NEW DESIGNS OF FOCUSSED AIR-COUPLED ULTRASONIC TRANSDUCER

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ABSTRACT

The paper describes new developments in air-coupled ultrasonic transducers that can be used to focus energy in air. All transducers to be described are based on a capacitive design, using a rigid backplate and a thin polymer membrane. There are three approaches that can be used to achieve focussing, all of which are described: focussing with a mirror, using curved back-plates, and linear phased arrays. The performance of these transducers is discussed.

INTRODUCTION

Air-coupled ultrasound has gained popularity recently, because of the non-contact nature of the transduction process. The most common transducers used for air-coupled experiments are based on piezoelectric and electrostatic designs. The first of these, using piezoelectric materials such as PZT, tend to be resonant, and hence require special backing and construction to obtain suitable damping coefficients. In addition, the characteristic impedance of the piezoelectric element is very different to that of air. Hence, a quarter-wavelength thick matching layer at the frequency of interest is thus usually introduced at the front surface. Many types of materials have been tested and found to be useful as the matching layers, but these limit the overall bandwidth. One way of reducing the impedance of the material is to use 1-3 connectivity piezo-polymer composites [1], which contain an array of piezoelectric ceramic rods in a polymer filler matrix. These have a wider bandwidth than traditional piezoelectric materials such as PZT.

An alternative transducer design is based on the capacitance or electrostatic principle. This has received much interest recently because of the extended bandwidths that can be obtained. These devices are composed of a thin membrane film and a rigid conducting backplate to form a capacitor. Applied voltages cause the membrane to vibrate, and hence generate ultrasound, whereas a change in charge across the membrane can be used for detection. Metallic backplates can be used [2], many employing machined backplates to improve the acoustic properties of the transducer. This type of transducer was found to be very sensitive at high bias voltages when a thin polymer membrane was used [3]. An increase in the device bandwidth requires more careful control of surface features, and hence silicon has been investigated as the backplate material [4,5]. An additional approach is the fully-micromachined device, where the complete structure is fabricated using CMOS technology from a silicon wafer. Typically, such designs use a silicon substrate and a silicon nitride or polysilicon membrane [6]. However, there appears to be relatively little work published on focussed air-coupled ultrasound from capacitive transducers.

This paper reviews various types of device that could be used. One approach is to use an external focussing element and a planar transducer. Here we describe the use of off-axis parabolic mirrors. In addition, a curved backplate has been investigated in a conical geometry. These have been investigated for use in situations where a relatively large depth of focus is required. Finally, a cylindrical device has been constructed, which shows interesting features. The following presents a description of the devices, and measurements of the frequency response, resolution and radiated field characteristics. This is then followed by images produced in pulse–echo mode of surface features.

CONICAL AIR-COUPLED TRANSDUCERS

The conical transducer consisted of a polished brass backplate, retained within a machined aluminium casing, and electrically isolated from the casing with an insulating nylon insert. A cut-away schematic diagram of the transducer is shown in Figure 1. The internal active area of the backplate is in the shape of a truncated (45°) cone, with inner and outer radii of 13mm and 30mm respectively. This was designed to produce a line of focus 34mm in length, starting at a position of z=26mm from the extrapolated internal apex of the cone. After manufacture of the transducer, the backplate was carefully polished by hand to a surface finish of 0.25 μm. It was then washed in acetone and cleaned further with an air jet. A 3.5μm thick Mylar metallised membrane was attached over the backplate, in the presence of an applied bias voltage to reduce the amount of trapped air. Conducting silver paint was used to electrically connect the metallised front face of the film to the aluminium casing.

The transducer was driven with wide bandwidth transients from a Panametrics 5055 pulser/receiver, which could also be used as a receiver charge amplifier in pitch-catch mode. The capacitance transducer required a 200V d.c. bias to operate as a receiver, and this was supplied via a power supply and a capacitance de-coupler circuit. This also attracted the membrane to the backplate, enhancing bandwidths in pulse-echo. Waveforms were stored on a Tektronix TDS430A digital oscilloscope, and transferred to a PC for analysis. The transducer was operated in pulse-echo mode, and the received signal in air from the surface of a flat glass block is shown in Figure 2(a), with the surface positioned at the centre of the nominal focal region in air. This shows a wide-bandwidth, well-damped signal at a relatively high-amplitude (50mV pk-pk). The time of flight of the received pulse-echo signal corresponds to a propagation distance of approximately 65mm. The frequency spectrum (Figure 2(b)) demonstrates that the peak response was at just over 0.5MHz.

