Non-contact ultrasound shear wave generation and wave speed measurement in soft tissue

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Abstract: This study investigates the feasibility of non-contact ultrasound shear wave generation and detection using a line focused air-coupled transducer and miniaturized fiber optic-based Sagnac system for soft tissue mechanical characterization. This paper focused on the measuring ultrasound shear wave velocity on a phantom tissue surface. Different phantoms with different stiffness were used as samples. The group velocity and phase velocity of the generated ultrasound surface wave were measured. The results showed that the proposed system was efficient in ultrasound shear wave generation and detection. It has potential applications in non-contact and non-invasive soft tissue mechanical properties characterizations.

1. Introduction

Soft tissue mechanical characterization plays a crucial role in various fields of medicine and biomedical research. The ability to accurately assess the mechanical properties of soft tissues provides valuable insights into their structural integrity and pathological conditions [1]. Traditional techniques for evaluating tissue mechanical properties often involve invasive procedures or direct contact with the tissue, which not only cause uncomfortable, but also may introduce artifacts to the tissue inspection. Hence, there is a growing need for non-contact and non-invasive methods that can accurately measure tissue mechanical properties.

Ultrasound-based techniques have gained significant attention due to their non-invasive nature and real-time imaging capabilities. Among these techniques, shear wave elastography has emerged as a promising tool for assessing tissue mechanical properties. By inducing and measuring propagating shear waves within the tissue, shear wave elastography enables the quantification of tissue stiffness, offering valuable diagnostic information in various clinical applications. Therefore, the primary objective of this paper is to measure ultrasound shear wave propagation in phantom tissues with varying stiffness in a non-contact way. The use of phantom tissues allows us to simulate a range of mechanical properties encountered in different soft tissues.

We utilized a line focused air-coupled transducer and a miniaturized fiber optic-based Sagnac system, enabling non-contact shear wave generation and high-sensitivity detection. By avoiding direct contact with the tissue, our proposed system aims to minimize potential measurement artifacts. The results obtained from this study demonstrate the effectiveness of the proposed non-contact ultrasound system in generating and detecting shear waves in soft tissue. These findings highlight the potential applications of our system in non-contact and non-invasive characterizations of soft tissue mechanical properties. Such advancements have significant implications for clinical diagnosis, treatment planning, and monitoring of various pathological conditions.

2. Line focused air-coupled PZT ultrasound excitation transducer and compact fiber optic Sagnac interferometer for shear wave detection

A piezoelectric cylinder was used to make the line focused air-coupled ultrasound transducer [2,3,4]. The material of this piezoelectric cylinder made with is very close to PZT5-A. It has a strong mechanical strength and a high electrical/mechanical conversion efficiency. The resonant frequency of the piezo cylinder in wall thickness dimension is 1MHz. The wall thickness of the cylinder is 2mm with an inner radius 13mm. To make the line focused air-coupled transducer, the cylinder was cut into a 10mm tall with a 90° span arc shape (Fig. 1). The focal line is 13mm to its inner surface. The focal line width is 0.34mm at diffraction limit. The characteristic acoustic impedance of the piezo material is 3.24×10^7 Rayl, while the air characteristic acoustic impedance is about 417 Rayl. There is a huge difference between them, which hinders the ultrasound wave transmission into air due to the large wave reflection at the interface of the piezo material and air. An acoustic matching layer is needed between piezo material and air to facilitate wave transmission [5]. The matching layer characteristic acoustic impedance should be the geometric mean of the characteristic impedance of piezo and air for the optimal wave transmission, which is 1.15×10^5 Rayl. A porous Nylon membrane with an characteristic acoustic impedance about 3.14×10^5 Rayl, which is close to the ideal value, was used for the matching layer. The thickness of the Nylon is about 180µm, which is also close to the quarter wavelength of the generated ultrasound wave as required. The Nylon membrane was glued to the inner surface of the cut piezo piece to form the acoustic matching layer. Two 26 gauge wires are soldered onto the inner and outer surface of the piezo piece to work as positive and negative electrodes to supply voltage to the piezo piece.

