distribution of the streaming velocity is shown in Fig. 6. Circles in black and white are all the measured data, and solid and dotted curves the theoretical data that are numerically predicted by the stream-function vorticity method [11]. Numerical parameters in computation are decided from consideration of accuracy and econ-
Eckart-type acoustic streaming may occur in inappropriate determination of step sizes in space and time via a finite difference scheme. Since the streaming is concentrated near the focus, the numerical integration of a set of stream-function vorticity equations are limited to a region of 12 cm in the axial direction and to 2 cm in the radial direction, and actually smaller than the water tank. Overall, the streaming speed is accurately predicted by the theory previously developed by the present authors. The in-phase excitation accelerates the flow near the focus and attain a maximum speed of 6.3 cm/s at around 62 mm just behind the focus. After that, the speed is gradually decreased. The speed profile for the out-of-phase excitation is different: two distinct peaks of the speed appear at 56 mm and 68 mm, and the streaming is slightly faster at the latter point by 5 mm/s. This diphasic-shaped profile resembles the axial propagation curve of the pressure shown in Fig. 3(b), although peaks and dips in the flow are not so pronounced as the pressure curve.

Axial speed profiles in the plane perpendicular to the axis are given in Fig. 7, where the plane is located at \( z = 61.5 \) mm, just behind the focal plane. Symbols and notations are the same as those in Fig. 6. The present measuring volume formed by the interaction of two laser beams enables us to observe flow speed with a spatial resolution of 120 \( \mu \)m. This resolution seems to be sufficient to compare experiment with theory. In the paraxial region less than 2 mm from the axis, the theoretical predictions accord with the experimental data in a relatively good fashion. Away from the point, however, the measured speeds are overall larger than the computed data. The reason why such discrepancies appear is not determined yet. One of the probable sources for the discrepancies is the limited integration region in numerical simulation that is much smaller than the actual dimensions of the tank. It should be noted that we can observe no valley in the flow around any regions where dips in pressure exist. This is different from the result that has been observed in speed profiles in ultrasound beams emitted from a planar source with a circular aperture [12].

Figure 8 shows the streaming change as a function of \( \theta \) from 0 to 360\(^\circ\). The observation point is located at \( z = 61.5 \) mm. The corresponding sound pressure data with theoretical predictions are also given in the figure for comparison. The speed changes smoothly and continuously, and exhibits cyclic behavior with 360\(^\circ\). It seems to be stressed that the speed variation is delayed by about 20\(^\circ\): i.e., the maximum of the speed appears at 20\(^\circ\) and the minimum at 190\(^\circ\).

Experimental data are shown for the sound pressure and speed profiles only when the phase difference \( \theta \) is changed from 0 to 180\(^\circ\) by an increment of 60\(^\circ\). Further measurements were carried out for \( \theta = 240^\circ, 300^\circ, \) and \( 360^\circ \). However, the data are not shown here because of their similar profiles as Fig. 9. Evidently, these experiments suggest that it is feasible to control the field of acoustic streaming by changing the distribution of sound pressure.

### 3 Summary

This report has dealt with Eckart-type acoustic streaming generated in a focused beam by an ultrasound transducer that consists of two coaxially arranged confocal piezoelectric elements. The elements were driven by sinusoidal signals at the same frequency of 3.45 MHz but with different initial phases. When the phase difference of the two signals was null, the pressure waves emitted from the elements were coherently added to be a strongly focused field as if the pressure (or more strictly, particle...
velocity) distribution over the transducer face is uniform. For the elements to be excited with a phase difference angle of 180°, a deep valley in pressure appeared at the focus. The streaming speed was measured using a Laser Doppler Velocimeter. It was observed that the streaming increases its speed abruptly before the focus and takes the maximum speed just behind the focus for the in-phase excitation. For the 180° out-of-phase excitation, however, the streaming deaccelerated its speed slightly behind the dip of the pressure and exhibited just like a saddle-shaped profile. These profiles were as a whole predicted by the theory of the stream-function vorticity method that was proposed by the present authors.

Acknowledgements

The authors are grateful Yoko Suzuki, a post-graduate student of the University of Electro-Communications, for his assistance with the experiment. This work is partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Exploratory Research, 16656062.

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