Imaging traveling surface acoustic waves on tissue using holographic interferometry

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Abstract: We evaluate a method for monitoring tissue surface acoustic waves with in-line digital holography without using a phase modulator. The acoustic waves directly modulate the phase and are reconstructed with knowledge of the vibration frequency.
OCIS codes: (090.1995) Digital Holography; (120.7280) Vibration analysis; (170.3880) Medical and biological imaging

1. Introduction

The human body, just like any object, exhibits surface acoustic waves (SAWs) under vibrational excitation. Holographic interferometry is well-suited to study SAWs because it provides nanoscale displacement sensitivity over a wide field of view. Holographic interferometry has been used to study SAW patterns on humans during singing [1], simulated operation of heavy machinery [2], and for breast lesion detection [3, 4]. Most previous methods employed off-axis holography and analysis of the resulting fringe pattern. Electronic speckle pattern interferometry (ESPI) may be considered a specific form of holographic interferometry [5], where an in-line configuration is used to image the speckle pattern, instead of fringes, relaxing requirements on the sensor pixel size. We recently reported a new method for imaging SAWs using an in-line configuration and no active phase-shifting element [6], which was applied to breast tissue-like phantoms. Effectively, the SAWs provide phase-shifting, and knowledge of the vibrational excitation frequency is used to extract the phase of the SAWs modulo π. This allows one to directly measure the SAW phase velocity, which is useful for quantitative elastography for breast cancer detection. Here we study the effects of noise and the use of temporal bandpass filtering on the accuracy of SAW phase reconstructions, both in simulations and experiments on tissue phantoms.

2. SAW Phase Reconstruction Method

The intensity resulting from in-line interference between a reference and sample beam while SAWs with out-of-plane amplitude A_{SAW} propagate across the surface of the sample at temporal frequency ω and spatial frequency k is:

$$I(\vec{r},t) = I_{DC} + I_{AC}\cos\left(\frac{4\pi A_{SAW}}{\lambda}\cos\left(\omega t + \vec{k}\cdot\vec{r}\right) + \varphi(\vec{r})\right)$$

where φ is the stationary speckle. Importantly, the SAW phase term, $\beta_{SAW} = \omega t + \vec{k}\cdot\vec{r}$, provides the phase velocity, $v_p=\omega/k$, which can be directly related to the elastic properties of the tissue [6, 7]. In the limit that $A_{SAW} << \lambda$ we can Taylor expand to show that [6]:

$$\beta_{SAW}(\vec{r},t) \approx \tan^{-1}\left(\frac{I'(\vec{r},t)}{I''(\vec{r},t)}\omega\right) = \tan^{-1}\left(\frac{I(\vec{r},t-\Delta t) - I(\vec{r},t+\Delta t)}{I(\vec{r},t-\Delta t) + I(\vec{r},t+\Delta t) - 2I(\vec{r},t)}\tan\left(\frac{\omega\Delta t}{2}\right)\right)$$

which is the same mathematical expression as temporal phase shifting generally, but instead of providing the optical phase (which is not needed as it only tells us the surface shape), here it provides the SAW phase.

3. Results and Discussion

We performed in-line holographic interferometry on silicone tissue phantoms with embedded TiO2 particles to generate a fully-developed speckle field. A piezo-electric transducer immediately outside the imaging area generated SAWs at 96 Hz, and a CMOS camera collected a time series of interferograms at 3 kHz. The results of the reconstruction method are shown in Fig. 1. As expected, the SAW phase appeared to be linearly ramped with a constant slope, k, as a function of x. The phase map consists of concentric rings centered about the transducer, with sharp discontinuities as it wraps from $\pi/2$ to $-\pi/2$, and the noise appears to be relatively constant over the phase sweep. In comparison, a simulation was performed using $A_{SAW} = \lambda/5$, which is pushes the validity of the small A_{SAW} assumption used in the reconstruction method. Random speckles were simulated across one dimension of a sample.

In this simulation, we found that the reconstructed phase profile is highly accurate near the center of the phase sweep (near 0) but very noisy near $\pm\pi/2$. This noise is directly a result of higher order terms dropped from the Taylor expansion, and is rapidly reduced as A_{SAW}/λ is reduced. Thus, there is a tradeoff between using A_{SAW} large enough to capture the speckle modulation within the dynamic range of the camera, and using A_{SAW} small enough to avoid this noise. Future work to account for higher order terms may alleviate this somewhat. However, we see in practice that other forms of noise are also present and even dominate our experimental phase reconstruction.

