Spherically focused capacitive-film, air-coupled ultrasonic transducer

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Abstract: A spherically focused (no mirrors) capacitive-film, air-coupled ultrasonic transducer, constructed using a spherically deformed backplate and metalized polymer film, has been designed, fabricated, and its performance characterized. A 1 cm diameter device has a center frequency of 805 kHz and a 6 dB bandwidth of 760 kHz. Comparisons of field strength in the focal zone with theoretical calculations for a spherically focused piston show that the device achieves diffraction-limited focusing. The nominal focal point of 25 mm lies within 0.01 mm of the calculated value for this device.

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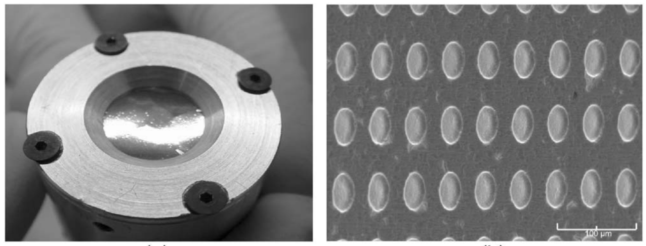
1. Introduction

Recently in nondestructive evaluation (NDE), attention has centered on noncontact ultrasonic inspection methods because they are practical and efficient when the test article under inspection cannot be brought into contact with water. Currently, most air-coupled ultrasonic inspection methods utilize either conventional piezoceramic transducers or capacitive film transducers. When a solid piezoceramic transducer is used to couple sound into air, the large acoustic impedance mismatch between the element and air renders broadband matching nearly impossible.[1,2] Capacitive film transducers skirt the impedance mismatch problem by using a thin polymer film of low areal density as the vibrating element.[3] Biased to 100 V dc or more, this type of transducer functions by detecting the vibrational motion induced in the film by incident sound waves and converting this motion to electrical current.[1] The capacitive film transducer has a relatively low fabrication cost, high sensitivity, and very wide bandwidth compared with conventional piezoceramic transducers. Previous attempts to develop natively focused transducers of this type have met with only limited success. Approaches employing external devices, such as acoustic mirrors,[4] cylindrical focusing,[5] or Fresnel zone plates[6] have all been attempted. Unlike these previous approaches, our spherically focused capacitive transducer utilizes a spherical radiating surface, and therefore needs no mirror, zone plate, or any similar external device to effect focusing. In this paper, we present the development, fabrication, and testing of a spherically focused capacitive film air-coupled transducer, utilizing a spherically deformed backplate and conformal metalized polymer film in the shape of a spherical radiator.

2. Transducer construction

Our 10 mm spherically focused capacitive film transducer is fabricated with a 25.4 mm geometric focal length and an active angular sensitivity of ±15° with respect to the normal axis. It is designed to excite a large range of plate wave modes when in normal incidence for low-density engineering materials, such as plastics, carbon or glass–fiber composites, and lightweight alloys. The radiating surface of a fully constructed spherically focused capacitive film transducer is shown in Fig. 1(a).



(a) (b)

Fig. 1. (a) A photograph of a 5 mm radius, 25.4 mm focal length spherically focused capacitive micromachined air-coupled ultrasonic transducer. A white line on a 6 μm Mylar/Al film is the reflection of a light source. (b) A SEM image of a flexible copper/polyimide backplate.

Our concept for a spherically focused transducer is based on the premise that both sides of the capacitor, the backplate and the polymer film, can be made to conform to a section of spherically curved surface. We have accomplished this goal by utilizing a flexible copper(Cu)/polyimide(PI) backplate, molded to a spherically curved backplate fixture, and a suitably prepared conformal metalized Mylar film. The flexible and permanently deformable Cu/PI backplate is a two-layer structure consisting of a 17 μm thick copper layer bonded to a 130 μm thick polyimide substrate, commonly used for flexible printed circuits. We pattern the copper layer of this material with 40 μm depressions having 80 μm center-to-center spacing, as shown in Fig. 1(b). Then, the backplate is carefully deformed to conform to a machined spherically curved backplate fixture, whose radius is the same as the desired geometric focal length of the transducer.

