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A novel two-axis micromechanical scanning transducer using water-immersible electromagnetic actuators for handheld 3D ultrasound imaging

Chih-Hsien Huang, Jun Zou*

Department of Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843, USA

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ABSTRACT

This paper reports the development of a new two-axis micromechanical scanning transducer for handheld 3D ultrasound imaging. It consists of a miniaturized single-element ultrasound transducer driven by a unique 2-axis liquid-immersible electromagnetic microactuator. With a mechanical scanning frequency of 19.532 Hz and an ultrasound pulse repetition rate of 5 kHz, the scanning transducer was scanned along 60 concentric paths with 256 detection points on each to simulate a physical 2D ultrasound transducer array of 60 × 256 elements. Using the scanning transducer, 3D pulse-echo ultrasound imaging of two silicon discs immersed in water as the imaging target was successfully conducted. The lateral resolution of the 3D ultrasound image was further improved with the synthetic aperture focusing technique (SAFT). The new two-axis micromechanical scanning transducer does not require complex and expensive multi-channel data acquisition (DAQ) electronics. Therefore, it could provide a new approach to achieve compact and low-cost 3D ultrasound imaging systems, especially for handheld operations.

1. Introduction

Ultrasound imaging (2D or 3D) has become a useful non-destructive diagnostic technique with a wide range of applications [1,2]. To conduct 3D ultrasound imaging, the time-variant ultrasound field at a 2D array of locations has to be properly recorded for image reconstruction [3–6]. Currently, there are three different methods to achieve 3D ultrasound imaging. First, a 2D ultrasound transducer array can be used to detect the incoming ultrasound signals [7–9]. In a 2D ultrasound transducer array, the transducer elements are usually arranged into an orthogonal matrix. Each transducer element or a sub-group of elements is interfaced with a data acquisition (DAQ) channel to send a short interrogating ultrasound pulse and also receive the time-variant backscattered signal ("echo"). The location of the transducer elements in the 2D array provides the lateral (x and y) information of the ultrasound scatterers in the imaging target, while the travel time of the echo signals is used to retrieve their depth (z) information. As a result, an ultrasound image with 3D scattering contrast can be reconstructed on a computer. The imaging resolution depends on the density and the working frequency of the transducer elements, while the field-of-view is determined by the overall size of the 2D transducer array. To obtain good imaging resolution (e.g., 1 mm) and field-of-view (e.g., a few cm), a large number of transducer elements (e.g., 1000s) and DAQ channels (e.g., 100s) are required. As a result, the entire imaging system could become complex, bulky, power-consuming, and expensive [10]. To address this issue, a 1D transducer array could be used to conduct "electronic" 2D B-Scan, while the scan in the azimuth dimension is conducted mechanically by using a one-axis motor stage or just by hand with the assistance of a position tracking device [11,12]. However, this method still requires an ultrasonic transducer array and multi-channel DAQ electronics. The need of a position tracking device complicates the imaging system design and operation [13,14]. Alternatively, the ultrasound signals can also be received by mechanically scanning a single-element transducer over the imaging target by using a two-axis motor stage. However, the use of 2-axis motor stages makes the entire imaging system complex and bulky. Second, the slow mechanical scanning frequency limits the date acquisition speed. As a result, this technique is mainly limited for lab use and is not suitable for handheld operations [15–17].

In this paper, we report a new 2-axis micromechanical scanning transducer technique to enable fast and versatile 3D ultrasound imaging. The 2-axis micromechanical scanning transducer consists of a miniaturized single-element transducer mounted a unique 2-axis water-immersicible electromagnetic micro actuator. When AC

* Corresponding author.
E-mail address: isafolkdance@tamu.edu (J. Zou).

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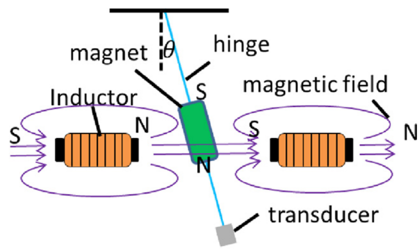
(a)



(b)

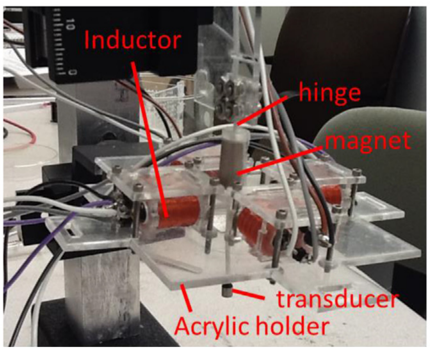


Fig. 1. (a) Schematic of the 2-axis micromechanical scanning transducer design. (b) Picture of the constructed prototype.

driving currents are applied, the single-element transducer can be scanned along concentric paths with different radii at a frequency of 10–100 Hz. By synchronizing the scanning frequency with the ultrasound pulse-echo repetition rate, the ultrasound signals from a 2D array of locations can be received sequentially with only one T/R channel for 3D image reconstruction. Compared with the scanning with motor stages, the two-axis micromechanical scanning transducer can achieve higher scanning speed and therefore imaging speed with lower power consumption, which is due to its smaller scan mass. More importantly, it can be further miniaturized to be fitted into a small liquid-filled probe for handheld operations. Therefore, it could provide a new approach for compact, fast and low-cost 3D ultrasound imaging systems.

