Quasi-omnidirectional shear wave generation using acoustic vortices for elastography

Enrique González-Mateo
Instituto de Instrumentación para Imagen Molecular (i3M)
Universitat Politècnica de València - CSIC
València, Spain
Corresponding Author, engonma@upv.es

Noé Jiménez
Instituto de Instrumentación para Imagen Molecular (i3M)
Universitat Politècnica de València - CSIC
València, Spain

Francisco Camarena
Instituto de Instrumentación para Imagen Molecular (i3M)
Universitat Politècnica de València - CSIC
València, Spain

***Abstract*—Ultrasound elastography is a reliable tool for medical diagnosis with the aim of finding pathologies that cause tissue stiffness irregularities. Currently, the most used techniques based on acoustic radiation force deform the tissue with a pulse in the direction of beam propagation resulting in linear momentum transfer, producing shear waves in the transverse direction of the beam. In this work we propose using focused acoustic vortices to transfer angular momentum. By twisting the tissue quasi-omnidirectional shear waves can be generated. The goal of this work is to show the first experimental evidence of angular momentum transfer from a vortex to a tissue-mimicking material, and apply this mechanism to improve ultrasound elastography.**

***Index Terms*—Acoustic Vortex, Acoustic Radiation Torque, Tissue twisting, Elastography**

I. Introduction

Elastography is a medical imaging technique used to quantify tissue stiffness that has become very popular in the last three decades. There are several elastography techniques, some of them measure tissue strain caused by an external or internal source of stress [1], and others measure elasticity by quantifying the speed of traveling shear waves, generated by transient acoustic radiation force (ARF) [2]–[4]. For example, in shear-wave elastography [5], ARF is used to deform the tissue producing transverse mechanical waves that propagate at a speed much slower than longitudinal ones. In this technique, tissue is deformed by a transient pushing pulse matching the direction of the ultrasound beam transferring linear momentum to the tissue. This results in the generation of shear-waves in the transverse direction, therefore, elasticity can be estimated around the lateral area. However, other mechanisms can be used to generate shear waves in others directions.

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We propose the use of acoustic vortex beams to twist the tissue, instead of pushing it. An acoustic vortex beam is a longitudinal wavefront containing a phase dislocation at the beam axis. These beams are characterized by a field having a rotating phase in the form $\exp(l\theta)$, where θ is the polar angle and the parameter l is the topological charge, usually an integer. Due to the phase singularity at beam axis, waves interfere destructively, and the field is null. In this way, while they show a helical phase distribution, the intensity pattern of a focused vortex beam shows a focal spot of toroidal shape. Vortex beams can be generated using helicoidal surfaces and phased array sources [11], [12], spiral gratings [6]–[8], or holograms [9], [10]. These beams are of particular interest because their exotic structured wavefront can trap particles, and they have been used as acoustical tweezers for biomedical ultrasound applications, or used for vortex-encoded transceivers for underwater communications. In addition, vortex beams carry angular momentum [13], and recently it was proposed that they can exert a mechanical torque on the tissue. By twisting a soft-tissue internally and in a transient way, the shear-wave wavefront is generated in

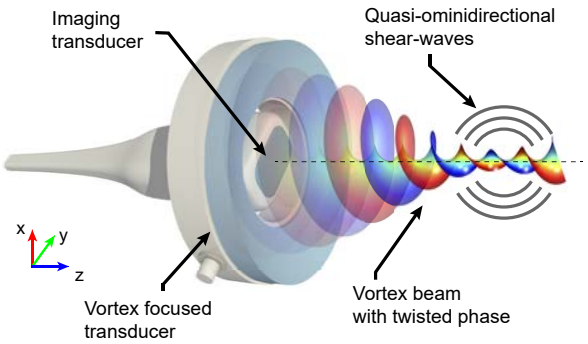


Fig. 1. Conceptual scheme of vortex beam for a custom elastography system application.

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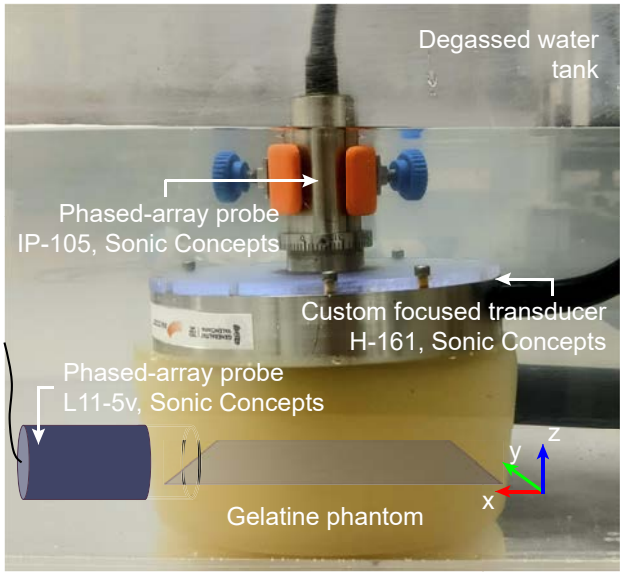


Fig. 2. Experimental set up.

a quasi-omnidirectional way improving the field of view of ultrasound elastography imaging systems [14].