A compact fiber optic Sagnac system was used to detect the shear wave generated by the line focused air-coupled PZT transducer. The core concept in a Sagnac interferometer system is that the two interfering beams have the same optical path for a static surface; while for a vibration surface, the vibration information is encoded in the two interfering beams through a delay line and the vibration speed is detected. The detected signal is directly an acoustic signal, not a displacement signal. The detailed fiber optic Sagnac system principle and construction can be referred to previous papers [6, 7]. In this study, the purpose is to detect the propagation of a shear wave, which has a significant lower frequency range compared to a longitudinal ultrasound wave. The shear wave we are trying to detect is in the range of KHz level. Therefore, we limit our system detection bandwidth to be about 2MHz to reduce the system noise. The bandwidth delay line we used in this system was a 50m long polarization maintained single mode fiber.

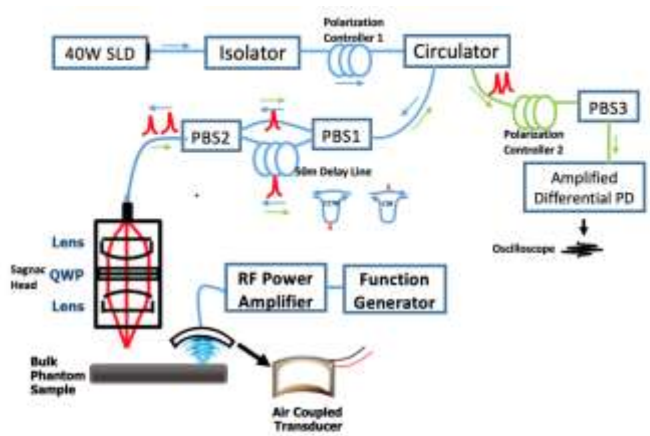

Fig. 1. Non-Contact shear wave generation and detection with air-coupled ultrasound transducer and Sagnac system

3. Shear wave velocity Measurement

Tissue mimicking phantoms with different stiffness were used as samples. The stiffness was controlled by the concentration of gelatin (CAS-No. 9000-70-8, Sigma-Aldrich, Co., 3050 Spruce Steet, St. Louis, MO, USA). Two concentrations were used in this study, 6% and 8% in weight respectively. Titanium Dioxide (Pantai Chemical USA Inc., Alpharetta, GA) was used as optical scatter with a weight concentration of 0.1%. The phantoms were made as cylinder shape with 15mm in height and 100mm in diameter. The ultrasound wave excited on a sample surface is a surface wave in this study.

The overall non-contact shear wave detection system includes the air-coupled ultrasound transducer and compact fiber-optic Sagnac system. The air-coupled ultrasound transducer was used to excite a shear wave that can propagate on the bulk sample surface. The Sagnac system was used to detect the propagating wave. In this experiment, the excitation wave to the air-coupled ultrasound transducer was a sine wave with a linear frequency sweep from 0.825MHz to 1.275MHz with a duration of 200 µs. The product of duration and bandwidth was 90 to optimize the power efficiency and reduce the ring-down effect of the generated ultrasound wave [8]. The excitation source from the function generator (AFG 3022B, Tektronix, Beaverton, OR, USA) has a Pk-Pk voltage of 800mV, then amplified by a RF power amplifier (240 L Power Amplifier, Electronics & Innovation, Ltd., Rochester, NY, USA) with a 50dB gain. The final voltage delivered to the air-coupled transducer is about 250V pK-pK. The excitation repetition rate is 20Hz. During the experiment, the orientation and position of both Saganc detection head and air-coupled ultrasound transducer are tunable, so they can be optimized to focus on sample surface for best signal excitation and detection.