We also investigated temporally bandpass filtering I, which is a Bessel function, about a harmonic of ω before performing the phase reconstruction. While this reduced the noise, it required careful choice of the harmonic for each experiment, as it is highly sensitive to A_{SAW}. Future work will be focused on modeling the noise in order to tailor a signal processing technique for the best SAW phase extraction. This will lead to higher accuracy in our elastographic reconstructions for breast cancer detection.

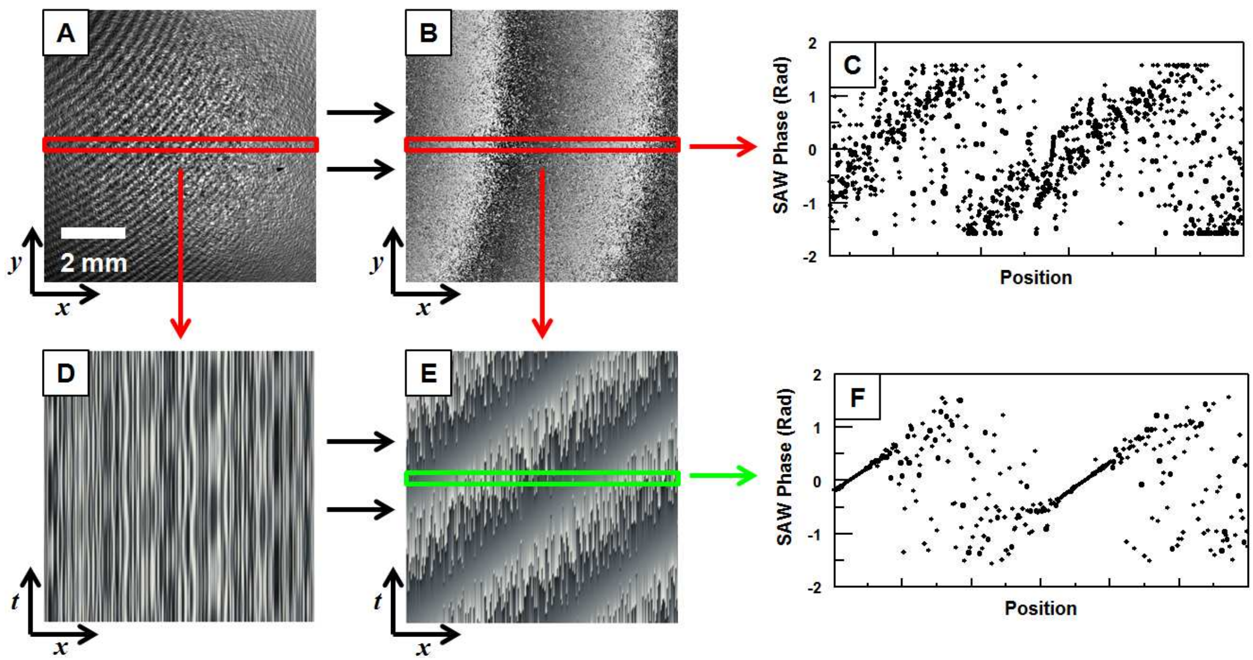

Fig. 1. A) Measured interferogram of a tissue phantom obtained by the camera at a given time. Fringes are an artifact of the cover glass in front of the sensor and are stationary; the dynamic speckle pattern provides the useful signal here. A piezo-electric transducer generates SAWs; it is immediately outside the imaging region to the left. B) Reconstructed SAW phase corresponding to A. C) Plot of SAW phase versus transverse position x corresponding to the central row of B. D) Simulated speckle fluctuation along x over time. E) Simulated reconstructed SAW phase in x over time. F) Simulated SAW phase versus x.

4. Acknowledgements

Related experimental work was carried out by Shiguang Li and Karan D. Mohan at the University of North Carolina at Chapel Hill. This work was supported by startup funds and a junior faculty award at UNC-Chapel Hill.

5. References

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