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Qualitative analysis of vibrating air columns by 2-dimensional computer simulation for visualization of acoustic waves.

音波の２次元可視化計算機シミュレーションによる､振動する気柱の定性的解析

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1. Introduction

Behavior of acoustic waves in air was well investigated[1)]. Especially, acoustic resonance of air in tubes i.e. air columns is one of elementary physics. However, the resonance still includes unknown terms. One of them is acoustic reflection at open-end of tubes. The reflection at two ends of tubes owes important part of mechanism of the resonance. It seems that mechanism of the reflection at open-end is not clarified yet. Another of the unknown is open-end correction. It seems to be an empirical correction method to accommodate the fact that the resonance frequency is lower than what is calculated from length of a tube. Viscoelasticity of air has been considered as source of the retardation of acoustic velocity, however, it is still under discussion.

To investigate those mechanisms, we used computer simulation for acoustic wave propagation in solid. The simulation method which is called Improved-FDM[2)], was developed for visualizing ultrasonic behavior in solid and it assists ultrasonic measument of non-destructive testing. We calculated propagation of acoustic wave in tubes, and succeeded to visualize acoustic behaviors at air-columns[3)]. By the investigation of the results, important characteristics of acoustic waves in air were revealed.

2. 2-Dimensional Computer Simulation for Acoustic Waves in Air-columns

Acoustic waves excited and propagating in a tube with closed and open ends were calculated as shown in **Fig. 1**. It shows snapshot images of volume strain of air in gray-scale in which white indicates expansion and black indicates compression. The waves were excited by sinusoidal stress pulse introduced at center of the tube.

In Improved-FDM, air is treated as solid which has stiffness matrix (elastic tensor) satisfying Pascal's law[2)]. Calculation parameters of air are

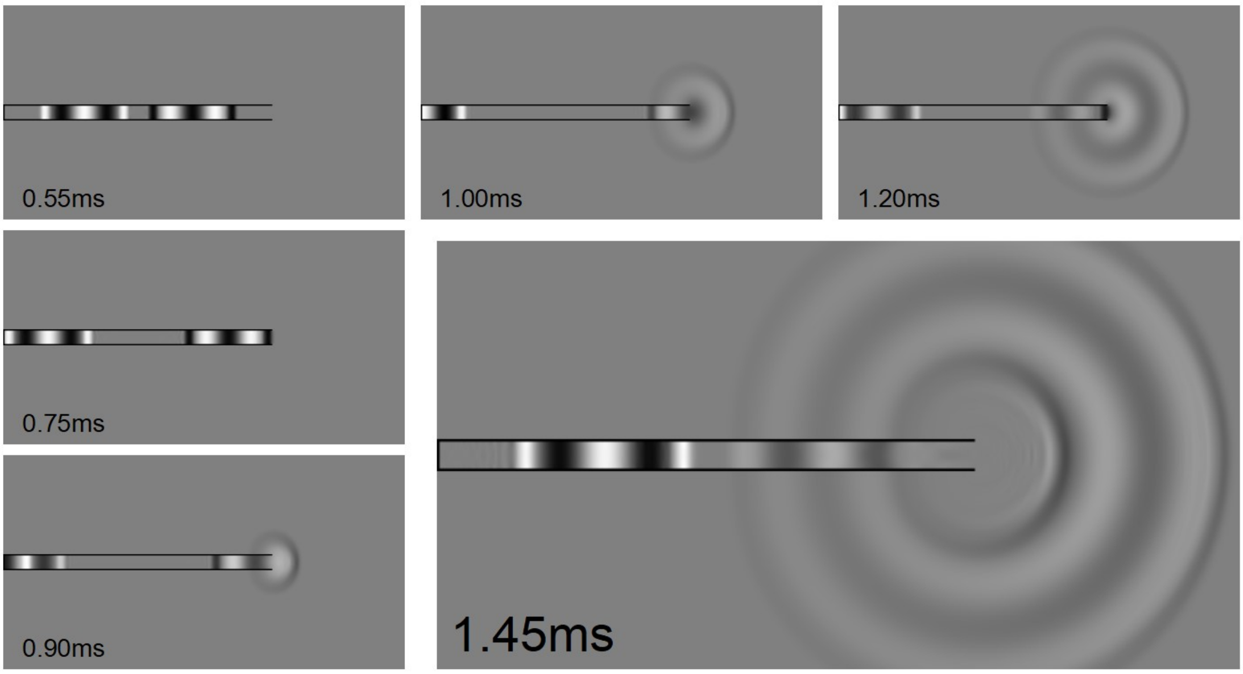

Fig. 1 Volume strain snapshot images of acoustic waves propagating in a tube, obtained by 2-D calculation. Tube is 0.5m long and 25mm in inner diameter. The wave is sinusoidal with 4kHz frequency and 2 cycles. Times in images show elapsed time after start of wave excitation.