A 6 μm thick aluminized Mylar film, mechanically deformed to give it a spherical shape, completes the transducer. The fabrication of a conformal polymer film was another innovation necessary for the construction of a natively focused capacitive air-coupled transducer. To suppress performance-robbing wrinkles in the Mylar film, we have mechanically stretched the metalized Mylar film using a warm steel ball bearing. The radius of the ball bearing is approximately the same as the geometric focal length of the spherically focused capacitive transducer. After stretching the Mylar film, it assumes a spherical shape and can be fitted directly to the Cu/PI backplate without wrinkling, when a bias voltage is also applied.

3. Transducer characterization

To characterize our new device, we measure the sound pressure fields radiating from the spherically focused transducer by a second 10 mm diameter capacitive film transducer, baffled by a 200 μm diameter aperture, giving a quasipoint receiver that is scanned through the focal zone of the spherical transmitter under study. The receiver uses the same film and construction details as the focused transmitter, so its bandwidth characteristics are identical to the probe under test. The receiver is biased to 200 V dc.

The focused probe is excited by a bandwidth-tailored 200 μs random-phase signal.[4] Figure 2(a) shows the typical response of our spherically focused capacitive transducer, and Fig. 2(b) shows its corresponding frequency spectrum. All our measurements are relative, so amplitude units are arbitrary. The latter shows that the frequency spectrum is centered at 805 kHz with a 6 dB bandwidth of approximately 760 kHz, which is measured at a lower and upper frequency of 446 and 1207 kHz, respectively. This bandwidth is not only far wider than all piezoceramic transducers, but also wider than most damped water-coupled piezoceramic transducers.

For reference we have defined a simple Cartesian coordinate system, as shown in Fig. 3(a). The origin of the coordinate system is located at the center of the concave face of the spherical backplate in the spherically focused capacitive transducer. Figure 3(a) shows the measured sound fields in the x-z plane at $y=0$, radiated from the spherically focused capacitive air-coupled transducer whose geometric focal length is 25.4 mm. The sound field is scanned in

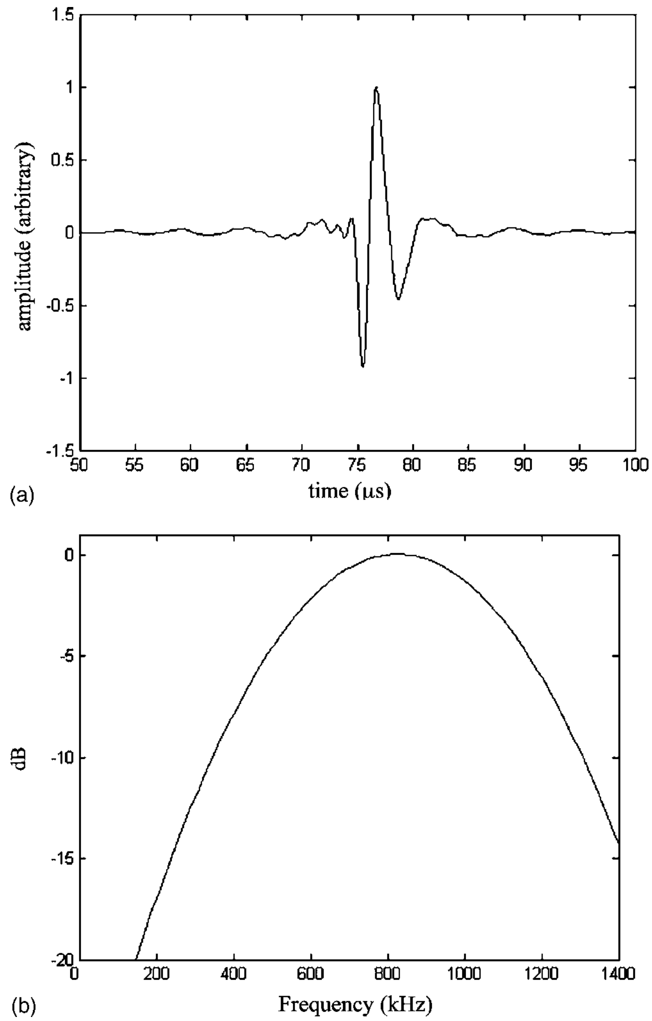


Fig. 2. (a) Typical amplitude response and (b) the corresponding frequency spectrum. The quasipoint receiver has a 200 V dc bias, and the transmitter is driven by a broadband excitation at 250 V peak to peak.

