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Shear Waves Generated with Magnetomotive Force on an Embedded Sphere

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Abstract—**The characterization of the material properties of tissue and tissue mimicking materials has been is an important area of study to develop methods for elasticity imaging. Many methods utilize acoustic radiation force to produce shear waves and to extract elastic or viscoelastic properties of the medium by measuring the propagation of the shear waves. However, the push beam geometry used to generate the shear waves can induce motion that may cause bias for conventional processing methods. Towards the aim of characterizing a medium with a simpler excitation distribution, we propose the use of magnetomotive force on an embedded metallic sphere to generate shear waves. The shear wave motion can be compared with an analytic Green's function for a spherical source. A gelatin phantom with an embedded steel sphere of 2 mm in diameter was placed above an electromagnet with diameter of 101.6 mm. A direct current (DC) voltage was applied for 20 ms to drag the sphere and the motion after the cessation of the excitation pulse was measured. A linear array transducer configured to perform compound plane wave imaging at a frame rate of 3.8 kHz was utilized to measure the shear wave motion. A Green's function simulation was used to compare with the motion induced in the experimental setting. The Green's function and the experimental results are in good agreement. Magnetomotive-generated shear waves could provide a unique tool to characterize material properties without the complications of an acoustic radiation force push beam.**

Keywords—shear wave, magnetomotive force, embedded sphere, Green's function, viscoelastic

I. Introduction

Elasticity imaging is becoming a clinically relevant tool for the diagnosis of various conditions such as liver fibrosis and breast and thyroid cancer [1-3]. Most currently used methods assume that the tissue is elastic and quantify the shear or Young's modulus from measurements of shear wave velocity. However, it has been shown in numerous reports that tissue is inherently viscoelastic and that the shear wave speed can vary with the frequency of the wave, a property called dispersion [4]. Some methods have used this property to characterize the viscoelastic material properties of different tissue mimicking materials or soft tissues [5-8].

There is a growing need to characterize viscoelastic materials that could be used as suitable phantom materials. Many methods have used external vibration [9] or radiation force [10-13]. External vibration methods can often be relegated to low frequency bandwidths, or require expensive equipment and complex inversion schemes. Radiation force-based methods can be complicated by bias produced in the motion related to the push beam geometry. Recently, research studies demonstrated the utility of an embedded magnetic material in tissue-mimicking materials to generate waves for characterization by applying a harmonic or transient magnetic field [14-16].

We propose to embed a sphere in a tissue-mimicking material and use noncontact magnetic excitation to generate shear waves and measure the propagation with high frame rate ultrasound imaging. The measured motion will be fit to a Green's function to extract viscoelastic material properties of the medium.

II. Methods

A gelatin phantom made with an 8% concentration by volume of gelatin (Bloom 300, Sigma Aldrich, St. Louis, MO) with an embedded steel sphere of 2 mm diameter was placed above an electromagnet with an outer diameter of 101.6 mm (EM400-12-212, APW Company, Rockaway, NJ). A steel cone with height 20 mm was placed on the inner core of the electromagnet to concentrate the magnetic field. A DC voltage was applied for 20 ms to drag the sphere and the motion after the cessation of the excitation pulse was measured. A wire with 2 turns was placed around the cone to obtain the temporal behavior of the magnetic excitation related to the magnetic field by measuring the electromotive force, ε, produced in the wire.

$$\varepsilon = -N\frac{d\Phi_B}{dt} = -N \cdot S\frac{dB}{dt}, \qquad (1)$$

where N is the number of turns, Φ_B is the magnetic flux, t is time, S is surface area, and B is the magnetic flux density. The magnetomotive force, F_z, can be calculated using

$$F_z = \frac{V_{sph}\chi_{sph}}{\mu_0} B_z \frac{dB_z}{dz}, \qquad (2)$$

where V_{sph} is the volume of the sphere, χ_{sph} is the volume magnetic susceptibility of the sphere, B_z is the component of the magnetic field in the z-direction which is perpendicular to the magnet surface.

