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Study of surface wave propagation analysis of body tissue with cylindrical structure

Yunfeng Lu[1]‡ and Marie Tabaru[2]（IIR, Tokyo Tech）

1. Introduction

Recently, studies of elasticity measurements using high-frequency airborne ultrasound[1)] and optical coherence tomography systems[2)] based on the propagation properties of surface waves have been carried out.

In order to study how blood vessels in body tissue influence to surface wave velocity, Refs. 2 and 3 substitute blood vessels in body tissue with copper wire inserted into agar. The measurement results show that the surface wave velocity becomes smaller than the actual velocity. However, it is not clear how the depth and diameter of the copper wires affect the surface waves. Since it is necessary to change the diameter and depth of the copper wire to conduct multiple experiments and the experimental error may be relatively large. In this report, we used the velocity-stress finite-difference method[4)] to investigate shear wave propagation properties near the surface of body tissue where cylindrical structures are present.

2. FDTD simulation

2.1 Velocity-stress FDTD method

We performed two-dimensional finite difference time-domain simulation using the Navier-stokes equations[5,6)]. Furthermore, we eliminate the effect of boundary reflections by PML (Perfectly Matched Layer). Equations (1)-(3) are partial formulas used in PML. In Eqs. (1)-(3), the particle velocity v_x is divided into v_{xx} and v_{xy} in the x and y direction, respectively. σ_x and σ_y are the damping coefficients in the x and y directions, respectively. ρ is mass density, σ_{xy} is stress tensor, Δh is space grid interval, and Δt is time interval. The wave is gradually attenuated by substituting these equations for Navier-stokes equations in PML. Then the effect of boundary reflections has been eliminated.

$$v_{xx}{}^{n+1}|_{i,j} = \frac{(2-\sigma_x|_{i,j}\cdot\Delta t)}{(2+\sigma_x|_{i,j}\cdot\Delta t)} v_{xx}{}^{n}|_{i,j} \tag{1}$$

$$v_{xy}{}^{n+1}|_{i,j} = \frac{(2-\sigma_y|_{i,j}\cdot\Delta t)}{(2+\sigma_y|_{i,j}\cdot\Delta t)} v_{xy}{}^{n}|_{i,j} + \frac{2\Delta t}{(2+\sigma_y|_{i,j}\cdot\Delta t)} \frac{1}{\rho\cdot\Delta h} (\sigma_{xy}^{n}|_{i,j+½} - \sigma_{xy}^{n}|_{i,j-½}) \tag{2}$$

$$v_x{}^{n+1}|_{i,j} = v_{xx}{}^{n+1}|_{i,j} + v_{xy}{}^{n+1}|_{i,j} \tag{3}$$

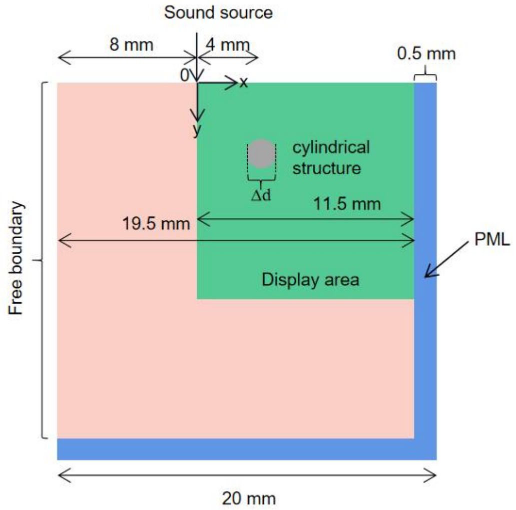

Fig. 1 Geometry of FDTD simulation.

2.2 FDTD simulation of shear wave propagation near body tissue surface with cylindrical structure

Velocity-stress FDTD simulations of shear waves near the surface of body tissue with cylindrical structure were performed. **Fig. 1** shows the geometry of FDTD simulation. The copper wire was set to x = 4 mm and y = 1.5 mm, and the radius of copper wire $\Delta d/2$ was changed by 0, 0.06, 0.12, 0.18, 0.24, and 0.30 mm. The simulation parameters were set to space grid interval Δh = 1.0×10^{-5} m, time interval Δt = 1.0×10^{-6} s and transverse wave velocity c_s = 3 m/s. Since the transverse wave velocity is 5% faster than the surface wave velocity in body tissue, the surface wave velocity can be calculated to $c_s{}'$ = 2.86 m/s. Modulus of rigidity and viscosity were referred to Ref. 4.