2. Design, construction and characterization

2.1. Design and construction

To enable 3D ultrasound imaging, scanning the single-element transducer in two axes is needed. Since ultrasound waves with a frequency in the MHz range have high attenuation in air (1.64 dB/MHz-cm @ 20 °C), a liquid coupling medium with low acoustic attenuation such as water (0.0022 dB/MHz-cm) is needed for their effective propagation. Therefore, a micro actuator that can work properly under water is desirable. Such that both the single-element scanning transducer and the micro actuator could be packaged into a liquid (water)-filled imaging probe, which is suitable for handheld operations along different orientations. Currently, the most commonly used micro actuators are piezoelectric actuators. However, they require high driving voltages (e.g., >75 V [18]), which could cause electrical breakdown or shorting in water. Their work distance is also limited (e.g., micrometers). In contrast, electromagnetic actuators do not need such high voltages to drive, which are able to work in a liquid environment. Besides, their work distance can reach millimeters or even centimeters. Therefore, electromagnetic actuation will be chosen as the driving mechanism for the scanning transducer.

Fig. 1(a) shows the schematic design of the 2-axis micromechanical scanning transducer. A miniaturized single-element transducer is fixed onto a flexible hinge structure with a permanent magnet attached onto it. To provide the driving force for scanning the transducer in two axes, two pairs of inductor coils are mounted close to the permanent magnet. The magnetic polarity of the two inductor coils in each pair is made opposite. When an AC current is flowing through the two inductor coils, a push and a pull force will be generated on the permanent magnet to vibrate the flexible hinge together with the transducer at a certain scanning angle (θ). The magnetic force (F) generated between the permanent magnets and the inductor coils can be determined by

$$F = V \times \mathrm{Ms} \times \frac{\partial H}{\partial z} \qquad ---(1),$$

where V is the total volume of the permanent magnet, Ms is its effective magnetization, and H is the magnetic field intensity generated by the inductor. Since the length of the hinge is much larger than that of the permanent magnet, the magnetic force can be considered as a point force and the resulting scanning angle (θ) can be determined by

$$\theta = \frac{FL^2}{2EI} \qquad ---(2),$$

where L, E and I are the length, effective Young's modulus and bending moment of inertia of the hinge, respectively. When driven with an AC current, the scanning motion can be described as a simple harmonic vibration. Its resonance frequency in air can be estimated by

$$f_{\mathrm{r\_air}} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad ---(3),$$

where k is the bending force constant of the hinge and m is the overall effective mass of the scanning transducer assembly. When the scanning transducer is immersed in water, the resonant frequency ($f_{\mathrm{r\_water}}$) can be estimated by

$$f_{\mathrm{r\_water}} = f_{\mathrm{r\_air}}\sqrt{1-2\delta^2} \qquad ---(4),$$

where δ is the effective damping ratio of the scanning transducer in water.

Fig. 1(b) shows the constructed prototype of the 2-axis micromechanical scanning transducer. As the initial demonstration, a miniaturized water-immersion single-element transducer (XMS-310-B, Olympus) was used as the scanning transducer. It has a center frequency of 10 MHz, a 6-dB bandwidth of 80%, and a diameter of 2 mm. However, to meet the actual imaging requirements, other single-element transducers can be used as well. The RF coaxial cable of the single-element transducer was directly used as the bending hinge, which was clamped onto a height adjustable stage. A neodymium ring magnet (R84 × 0, K&J Magnetics) was used as the permanent magnet. It has a length of 10 mm, an outer diameter of 5 mm, and an inner diameter of 2 mm, respectively. Its nominal peak magnetic field intensity is ~13200 Gauss. Eight RF coil inductors (70F331AF-RC, Bourns) were used as the driving coils. The inductance of each inductor is 330 mH. To provide the needed driving force, two inductors were connected in parallel. The use of two smaller coils instead of a larger one results in a more compact structure and more uniform field distribution. The inductors and their wire connections were coated with water-proof epoxy. All the components were assembled together with acrylic fixtures made by laser cutting.

When the frequency of the AC driving current matches the resonance frequency, θwill reach its maximum, which results in the most efficient driving condition. Due to its centrosymmetric structure, the resonance frequencies in both axes are identical. Therefore, an ideal 2D scanning pattern will be a circular path (clockwise or counterclockwise), where both axes are driven at the