For the purposes of this study, it is important to note that the force on the sphere is proportional to the magnetic field.

The experimental setup is shown in Fig. 1 and the temporal profiles for the excitation and measurement are shown in Fig. 2.

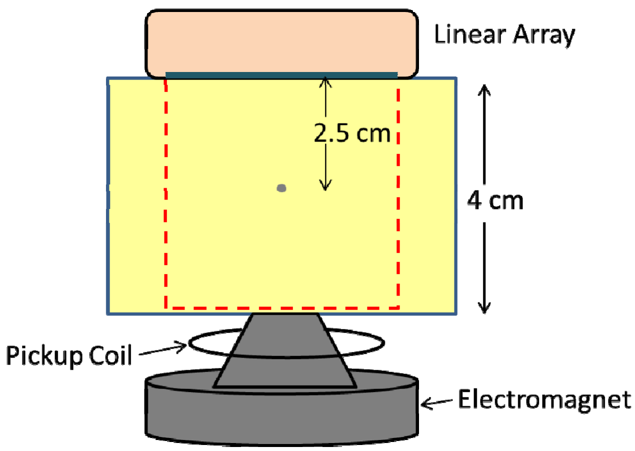

Fig. 1. Experimental setup. Electromagnet underneath the gelatin phantom with embedded steel sphere. A pickup coil is used to measure the electromotive force. The motion is measured with the ultrasound transducer using pulse-echo plane wave imaging.

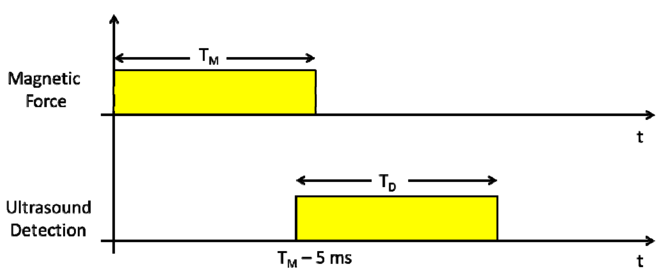

Fig. 2. Timing of magnetomotive force application and data acquisition. The force is applied for T_M = 20 ms and the ultrasound detection is started 5 ms before the end of the magnetic force application and lasted for T_D.

A linear array transducer (L11-4v, Verasonics, Inc., Redmond, WA) driven by a Verasonics V1 system (V1, Verasonics, Inc., Redmond, WA) used compound plane wave imaging with 3 angles with an effective frame rate of 3.8 kHz to measure the shear wave motion [17]. The acquired in-phase/quadrature (IQ) data were processed using a one-dimensional autocorrelation scheme to extract the displacement [18]. A bandpass filter with passband of 100-700 Hz was applied to the displacement signals.

A radiation force experiment was also performed in the gelatin phantom away from the sphere to obtain a measurement of the group shear velocity. The processing of the data was the same as described above. The shear wave group velocity was found using a Radon transform-based algorithm [19].

An analytic Green's function formulation for a spherical source was used to compare with the displacement results [20]. The same temporal excitation was applied for the Green's function for a spherical volume equal to the sphere used in the experiment. The force function was applied as a step function for 20 ms and the response after the excitation was turned off was used for comparison. Additionally, the displacement was filtered with the same bandpass filter as mentioned above.

III. Results

A plot of the signal obtained from the wire around the cone fixed to the electromagnet is shown in Fig. 3. The signal was integrated in time to obtain a relative form for the temporal behavior of the magnetic field. The magnetomotive force is proportional to the magnetic field.