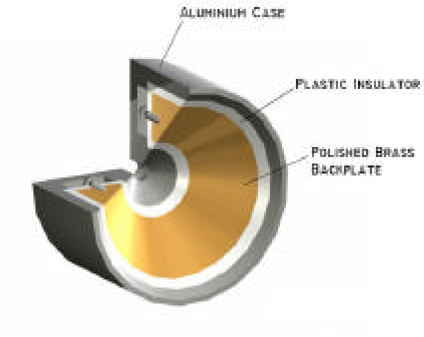

Figure 1 Schematic diagram of the conical transducer

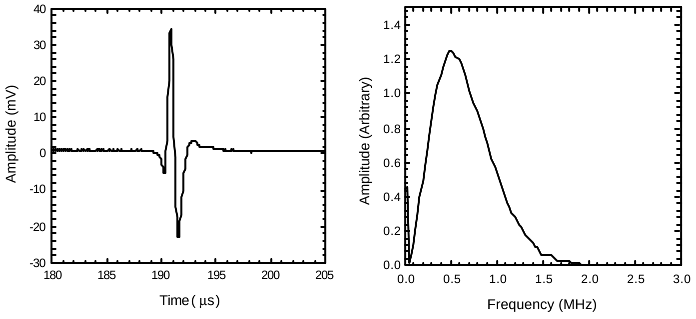

Figure 2 Response of the conical device in pulse-echo from a flat surface

The radiated fields of focussed air-coupled transducers was measured by scanning a miniature detector through their fields, using a PC-controlled stage. The results for the conical transducer are shown in Figure 3 for transient excitation. Note that the area where *z* <20 mm has been shaded black to show the un-scanned area (the scan was initiated at z = 20 mm). As can be seen, there is an extended region of focussing along the transdcuer axis, demonstrating the large depth of field of this device.

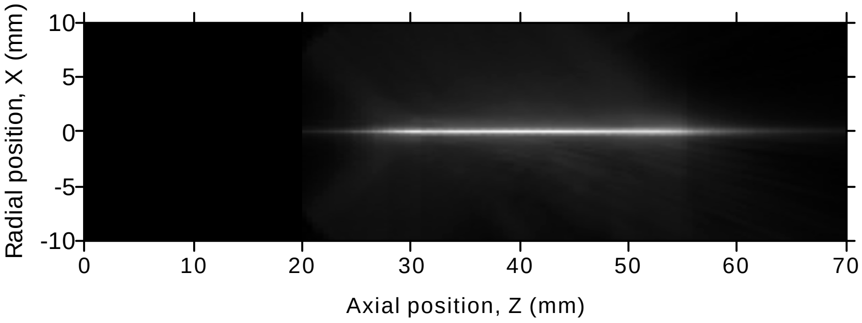

Figure 3 Experimental field variations from a conical transducer under transient excitation.

CYLINDRICAL TRANSDUCERS

An illustration of the cylindrical transducer shown in Figure 4. It consisted of a polished rectangular brass backplate, measuring 19.5 mm wide by 45 mm in length, which was retained within a machined aluminium casing using an insulating nylon insert. An electrical connection was made from the backplate to the centre pin of a BNC connector mounted on the exterior of the device, with the case itself being grounded via the shield contact of this connector. As above, final assembly involved fitting of the membrane, after thorough cleaning by an air jet. A section of the 3.5 µm thick Mylar metallised film, large enough to cover the whole of the front of the device, was fixed in place by gluing around its edge. Electrically conducting silver paint was then used to connect the front metallised surface of the film to the case. This whole procedure was accomplished with an applied d.c. bias of 100 V, to minimise trapped air between the membrane and backplate.

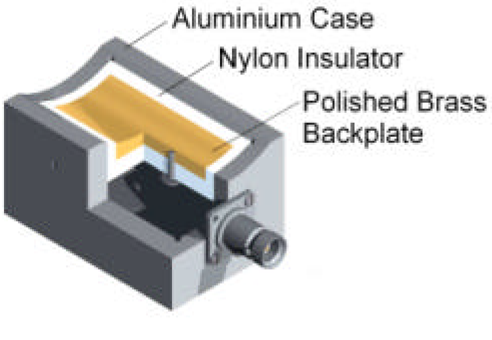

Figure 4 The cylindrical air-coupled transducer

The transducer was first positioned above a flat polished glass block, with its front face parallel to the surface. It was then carefully aligned to give maximum amplitude of the received signal, so that the focal region was on the surface of the block. Figure 5(a) shows the received waveform. It can be seen that a clean, well-damped signal has been produced. It can also be noted that the time of arrival of the reflected wave was approximately 163 µs, which corresponds to a distance of ~56.9 mm in air (assuming a velocity of 343.4 ms^{-1}), hence a distance of 27.95 mm between the transducer and the surface of the block. This is consistent with the designed focal length of the transducer (28 mm). The corresponding frequency spectrum of the waveform is shown in Figure 5(b). It is evident that the transducer has a –6dB bandwidth of approximately 700 kHz, with lower and upper frequency points of 150kHz and 850kHz respectively, and a peak response at ~400 kHz.

