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Numerical simulation of compressible fluid flow on an ultrasonic suction pump

圧縮性流体計算による超音波液流ポンプ揚水特性解析

Yuji Wada[1 ‡], Daisuke Koyama, and Kentaro Nakamura[1] ([1]P&I Lab. Tokyo Tech; [2]Fac. Sci. & Eng., Doshisha Univ.)
和田有司 [1 ‡]，小山大介 [2]，中村健太郎 [3] ([1]東工大・精研, [2]同志社大・理工)

1. Introduction

In recent years, miniature fluidic pumps have been in great demand in the fields of cooling systems, liquid-dispensing systems, fuel delivery systems for miniature fuel cells, artificial heart pumps, and medical apparatus. Conventional electromagnetic pumps have had difficulties in miniaturization and in the suppression of electromagnetic noise.

The authors have been investigating the phenomena associated with an ultrasonically vibrating pipe dipped in water. If the end of a thin pipe is located perpendicularly near a piston-vibrating surface which is immersed in a fluid, the fluid rises 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. Despite these studies, the working mechanism of the generation of static pressure and flow has not been elucidated[1].

In this study, we simulated the motion of the fluid in the pump under a full-fluid dynamics calculation on the pump, which is an extension of FDTD method by considering the viscous and nonlinear terms. Boundary condition is frequently modified within a period of ultrasound to consider the change in structure brought by ultrasound vibration.

2. Structure

Fig. 1 shows a schematic view of an actual ultrasonic pump using a piston-vibrating surface and a pipe. 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 equipped with a node of the horn. The aperture diameter of the water tank is 90 mm. An aluminum pipe is installed perpendicularly to the piston-vibrating surface with a small gap. If the piston vibration is activated at the fundamental resonance frequency of the transducer (18 kHz), we can see that water is sucked into the pipe. The pump performance is evaluated in terms of the pump pressure and flow rate.

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wada@sonic.pi.titech.ac.jp

3. Calculation model

Fig. 2 shows the calculation regions of fluid analysis. Since the pump has the axisymmetric structure, the calculations are performed in axisymmetric-two-dimensional model. Calculation space domain is set to the region of r < 7.5 mm, 0 mm < z <1 mm, which is smaller than the actual fluid domain considering calculation cost. Calculation space is divided in Δr = 10 μm-grid in radial direction, and Δz = 1 μm-grid in height direction, which is 1/83,333 of the wavelength in water at 18 kHz. Therefore, calculation time step Δt is set to be 156,250 per period.

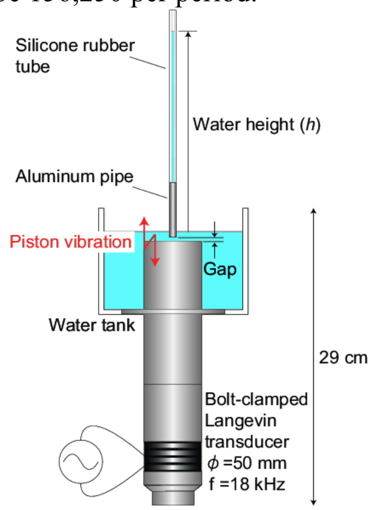

Fig. 1 Configuration of the ultrasonic pump.

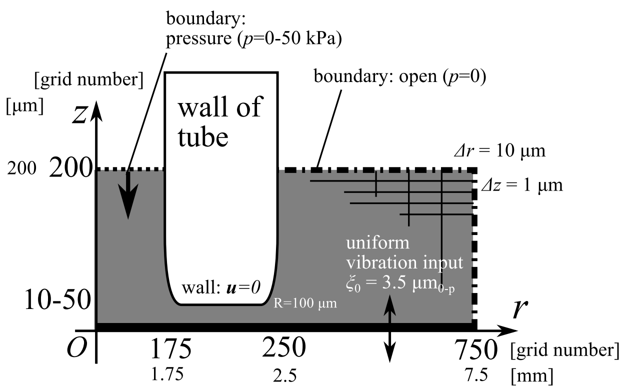

Fig. 2 Calculation model in cylindrical coordinate.