To measure the wave velocity, the excited propagation wave on the phantom surface was recorded by the Sagnac interferometer. A series of waves was recorded at different interval distances between excitation point and detection point. By finding the time delay Δt with the change of the distance Δd, wave velocity can be calculated with $\Delta d/\Delta t$. The original waveform tracking was used to calculate the group velocity, while the dispersive involved phase velocity was calculated through spectrum analysis.

In figure 2, an example of recorded one series of waves was displayed. Total of five waves were recorded with five different intervals between exciting and receiving points. From the first wave to the last wave, each wave is delayed by an extra distance of 0.635mm.

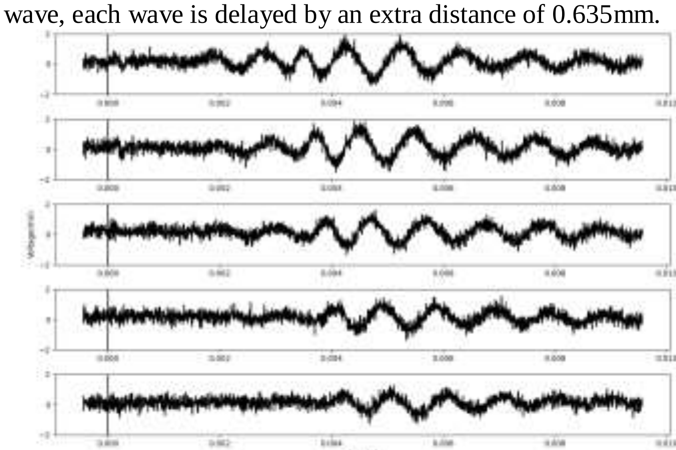

Fig. 2. The five recorded shear waves on the 8% Phantom generated by the focused PZT transducer and measured by the fiber optic Sagnac system, with interval distance of 0.635 mm.

With the recorded waves in a series, to accurately calculate the group velocity, we need to align the waves correctly in order to find a correct time delay due to the change of interval distance between the excitation and receiving points. Cross correlation method was used to align two waves. Here we use an example to illustrate the procedure. To perform cross correlation, we started by computing the correlation between the two waves as a function of the lag between them. Specifically, we slid one of the waves along the time axis and computed the correlation between the two waves at each lag. The result was a correlation coefficient curve (Fig. 3(b)) that showed how similar the two waves were at each lag. The maximum correlation coefficient 0.98 was found at a lag point of 134, which also had a near zero phase difference between two waves. This lag corresponded to the amount of time need to shift for these two waves to have a perfect overlap. This is the time delay that was needed for one wave to travel a pre-set distance and the group velocity could be calculated with the pre-set distance divided by the time shift.

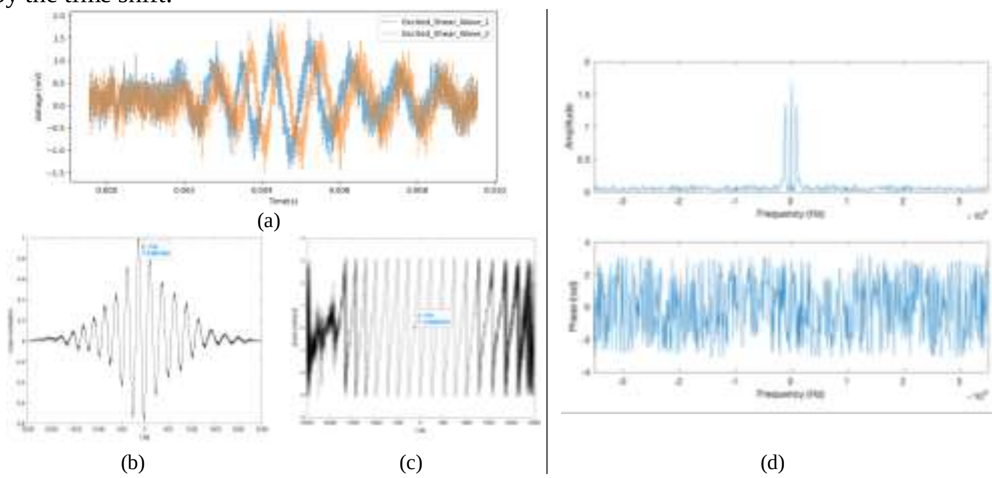

Fig. 3. (a) The two excited shear waves on the 8% Phantom with interval distance 0.635mm. (b) The cross correlation between these two recorded shear waves. (c) Phase difference between these two recorded shear waves. (d) The frequency domain magnitude and phase of the excited shear wave by Fourier transformation.