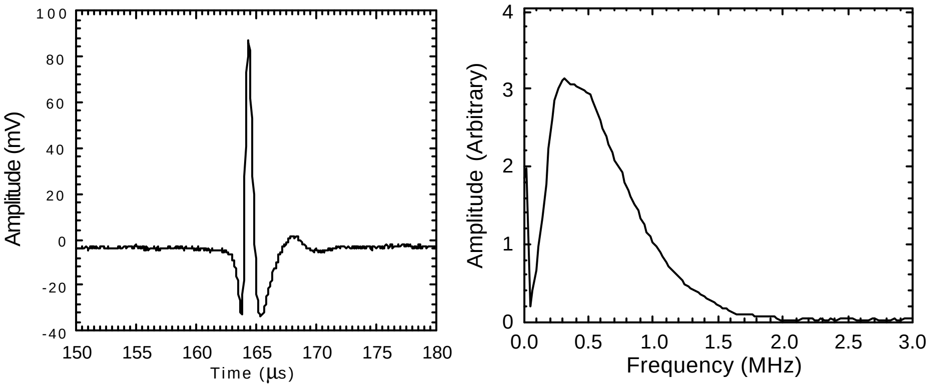

Figure 5 Response of the cylindrical transducer from a flat surface in air.

The sound pressure field resulting from broadband transient excitation is shown in Figure 6 as a greyscale image, where black represents low amplitude and white high amplitude. As before, the area where *z* <15 mm has been shaded black to show the un-scanned area. The plot demonstrates that focusing has indeed taken place. This is evident as a single large peak, with a maximum amplitude at *z* = 28 mm, the designed focal length of the transducer.

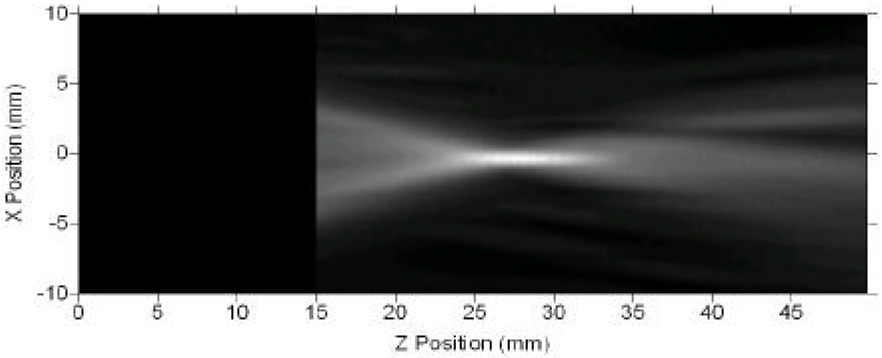

Figure 6 Experimental radiated field from a cylindrical air-coupled transducer.

FOCUSSING WITH AN EXTERNAL PARABOLIC MIRROR

A final method investigated in this paper is the use of an external focussing element in the shape of an off-axis parabolic mirror. This transducer was designed and constructed as part of a collaboration with MicroAcoustic Instruments Inc., Ottawa, Canada. It consisted of a planar capacitive air transducer with a micromachined backplate, the construction of which has been described in previous publications [9]. This transducer, which had a 30mm diameter aperture, was attached to an off-axis parabolic mirror that was fixed inside a machined aluminium housing.

A schematic of the externally-focussed transducer is shown in Figure 7. The focal point of the off-axis mirror was positioned 25.4mm from its central axis, at an angle of 12.8° to its normal. As for the conical and cylindrical transducers, an initial pulse-echo measurement was performed to determine the bandwidth of the transducer. The same equipment was used as before, but with the transducer carefully aligned above the glass block at an angle of approximately 12.8°, so the focal region was normal to the reflector surface.