For the driving conditions, the vibration surface plane, which is initially located at z=0, is set to have the uniform velocity amplitude $v=A\omega \sin\omega t$. In addition to that, the vibration surface moves up and down periodically along the z-direction, corresponding to the change of the structure for fluid calculation. Since there is the grid division Δz = 1 μm, the position of the vibration surface front z_f is defined only at discrete positions and can be expressed using round-off function as:

$$z_f(t) = -round\left[\frac{A}{\Delta z}\cos\omega t\right]\Delta z \qquad (1)$$

As to the other tube end, which is located on outer boundary, external pressure of 0-5 kPa was set to express the reverse pressure and calculate characteristics in static flow and static pressure.

The compressible fluid calculation considering viscosity and nonlinearity [2] under Yee-FDTD algorism [3] is carried out for 50 periods, which is 5.5 ms and 5,812,500 time-steps, and then, the final values for static variables are used for plotting the results. Fluid calculations are performed in parallel on a GPU board NVIDIA Tesla M2070, which is on TSUBAME 2.0, a supercomputer of Tokyo Tech. Total time elapsed for the calculation was 12 hours for one analysis.

4. Results

Fig. 3 shows the calculation results of the waveforms for the velocity and its low-pass filtered results. Due to the nonlinearity, the waveform was distorted into N-shape and the static component of the velocity as large as the wave amplitude has appeared. **Fig. 4** shows the instantaneous fluid velocity distributions at the phase of 0, π/2, π and 3π/2 in a cycle. The velocities at the phase of 0 and π are almost symmetric; however, the gap is open in the phase of flow-in (π/2) while the gap is almost closed in the phase of flow-out (3π/2). This motion acts as a check valve. As a result, in **Fig. 5**, static flow channel toward the center of the pump can be observed. **Fig. 6** shows the calculated flow rate for various external pressures. Compared to the measurement results, flow rate are in good agreement, though static pressure is several times larger due to the higher viscosity assumed for the purpose of convergence of the calculation.

5. Conclusion

Fluid analysis on an ultrasonic suction pump was carried out where the nonlinear term and the active moving wall boundary condition was considered. As a result, pump suction mechanism was well simulated through the calculation.

References

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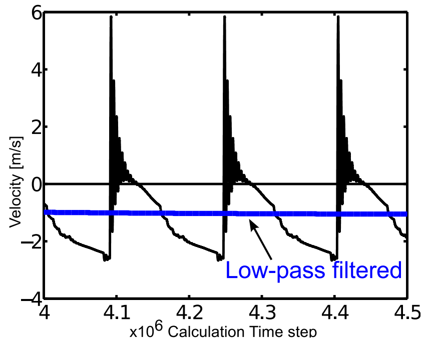

Fig. 3 Temporal waveform of the velocity

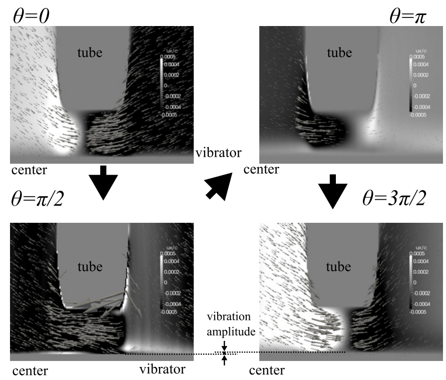

Fig. 4 Instantaneous velocity distribution

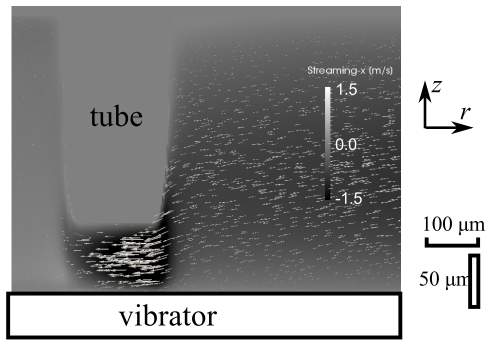

Fig. 5 Static velocity distribution

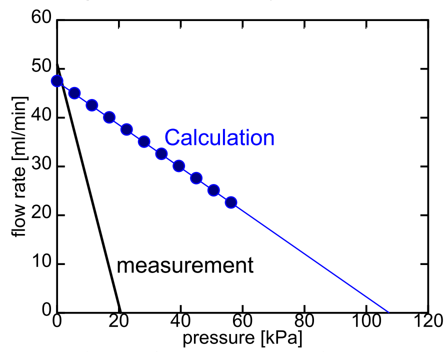

Fig. 6 Flow rate vs. static pressure