Note that an important challenge in elastographic imaging is to have a robust and wide shear-wavefront information along the target area. Usually, different focal points at different depths in order to generate a flat wavefront are used [15]. Other approaches include using push pulses at different angles and averaging and compounding the information obtained [16], to achieve a more robust composition or to improve contrast and signal-to-noise ratio. Using vortex beams to twist the tissue may be an improvement for this challenge due to the possibility of creating a quasi-omnidirectional pattern in all directions. In this work we present the first experimental results of the patented method [17] for obtaining the elastic properties of a soft solid using acoustic vortices.

II. Methods

A custom probe consisting in a sectorial focused transducer and a concentric imaging probe was developed (Fig. 2). A 16-element sectorial source, 125-mm OD, 50-mm ID, 125-mm ROC (H-161, Sonic Concepts, USA) was used to twist (or push) the tissue by focusing a 700-μs duration and 1.1-MHz pulse-burst at 105.79 mm depth. The tracking pulses were transmitted using a 5.2-MHz, 64-elements imaging probe (IP-105, Sonic Concepts, USA), and a pulse repetition frequency of 4 kHz. B-mode frames are acquired and compounded using plane wave imaging after the ARF excitation. Tissue displacement is estimated by means of two-dimensional auto-correlation [19]. Then, shear wave speed, c_s, was calculated by time-domain tracking and spatio-temporal spectral analysis [20]. Finally, elasticity was calculated as $E = 3c_s^2$ assuming a mechanical model for a homogeneous, elastic, isotropic and incompressible soft tissue.

The acoustic field is calibrated using water tank measurements. The magnitude and phase of the acoustic field is measured with a piezoelectric hydrophone (-225.5 dB re 1 V/μPa at 1 MHz, model Y-104, Sonic Concepts, USA), calibrated from 40 kHz to 2 MHz, attached to a 3D axis system (5 μm accuracy, PI Micos GmbH, Germany). The experimental results are compared with the analytical expressions [14] to confirm the generation of the vortex with the 16-element sectorial source.

A second experiment is performed to validate the angular transfer of the vortex in the tissue. A homogeneous gelatin phantom was manufactured, designed to show a Young's modulus of 60 kPa at room temperature [18]. For this purpose, the shear-wave displacements in the (x, y) plane are measured. A 7.6-MHz 128-elements validation imaging probe (L11-5v, Sonic Concepts, USA) (Fig. 2) placed perpendicular to the acoustic vortex probe z-axis is used with a pulse repetition frequency of 6.6 kHz.

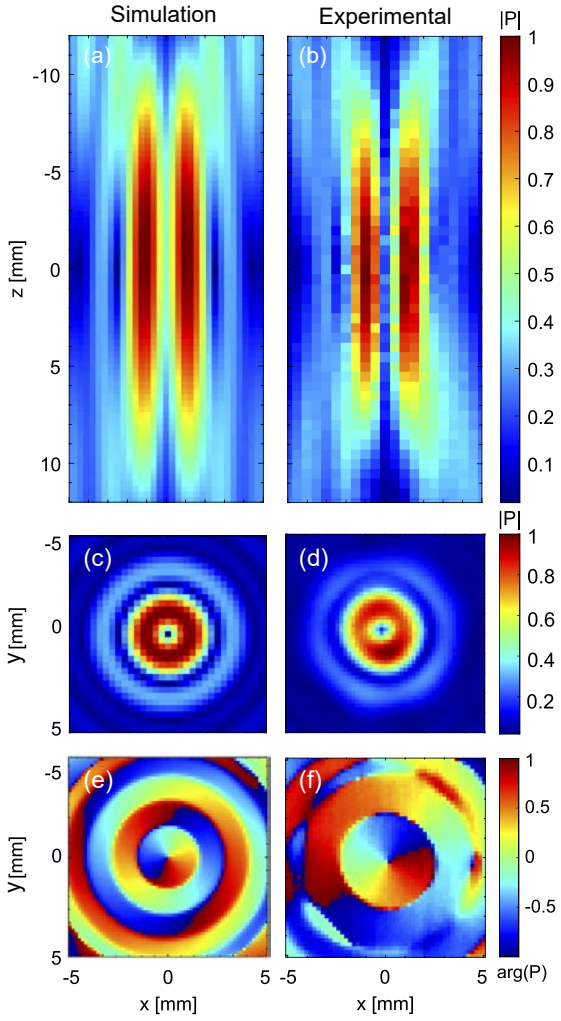


Fig. 3. Magnitude of the (a) simulated and (b) experimental pressure field in the $p = p(x, 0, z)$ plane. Magnitude and phase of the simulated (c) (e) and experimental (d) (f) pressure field in the transverse $p = p(x, y, F)$ plane.