the x-z plane over an area of 8 mm $\times$ 35 mm and with spatial resolutions of 0.1 and 0.2 mm in the x and z axis, respectively. The figures show peak-to-peak sound field amplitudes at each point where dark red represents a much stronger sound field amplitude than a dark blue region. For broadband excitation, we have obtained the maximum amplitude at 24.9 mm. The focal zone extends from 17.1 and 34.1 mm, respectively. Figure 3(b) shows the measured sound field in the x-y plane at $z=15$, 25, and 35 mm. The figure clearly shows a point focusing performance of the transducer.

To evaluate the transducer's performance, we compare our experimental result with a theoretical prediction using the Rayleigh–Sommerfield model.[7] Figure 4 shows the cross section of the focal region of the measured and theoretical sound pressure fields for a 10-cycle 800 kHz tone burst excitation, radiated from the spherically focused air-coupled transducer. The sound pressure from a focused piston radiator is

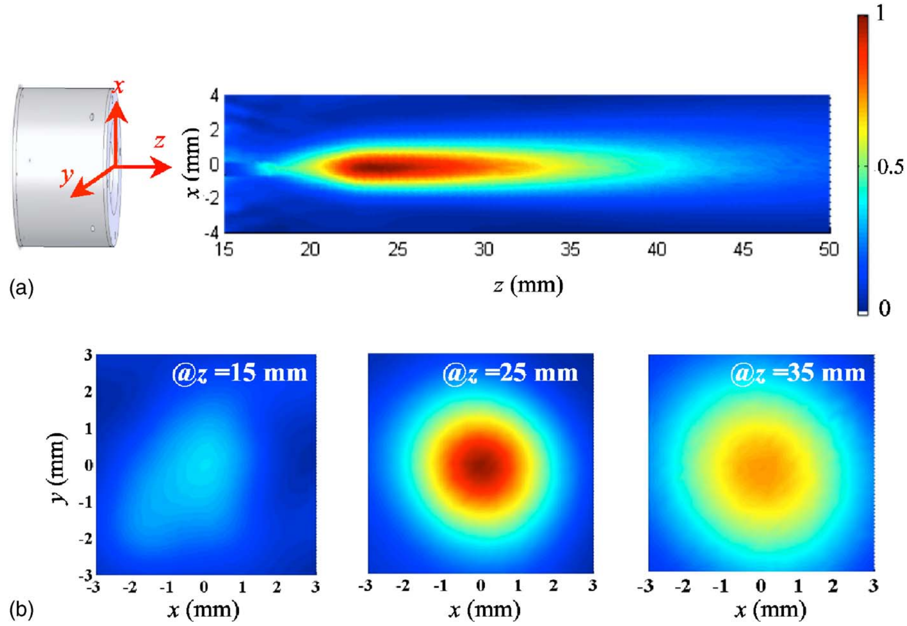


Fig. 3. (Color online) Measured sound pressure fields radiated from a 5 mm radius, 25.4 mm focal length spherically focused air-coupled transducer driven by broadband transient signals: (a) sound pressure field in the x-z plane at $y=0$, and (b) sound pressure fields in the x-y plane at $z=15,25$, and 35 mm. Darker red regions represent stronger sound pressure fields than dark blue regions. (*Those looking at a printed black and white version of this figure may find it helpful to look at the color version of this figure in the online publication*).

$$p(R_0,y,\omega) = -i\omega\rho v_0 a^2[\exp(ik\bar{R}_0)/\bar{R}_0][J_1(kay/\bar{R}_0)/(kay/\bar{R}_0)], \qquad (1)$$

where R_0 is the focal length, $\bar{R}_0=\sqrt{R_0^2+y^2}$, y is the radial distance, k is the wave number, ρ is the mass density of the medium, p is the radiating sound pressure, a is the radius of a piston