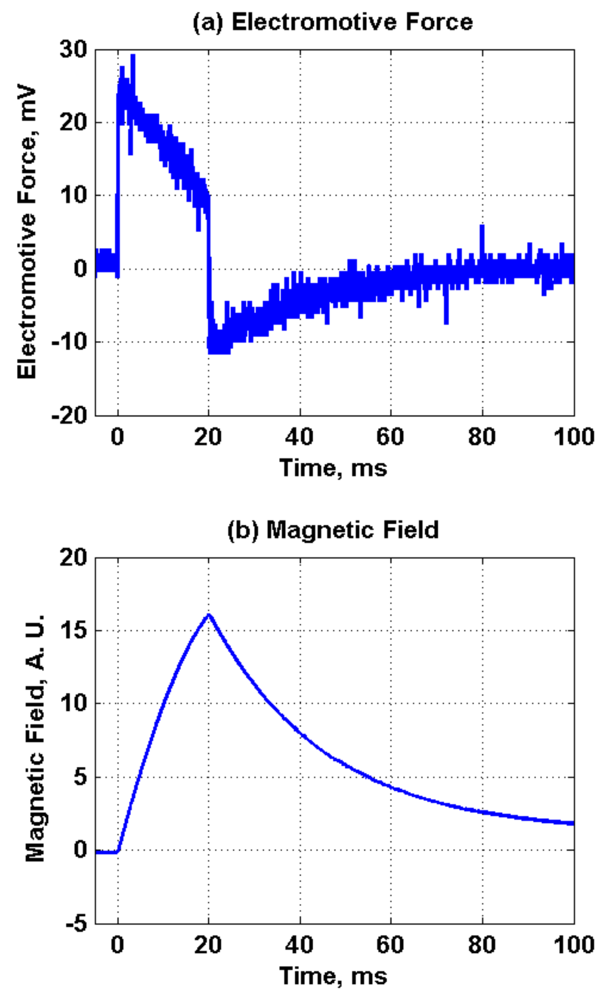

Fig. 3. Measurement of magnetic field. (a) Measurement of electromotive force, (b) measurement of relative magnetic field.

The radiation force experiment that was performed found a shear wave velocity of c_s = 1.65 m/s from three averaged measurements. The axial motion produced lateral to the sphere in the x-direction is shown in Fig. 4 along with the Green's function plot using the group shear wave velocity of c_s = 1.65 m/s from the radiation force experiment and using a shear viscosity of 1.50 Pa·s. Figure 5 shows plots of the motion shown in Fig. 4 for more qualitative comparison. The agreement between the data obtained from the experiment and the analytic Green's function is quite good. The peak motion amplitude found was around <1 µm and the Green's function results were scaled to be close to the experimental results.

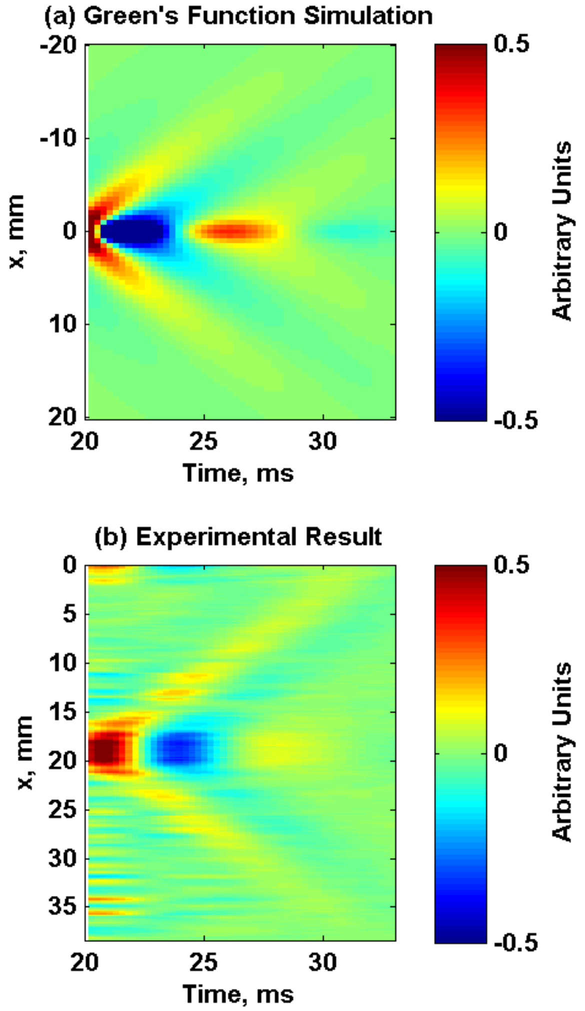

Fig. 4. Comparison of shear wave propagation. (a) Green's function numerical result, (b) experimental result