To calculate the phase velocity of shear waves, Fast Fourier Transform (FFT) method was used. With the FFT, we could obtain the amplitude and phase spectra of a wave in the frequency domain (Fig. 3(d)). We chose the peak amplitude frequency component to calculate phase velocity. From the phase spectrum, we could find the correspondent phase angle of the chosen frequency component. By finding the correspondent phase angle change between two matched wave after traveling the known distance, using the formula $[\Delta\theta/(2\pi)]*\lambda$ = the distance of traveled, where λ is the wavelength, which is phase velocity c multiplying wave period T, the phase velocity c could be calculated since we know the chosen wave frequency.

From the measured propagation waves, it appears that the wave dispersive is not significant, which means the group velocity is likely to be the same as the phase velocity. From the FFT, we could tell that the major frequency component was around 1KHz. So we compared the group velocity with the phase velocity at 1KHz. We used a T-test to do this comparison. T-test method is a statistical hypothesis test that can be used to evaluate whether two groups of data are similar or not.

Table 1. Measured group velocity and phase velocity and the correspondent T-test

T-test Evaluation				
Null hypothesis (H0)	$\mu_{group\_v} = \mu_{phase\_v}$			
Alternative hypothesis (HA)	$\mu_{group\_v} \neq \mu_{phase\_v}$			
6% Phantom	**group_v_mean (m/s)**	**group_v_std**	**phase_v_mean(1KHz) (m/s)**	**phase_v_std**
	2.3905229	0.8093180	2.1062448	0.2513029
	T-statistic	1.4889378	p-value	0.148546
	Accept the Null Hypothesis: $\mu_{group\_v} = \mu_{phase\_v}$ (significance level = 0.05)			
8% Phantom	**group_v_mean (m/s)**	**group_v_std**	**phase_v_mean(1KHz) (m/s)**	**phase_v_std**
	3.3078872	0.4525601	3.3878793	0.81108878

	T-statistic	-0.321555	p-value	0.752565
	Accept the Null Hypothesis: $\mu_{group\_v} = \mu_{phase\_v}$ (significance level = 0.05)			

Here, we used t-test to evaluate the similarity between group velocity and phase velocity in the same sample. Specifically, it tests the null hypothesis that the obtained results of the two groups are equal, against the alternative hypothesis that the obtained results are not equal. Table 1 shows the t-test results. For both 6% phantom and 8% phantom, the results indicated that their group velocity and phase velocity belong to the same data source. Therefore, the T-test concluded that group velocity and phase velocity did not have a significant difference within the same sample.

The measured group velocity and phase velocity at 6% phantom was slower than those in 8% phantom. The higher concentration phantom has higher stiffness, i.e. higher Young's modulus [9]. A higher Young's modulus corresponds to a higher wave velocity. This result is as the expected.

4. Conclusions

To demonstrate the potential capability in the mechanical characterizations of soft biological tissue, we employed phantoms with different mechanical stiffness as samples to study the ultrasound shear wave generation and detection using our home developed line focused air-coupled ultrasound transducer and miniaturized fiber-optic based Sagnac interferometer. The generated shear wave group velocity and phase velocity were measured to study the potential capability of the proposed system in mechanical characterization of soft tissue. The results showed that the system is efficient in wave generation and detection. The expected shear wave can be generated and the generated wave can be detected. Both wave group velocity and phase velocity can be correctly measured. Next, we will study the correlation of the wave group velocity and phase velocity measured by this developed system with the traditional texture analysis system measured mechanical properties.

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