Transducers in Ultrasonics

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There is a wide range of transducer types used in ultrasonics and acoustics.

A. Piezoelectric transducers

Below 100 kHz electromagnetic and electrostatic devices can be used as the active electromechanical components in transducers. Up to about 50 kHz magnetostrictive devices were popular for power transmitters some years ago but are less so now. A magnetostrictive material deforms and generates strain energy when a magnetic field is applied to it. Above and below 100 kHz it is common to use ferroelectric ceramics such as Lead Zirconate Titanate (PZT) as the electromechanical devices in transducers. Ferroelectric materials can be electrically poled to impart apparent piezoelectric properties to them. A piezoelectric material deforms and creates strain energy when an electric field is applied to it. Piezoelectric ceramics have relatively high Q or quality factors but one exception is modified Lead Metaniobate, which is naturally damped.

A commonly used shape for a PZT component is a thin disc, it has three principal modes of vibration:

- Flexural, a bending motion.
- Through the thickness, compression of a disc along its cylindrical axis.
- Along the radius, symmetric or anti-symmetric compression of a disc in radial motion.

If the thickness of the disc is less than its radius then the frequency of the thickness mode will be the highest of all the modes and simple electrical circuits can be used to suppress the low frequency modes. Discs of PZT can be used in this way to make transducers with relatively simple frequency responses based about chosen centre frequencies. Manufacturers usually describe transducers in terms of the centre frequency, aperture size and wave type (compression or shear). Sometimes the number of cycles resulting from a single impulse excitation is also given, for example two and a half cycles ring-down, which is related to the frequency response and the Q of the transducer. Although shear-wave transducers can be made from PZT in the form of shear-plates it is more common to use compression discs, angling the disc inside the transducer body at the transmitting surface at, for example, 45^o instead of 90^o then shear waves are generated by mode-conversion at the interface with the test sample and the compression waves in the transducer are reflected internally and absorbed.

Commercial transducers (see figure 1) generally have a block of tungsten-loaded epoxy resin bonded to the surface of the PZT disc that is not coupled to the sample. The block is typically several wavelengths long and provides strong mechanical damping. A transducer also has a face-plate to protect the disc, generally in the form of a thin polymer membrane. In some instances the face-plate is made thicker, from an epoxy-resin material, to be a quarter-wave plate. The thickness is made equal to a quarter of the wavelength at the centre frequency of the transducer and the acoustic impedance is made equal to the geometric mean of the piezoelectric disc and the test sample. Under these special circumstances the face-plate acts as a matching layer between the disc and the material under test, maximising the coupling of energy between the test sample and transducer. The transducer must be mechanically coupled to the test sample while testing. Common commercial coupling materials are water-based gels but water, grease, sodium salicylate and adhesives can be used. It is possible to use air as the coupling material but this approach results in exceptionally high signal losses because of the high attenuation of air and very low transmission coefficients between transducer materials and air (acoustic impedance mismatch).

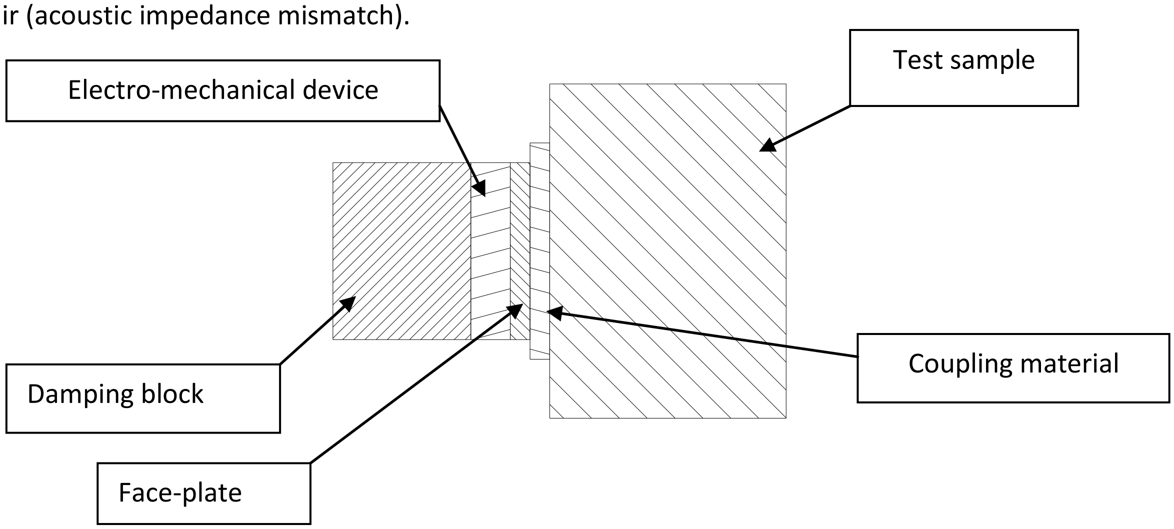

Figure 1

Sketch to illustrate the construction of an ultrasonic transducer with a working frequency greater than 100 kHz.

B. Transducers for acoustics

Electromagnetic and electrostatic devices are popular electromechanical elements in microphones and loudspeakers. A moving coil loudspeaker has a coil of wire suspended in the strongest part of the magnetic field of a permanent magnet (see figure 2). A lightweight, rigid cone, supports the coil at its apex and is loosely supported in turn at its outer perimeter by a rigid metal frame. The cone is free to move through a distance of several millimetres parallel to the axis of the coil.