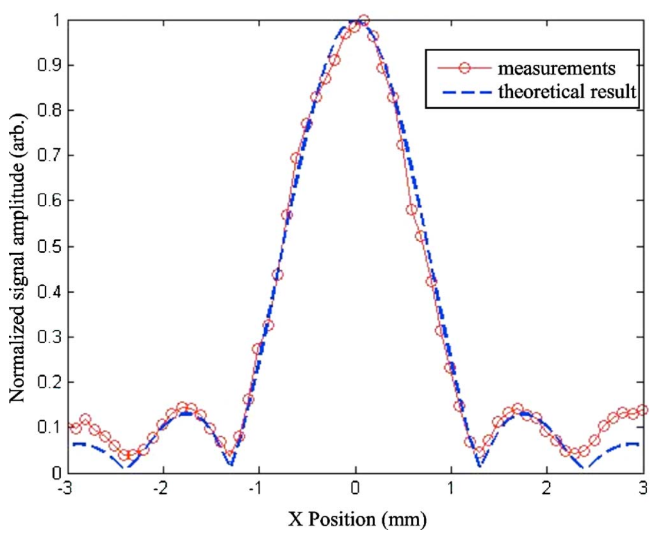


Fig. 4. (Color online) Cross sections of the focal region of the measured and theoretical sound pressure fields radiated from a 5 mm radius, 25.4 mm focal length, spherically focused air-coupled transducer when driven by an 800 kHz tone burst.

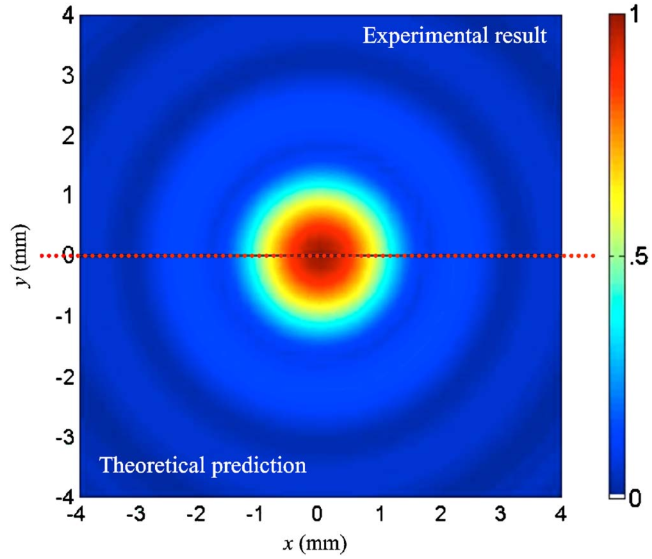


Fig. 5. (Color online) A comparison of the experimental measurement in the focal plane and Rayleigh–Sommerfeld theoretical prediction for a narrow band 500 kHz tone burst. The upper half is the experiment, and the lower half is the theoretical prediction, illustrating the transducer's nearly perfect axial symmetry. (*Those looking at a printed black and white version of this figure may find it helpful to look at the color version of this figure in the online publication*).

transducer, ν_0 is the piston velocity (assumed uniform over the face of the radiator), and J_1 is the first-order Bessel function. The calculation has no adjustable parameters except for the arbitrary amplitude. Our measurements are obtained at the focal zone for each excitation signal, which we have found in the *x*-*z* plane scan. The full width at half-maximum (FWHM) value, or 6 dB dropoff point, is measured to be 1.38 mm, and its theoretical prediction is 1.37 mm. The theoretical prediction is sufficiently close to the experimental measurements for us to conclude that our device is operating like an ideal spherically focused piston radiator. Figure 5 shows the experimental measurement (in the upper half-frame) compared with the theoretical prediction (in the lower half-frame) of the focal-plane behavior of the focused transducer at 500 kHz. Because the radiating surface is spherical, resolution of the focused beam is diffraction limited, controlled only by deviations in the fixture sphericity, the device diameter, medium sound wave speed, and the frequency.

4. Conclusion

We have presented a simple, yet reliable, design of natively focused micromachined capacitive air-coupled ultrasonic transducers and have shown a simple method to fabricate them. By selecting a flexible substrate as a backplate, we eliminate one of the most difficult and unsolved problems in backplate fabrication. Moreover, because our device is natively focused, this transducer eliminates the need for auxiliary focusing devices, such as acoustic mirrors or zone plates. We have demonstrated that it behaves accurately like a spherically focused piston radiator. We anticipate this device's high signal amplitude, wide bandwidth, and optimal spatial resolution will significantly improve air-coupled ultrasonic nondestructive evaluation and imaging applications.

Acknowledgments

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