Stress V_{pp} = 2 N was applied at t = 0 ms with burst sine wave (2 kHz, 3 waves) to body tissue with cylindrical structure as initial sound source. The surface wave phase velocity was calculated by using Eq. (4), where ω is the angular frequency, Δd = 0.01 mm is the distance between two points, and $\Delta\varphi$ is the phase difference between the two points.

$$V_p = \frac{\omega\Delta d}{\Delta\varphi} \tag{4}$$

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lu.y.an@m.titech.ac.jp

3. Result and discussion

Fig. 2(a) and **2(b)** show the propagation characteristics of shear waves at t = 2.7 and 4.2 ms by visualizing the stress, σ_{xy}, of the simulation results with grid plots (area: the display area in **Fig. 1**). **Fig. 2(a)** illustrates that the waves are almost completely reflected at the cylindrical structure.

Fig. 3 shows the calculation results of the surface wave phase velocity under cylindrical structures of different diameters. At the cylindrical structure, i.e. at x = 4 mm, the surface wave velocity is less than c_s' = 2.86 m/s (without the cylindrical structure). The results show that the surface wave velocity is affected by the cylindrical structure, and the influence increases with the increase of the diameter of the cylindrical structure. Although the trend that the surface wave velocity near the cylindrical structure first decreases and then increases in the calculation results is roughly consistent with the conclusion of Ref. 4, however the position of the cylindrical structure is slightly different in the picture. The difference is considered to be caused by the introduction of the calculation formula of the phase velocity of Eq. (4).

4. Conclusion

Through velocity-stress FDTD simulation, the influence of cylindrical structure on the shear wave propagation characteristics of body tissue surface was successfully obtained, and the specific changes were preliminarily confirmed. This phenomenon will be theoretically deduced, and the effects of cylindrical structures of different depths and sizes in body tissue on the surface wave velocity will be obtained and confirmed through experiments.

References

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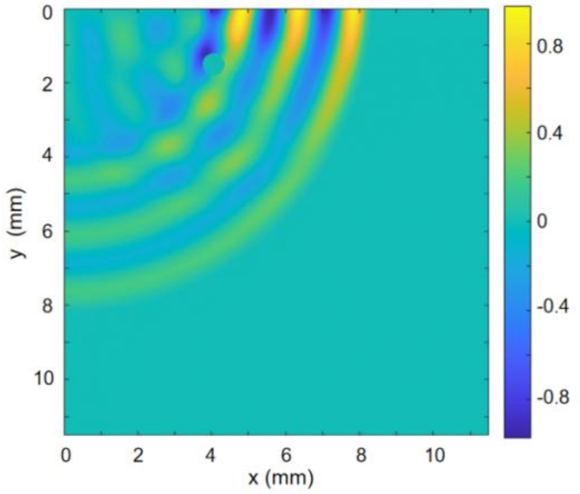
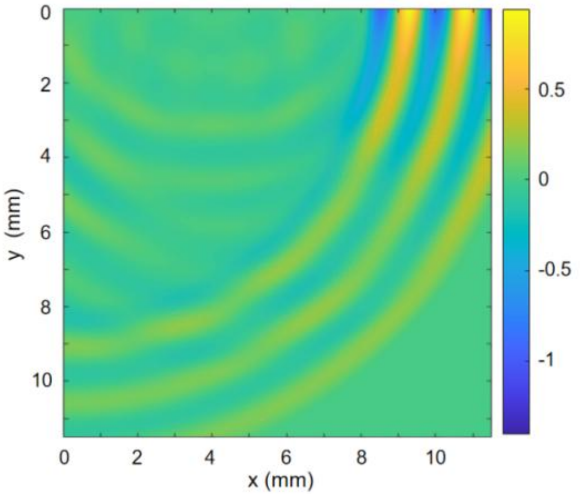


(a) t = 2.7 ms



(b) t = 4.2 ms

Fig. 2 Mesh plots of stress calculated by FDTD simulation.

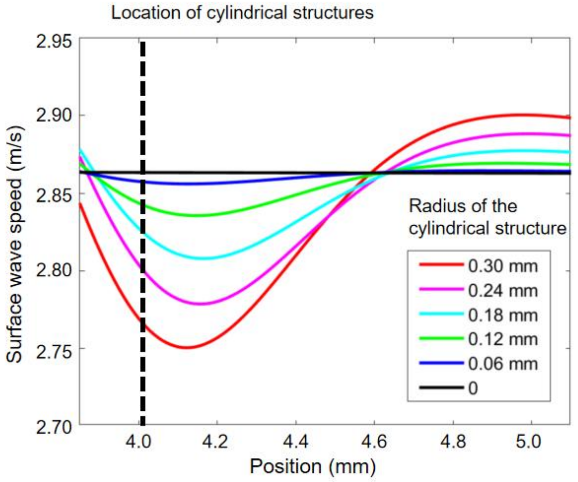


Fig. 3 Surface wave velocity when the cylindrical structure is at x=4.0 mm and y=1.5 mm.