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Finally, Three vortex beams with different topological charges, from $L = 1$ to $L = 3$, were studied, and tissue displacements were compared with those obtained using a conventional push beam ($L = 0$) using an excitation voltage of 45 V.

III. Results

First, the acoustic fields obtained by simulation and experimentally were in good agreement as shown in Fig. 3. The magnitude of the field of the vortex beam generated by the custom sectorial focused transducerfield shows a toroidal structure Fig. 3(a-d). In addition, the field shows a phase dislocation on the axis for a topological charge $L = 1$ in the simulation, Fig. 3 (e), and experimental case, Fig. 3 (f).

Second, shear-wave axial displacements in $x - y$ plane for focused ($L = 0$) and vortex beam ($L = 1$) are compared in Fig. 4. In the focused case, Fig. 4 (a), a quasi-omnidirectional wave can be seen, but this wave only occurs in the transverse direction of the beam. However, in the vortex case, Fig. 4 (b), transferring angular momentum into the medium results in a source of torsional shear-waves where a positive versus a negative wavefront can be seen propagating quasi-omnidirectionally from the focus in all directions.

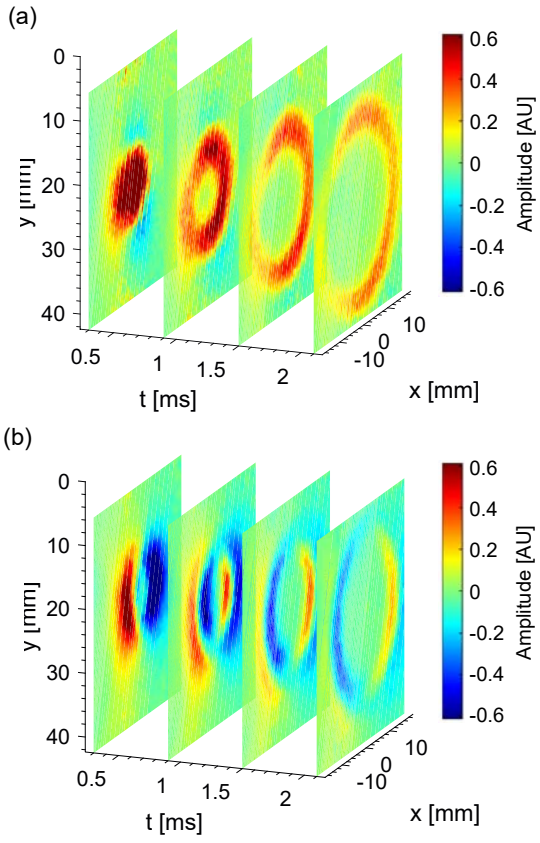


Fig. 4. Shear-wave displacements data (x, y, t) for (a) focused beam and with (b) acoustic vortex of topological charge $L = 1$.

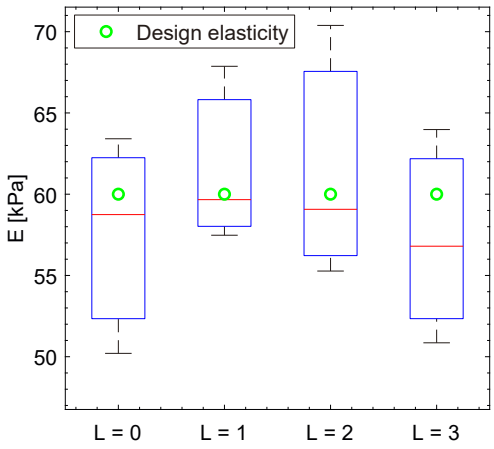


Fig. 5. Box-plot of the measured elasticity of the customized viscoelastic phantom (60 kPa) at different topological charges.

Finally, the elasticity of the gelatin phantom has been analyzed, Fig. 5, and values obtained without topological charge and with different topological charges agree with the design elasticity (60 kPa) with relative errors between 3% and 5%.

IV. Conclusions

We have designed and experimentally characterized a customized elastography system based on vortex acoustic beams. It has been shown that, due to its angular momentum transfer capability, acoustic vortices allow the generation of quasi-omnidirectional waves that cover a wider area in comparison with conventional push beams. Furthermore, it has been proven that elasticity values calculated with and without vortex beam have small relative errors.

By using focused torques, shear waves are generated with a quasi-omnidirectional radiation pattern, extending both, the field of view, and the angular spectrum of the displacement field in a controlled manner. These finding pave the way to improve two-dimensional elasticity mapping techniques using spectral methods.

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