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Numerical simulation of compressible fluid flow in an ultrasonic suction pump

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ABSTRACT

Characteristics of an ultrasonic suction pump that uses a vibrating piston surface and a pipe are numerically simulated and compared with experimental results. Fluid analysis based on the finite-difference time-domain (FDTD) routine is performed, where the nonlinear term and the moving fluid–surface boundary condition are considered. As a result, the suction mechanism of the pump is found to be similar to that of a check valve, where the gap is open during the inflow phase, and it is nearly closed during the outflow phase. The effects of Reynolds number, vibration amplitude and gap thickness on the pump performance are analyzed. The calculated result is in good agreement with the previously measured results.

1. Introduction

In recent years, miniature fluidic pumps have been in great demand in the fields of cooling systems [1], liquid-dispensing systems [2], fuel delivery systems for miniature fuel cells [3,4], artificial heart pumps [5], and medical apparatus [6]. Conventional electromagnetic pumps have had difficulties in miniaturization and in the suppression of electromagnetic noise. For these reasons, several miniature pumps using piezoelectrically [7] or electrostatically [8,9] excited membrane vibration have been proposed. Most of these pumps require check valves to control the flow direction. However, the check valves have problems with wear and clogging due to bubbles and particles. Additionally, the driving frequency is at the low end of the audible range in the conventional design, and noise and vibrations create difficulties for practical installation. However, check valves can be eliminated if the acoustic effects of high-frequency ultrasound, such as acoustic radiation force and acoustic streaming [10–15], are used to directly act on the fluid.

The phenomena associated with an ultrasonically vibrating pipe dipped in water has been investigated [16–20]. When the end of a thin pipe was located perpendicularly near a vibrating piston surface that was immersed in a fluid, the fluid rose inside the pipe. The pump produced a maximum pump pressure of 20.6 kPa and a maximum flow rate of 52 ml/min when the gap was 10 μm. Hasegawa et al. [20] has studied the working principle and a physical model of the pump under the squeeze film hypothesis. To some extent, this physical model explains the phenomenon such as the effect of the vibration amplitude or gap thickness on the pump pressure characteristics. However, the actual motion of the fluid and the pump pressure dependency on the viscosity and tube thickness remain unexplained.

Many theoretical [21–25] and numerical [15,26–29] derivation of the acoustic streaming has been reported so far. The main targets of those reports are the streaming in an open domain (Eckart streaming [30]) or an acoustic resonant tube [21]. The numerical difficulty to simulate acoustic streaming in the ultrasonic pump exists in the fact that the thickness of the gap between the tube and the vibrating surface 10–50 μm is far smaller than the wavelength of 80 mm in the fluid at 18 kHz. To obtain convergence of the acoustic or fluid transient analysis, the temporal division in a period must be larger than the spacial division in a wavelength [31]. Thus, the calculation must be performed at least several ten-thousand times in one cycle of the ultrasonic vibration for a hundred periods, so that the static pressure and streaming become stable, because the gap is several-ten-thousandths of the wavelength. Simultaneously, the ultrasonic vibration amplitude is so large compared to the gap that the change in the structure caused by the vibration is no longer negligible. Therefore, the phenomenon cannot be considered with only simple fluid dynamics simulations.

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Recently, parallel computing techniques using cores of graphic processing units (GPUs) or general purpose GPUs (GPGPUs) are drawing attention as a solution for such computationally burdensome problems. Many parallel computing results of spatial differential equations have been reported; sound field analysis using the finite-difference time-domain (FDTD) method is an especially popular application of the GPU-oriented parallel computing. [15,32,33].

In this study, we simulate the motion of the fluid in the pump under a full fluid-dynamics calculation on the pump that extends the FDTD method by considering the viscous and nonlinear terms. The boundary condition is frequently modified within a period of ultrasound to consider the change in structure brought by ultrasound vibration. The parallel calculation is performed on a GPU, which enabled us to finish the calculation within 24 h.

2. Schematic view of ultrasonic pump

Fig. 1 shows a schematic view of an actual ultrasonic pump that uses a vibrating piston surface and a pipe. A longitudinal bolt-clamped Langevin transducer is combined with an aluminum straight horn. The bolt-clamped Langevin transducer is 130 mm in length and 50 mm in diameter. The straight horn is 131 mm in length and 50 mm in diameter. A water tank is attached at a node of the horn. The aperture diameter of the water tank is 90 mm. An aluminum pipe is installed perpendicularly to the vibrating piston surface with a small gap. A silicone rubber tube is connected to the aluminum pipe for observing the water height. The distance from the vibrating piston surface to the water surface in the water tank is 2 mm. If the piston vibration is activated at the fundamental resonance frequency of the transducer (18 kHz), we can see that water is directed into the pipe. The pump performance is evaluated in terms of the pump pressure P and flow rate Q. In this case, the vibration amplitude of the piston vibration is discussed mainly in the peak-to-peak case of $\xi = 3.5$ μm. The gap thickness g, i.e., the distance between the tube and the surface, is discussed mainly in the case of $g = 10$ μm.

