Capturing the shear and secondary compression wave: High frame rate ultrasound imaging in saturated foams

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Background, Motivation and Objective

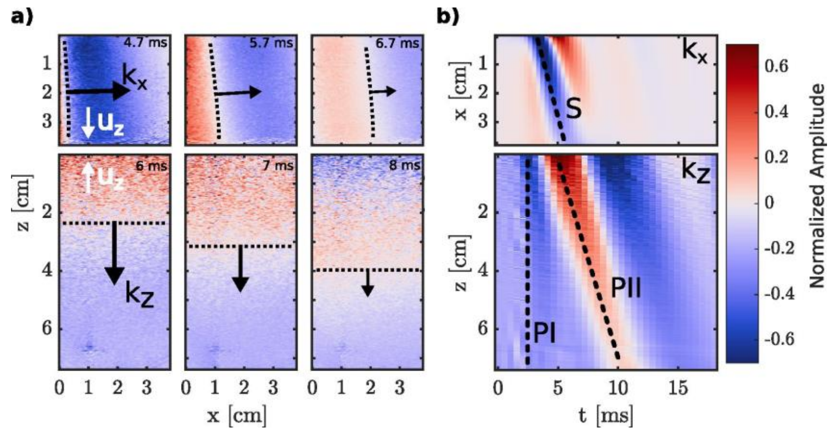
The characterization of wave propagation in porous materials was historically developed in geophysics. Lately, application to bone characterization and the need for noninvasive methods to characterize pulmonary tissue show the importance of poroelasticity in medical imaging. Here, elastography imaging of the lung's surface wave has only recently brought attention to ultrasound characterization of soft porous tissue. In contrast to classical elastic materials, poroelastic materials support three types of elastic waves and exhibit a distinctive dispersion in the presence of viscous fluids. The resulting high attenuation of the shear and slow longitudinal waves pose crucial difficulties for experimental detection. We overcome this challenge by using high frame rate ultrasound imaging for wave tracking inside saturated, highly porous melamine foams.

Statement of Contribution/Methods

We use a Basotect melamine resin sponge, fully immersed in water to ensure complete saturation, as a lung model. A piston excites the shear and slow longitudinal waves in a frequency range from 60 to 600 Hz. The imaging device is a 128-element ultrasound probe centered at 5 MHz and is connected to a high-frame-rate ultrasound scanner. We apply phase-based motion estimation on subsequent beamformed ultrasound frames to retrieve the relative displacement inside the foam in the micrometer range. Through Fourier transformation, we recover phase velocity and attenuation for frequencies between 60 and 600 Hz (shear wave) and between 60 and 150 Hz (slow longitudinal wave). The results are compared to the dispersion prediction by Biot's theory and their quality is accessed by the Kramers-Kronig relations.

Results/Discussion

Both wave speeds are supported by the weak frame of the foam. The first and second compression waves show opposite polarity, as predicted by Biot theory. The shear wave velocity increases from 10 to 30 m/s in the investigated frequency band and shows a good fit with Biot's prediction. This is a strong indicator that the observed dispersion is due to friction between the solid and viscous fluid. Our experiments have direct implications for medical imaging: Melamine foams exhibit a similar microstructure as lung tissue. In the future, combined shear wave and slow compression wave imaging might provide new means of distinguishing malign and healthy pulmonary tissue.



Experimental wave-fields by ultrafast ultrasound and phase correlation: a) Snapshots at three time-steps of a propagating shear wave (S) pulse (top) and slow longitudinal wave (PII) step (bottom). The top row shows the particle velocity and the bottom row shows the z-gradient of the particle velocity. b) Corresponding time-space representation retrieved through summation orthogonal to the x-axis (top) and z-axis (bottom). In the top row, the S-wave (S) and in the bottom row, the first (PI) and secondary compression wave (PII) can be identified. u_z - Direction of particle motion. $k_{x/z}$ - Direction of wave propagation.