IV. Discussion

We demonstrated that magnetic excitation of an embedded sphere could be used to characterize the viscoelastic properties of a tissue-mimicking material. The analytic Green's function fitting was used to find the viscoelastic properties after using the group shear wave velocity from an acoustic radiation force measurement.

Other types of models could be used for extracting viscoelastic properties from an experiment similar to what is used in this work. Methods for harmonic or transient excitation could be used either by fitting the time-domain profile as was done here or by examining shear wave velocity dispersion or frequency-domain resonance as has been done in other studies [4, 10].

One limitation of this method is the signal-to-noise ratio because of the low motion amplitudes produced by the magnetic excitation. Larger field magnets or more magnetic spheres could be used to increase the motion [14, 21]. Additionally, it has been shown that optical techniques such as optical coherence tomography (OCT) can be used, but this requires multiple repetitions of the experiment to move the interrogation point for the laser and measurement depth is very limited [15, 16]. The ultrasound method demonstrated here acquired all the data at high frame rate in one acquisition. Data from multiple acquisitions could be averaged together to improve the SNR. The ultrasound can penetrate deeper and is also a nondestructive means of evaluation.

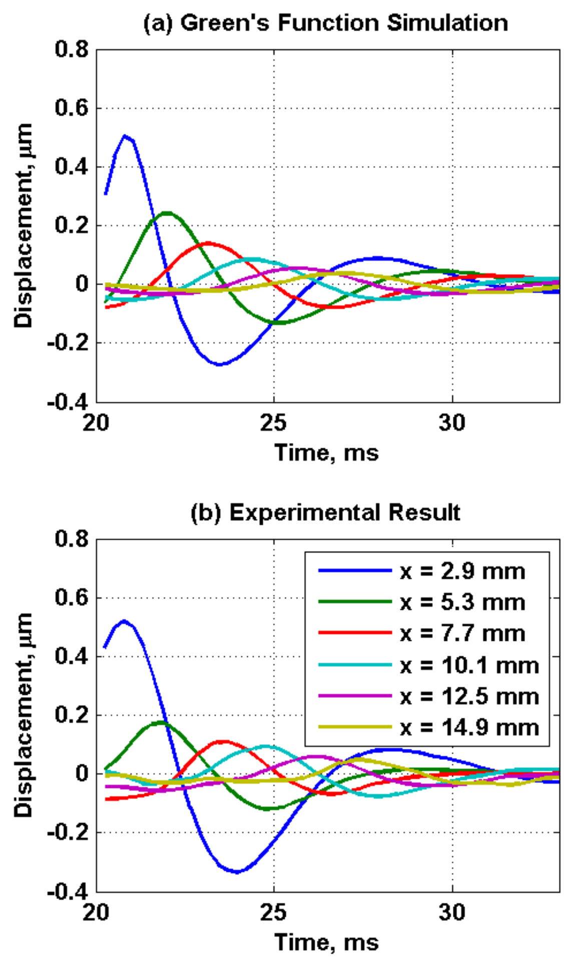

Fig. 5. Comparison of shear wave propagation plots. (a) Green's function numerical result, (b) experimental result.

V. Conclusion

A Green's function formulation was used to compare with the motion induced by a magnetically excited metallic sphere embedded within a gelatin background. The agreement between the Green's function simulation and experimental results is very good. Magnetomotive-generated shear waves provide a unique tool to characterize material properties without the complications of an acoustic radiation force push beam. Combining magnetic and ultrasound methods could provide a low-cost way to evaluate viscoelastic properties of tissue mimicking materials.

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