density ρ=1.2kg/m^3, and a stiffness component C_{11}=1.39x10^{5}Pa. Walls of tubes are treated as rigid body with parameters of ρ=2.37x10^{6}kg/m^3, C_{11}=2.74x10^{11}Pa and C_{44}=8.20x10^{10}Pa. Finenesses of FDM are spatial step Δx=0.5mm and time step Δt=0.5μs.

In the figure, it is obvious that wave reflection at open-end of the tube occurres in conjunction with emitting and spreading wave. By precise observation, phase inversion in the reflected wave are recognized in contrast with reflected wave at closed-end. This result shows good agreement with common knowledge about acoustic resonance of air-column, qualitatively.

Fig. 2 shows calculated results for different diameters of tubes. It shows two significant phenomena of acoustic waves in tubes. The one is unique diffraction at open-end of tubes. In the images for large diameters, it is obvious that reflection waves from open-end is constructed with reversely diffracted waves at two edges of the open-end. As for the circular diffracted wave, the wave is seamlessly constructed with waves diffracting forward with no phase change, and waves diffracting backward with phase inversion.

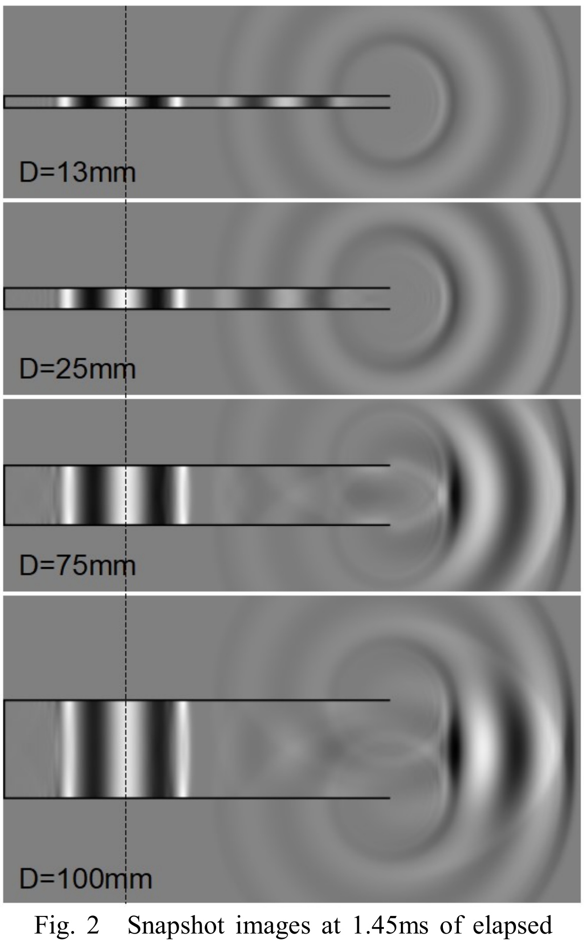

Fig. 2 Snapshot images at 1.45ms of elapsed time for 4 diameters of tubes.
Vertical dotted line is a mark for comparing positions of each acoustic wave reflected at closed end.

The other is velocity retardation of acoustic wave in narrow tubes. By comparison between positions of each wave reflected at closed-end, difference of wave velocities is recognized. It is also recognized with positions of wave front of emitting wave from open-end. Previously, such retardation had been considered effect of viscosity of air. however in the calculation, no viscoelastic term is included. From additional calculations not shown here, a kind of wave reflection was observed at wall boundary. It is similar to mode conversion from longitudinal wave to shear wave in solid surface. Therefore, it can be considered that, at wall boundary, conversion from longitudinal wave propagating parallel to wall to longitudinal wave propagating perpendicular to wall is occurred, and its reduction of the wave propagating parallel to wall causes the retardation.

3. Conclusions

Using elastic solid model for air satisfying Pascal's law, reflection of acoustic wave at open-end of air-column was visualized in computer simulation, successfully. In addition, significant knowledge was obtained about diffraction of acoustic wave in air, and velocity retardation of the wave in air-column. Obtained results can be expected to utilizing for explaining mechanism of various phenomena about acoustic wave in air.

References

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