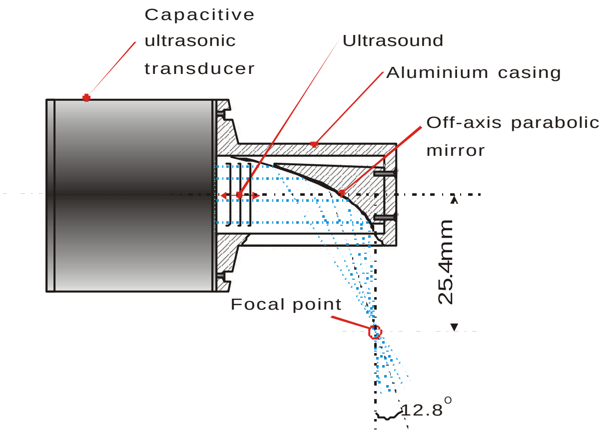

Figure 7 Schematic diagram of an externally-focussed transducer for use in air

The received signal is shown in Figure 8(a) as a relatively high amplitude, well-damped signal. Its frequency spectrum was also calculated, and is displayed in Figure 8(b). This shows the pulse-echo signal has a bandwidth of approximately 550kHz, ranging from 250kHz to 800kHz, with a centre (peak) frequency of 550kHz. However, due to the design of this transducer, there is a relatively long transit distance from the source to the focal point (95mm in pulse echo mode).

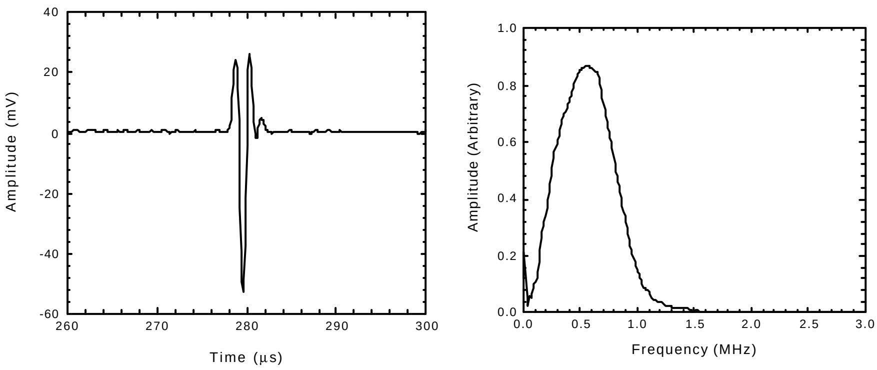

Figure 8 Pulse-echo response of the externally-focussed device.

As before, the radiated field was scanned using a miniature detector. An area measuring approximately 20mm x 20mm was scanned, using a spatial resolution of 250µm, and initiated within the front aperture of the transducer at a position of *z*=-4mm. A 200V bias was applied throughout the experiment. Figure 9 shows the measured sound amplitude field for the broadband transient case, plotted as an interpolated greyscale image. It is evident that a focused field has resulted, with the point of highest amplitude at a position of ~*z*=5mm.

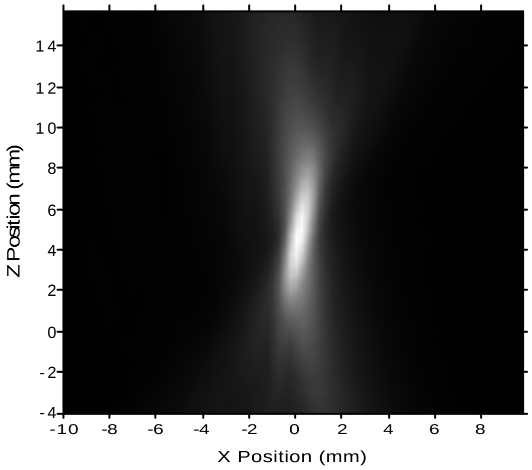

Figure 9 Experimental radiated field of the transducer fitted with an external parabolic mirror.

DISCUSSION AND CONCLUSIONS

The paper has compared three different types of focussed ultrasonic device for use in air. All three show a good response in terms of bandwdth and sensitivity in pulse-echo mode. However, there are large differences in the spatial characteristics over the focal regions, as would be expected from the different geometries used. The conical transducer exhibited a large depth of field, which would be useful for the scanning of surfaces with large features. The cylindrical device showed an intermediate spatial resolution, whereas the device using a parabloic mirror had the best lateral resolution, but also the smallest depth of field. The comparison has served to demonstrate that such devices can be constructed for use in air, and that many applications are now possible in imaging and measurement using air-coupled ultrasound.

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