3. Governing equations and analysis procedure

The flow rate of the ultrasonic pump Q is expressed in cylindrical coordinate using the dynamic velocity $\boldsymbol{u}(t)$, density $\rho(t)$ and acoustic streaming U as [25]

$$Q = \iint_S U dS = \int_0^g 2\pi r U_r dz, \tag{1}$$

$$\boldsymbol{U} = \frac{1}{T}\int_T \frac{\rho(t)\boldsymbol{u}(t)}{\rho_0} dt, \tag{2}$$

where ρ_0 is the density without any sound at room temperature, T is a time duration much longer than the ultrasonic period and shorter than the characteristic time of a change in streaming, S is the sectional area at the gap between the vibrating surface and the reflector. The static pressure of the pump P is determined from the flow rate characteristics against the external pressure.

Therefore, the time waveforms of $\boldsymbol{u}, p$, and ρ need to be calculated from three compressible fluid equations, namely, continuity, Navier–Stokes, and state of fluid [24,25,34]:

$$\frac{\partial \boldsymbol{q}}{\partial t} + \frac{1}{r}\frac{\partial (r\boldsymbol{E})}{\partial r} + \frac{\partial \boldsymbol{G}}{\partial z} = 0, \tag{3}$$

where,

$$\boldsymbol{q} = \begin{Bmatrix} \rho \\ \rho u_r \\ \rho u_z \end{Bmatrix}, \tag{4}$$

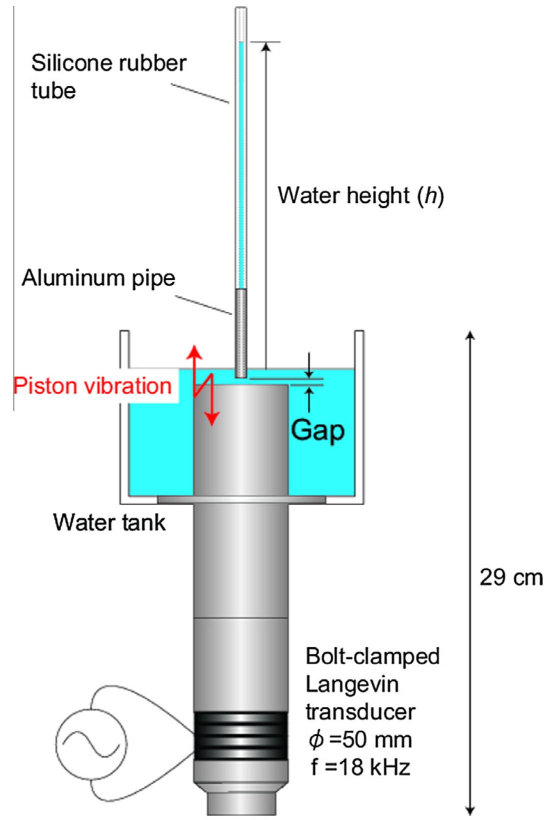

Fig. 1. Basic structure of the ultrasonic suction pump.

$$\boldsymbol{E} = \begin{Bmatrix} \rho u_r \\ \rho u_r^2 + \tilde{p} - (\partial u_r/\partial r)/Re \\ \rho u_r u_z - (\partial u_z/\partial r)/Re \end{Bmatrix}, \tag{5}$$

$$\boldsymbol{G} = \begin{Bmatrix} \rho u_z \\ \rho u_r u_z - (\partial u_z/\partial z)/Re \\ \rho u_z^2 + \tilde{p} - (\partial u_z/\partial z)/Re \end{Bmatrix}, \tag{6}$$

$$p = (\rho - 1) + \frac{B}{2A}(\rho - 1)^2 + \frac{(c_p/c_v) - 1}{RePr}\mathrm{div}\boldsymbol{u}, \tag{7}$$

$$\tilde{p} \equiv p + \frac{1}{Re}\left(\frac{1}{3} + \frac{\zeta}{\eta}\right)\mathrm{div}\boldsymbol{u}, \tag{8}$$

$$Re \equiv \frac{\rho_0 c\lambda}{\eta}, \quad Pr \equiv \frac{\eta c_p}{\kappa}. \tag{9}$$

All equations are normalized by the wavelength for the length, the ultrasonic cycle for the time, sound speed of air c for the velocity, density without sound in air ρ_0 for the density, and $\rho_0 c^2$ for the pressure. $\eta, \zeta, Re, B/A, c_p, c_v, \kappa$, and Pr are the shear and bulk viscosity coefficients, Reynolds number, acoustic nonlinear parameter of water, isobaric and isochoric specific heats, thermal conductivity, and Prandtl number of water, respectively.

Eq. (3) is discretized with second-order accuracy for the time and fourth-order accuracy for the domain; both domain terms are discretized in the central difference scheme while the convection term is discretized in the upwind difference scheme under the staggered grid. The FDTD calculation is performed under the Yee algorithm [31]. Table 1 shows the material properties used for the calculation [34–38].

To ensure the stability of the calculation, this calculation scheme requires a certain amount of attenuation. The Reynolds number of the grid, $R_g = Re/N_x$, must be smaller than 1000 in this scheme, where N_x is the number of space divisions in a wavelength. The typical numerical measure to sustain calculation under