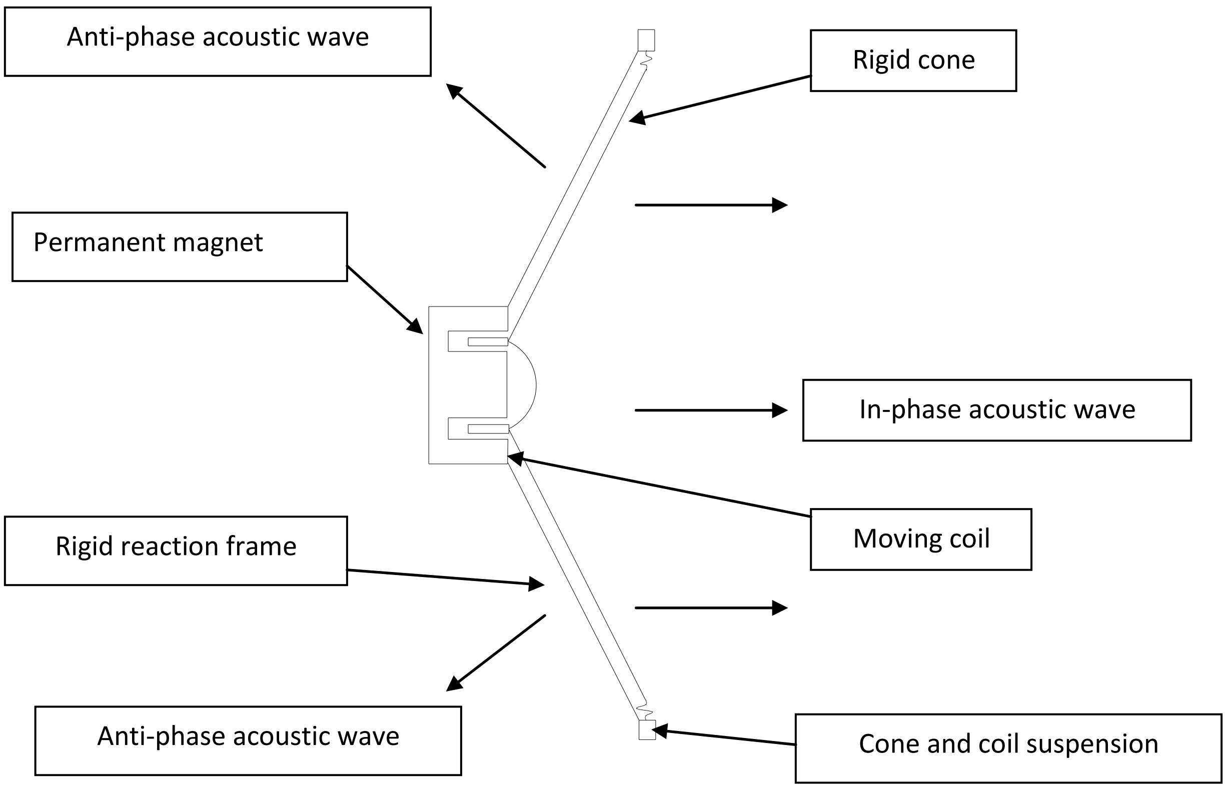

Figure 2

Sketch showing a cross-section through a loudspeaker drive unit.

When an electric current passes though the coil, a force is generated parallel to the axis of the coil that causes it and the cone to move, compressing a large volume of air and creating a sound wave. Without the cone the coil would be virtually inaudible. When the coil moves out from the magnet it compresses the air moving towards the listener but on the opposite side of the cone the air is rarefied. The rear of the loudspeaker therefore generates an anti-phase acoustic signal. It is common to include two or three loudspeaker drive units of different sizes into a single assembly or housing to improve the overall fidelity of reproduction. The smallest drive unit transmits the high frequency sounds (usually above 1 kHz) and the largest drive unit transmits the low frequency sounds (usually below 200 Hz). Electrical filters, made of capacitors and inductors, known as cross-overs, direct electrical energy of an appropriate frequency range to each drive unit. The drive units are mounted in one housing, which contributes to the tonal quality of the final sound. The housing is sealed, apart from one aperture, which provides a path for the release of pressure from the inside of the housing and it is packed with material to absorb anti-phase acoustic energy. This construction is called an *infinite baffle* because the loudspeakers operate as if the rear of the cones were coupled to a semi-infinite volume of air, which presents the minimum mechanical load. The anti-phase sounds generated inside the assembly should not be transmitted to the listener because they would interfere with the in-phase acoustic waves and degrade the fidelity of reproduction. The working frequency range of moving-coil loudspeakers is approximately 20 Hz to 20 kHz.

An electrostatic force is created when two exposed electric charges are brought close together. In an electrostatic transducer one of the electric charges is distributed over a thin, metallised polymer film which is separated by a distance of a few millimetres from the second electric charge on a rigid metal plate. The film and plate form an air-filled capacitor with the film free to vibrate. A generator of electrostatic charge maintains approximately constant charges on the film and plate. The device acts as a microphone if an acoustic wave reaches the polymer film and the resulting charge modulations are used as a signal; alternatively, the device can be used as a loudspeaker if the charges are modulated by a driving signal. Electrostatic microphones are intrinsically simple and can be made as small as 10 mm. Electrostatic loudspeakers are generally made with much larger transmitting areas (up to 1 m^2) to give higher efficiency. The working frequency range of electrostatic transducers is approximately 20 Hz to 100 kHz.

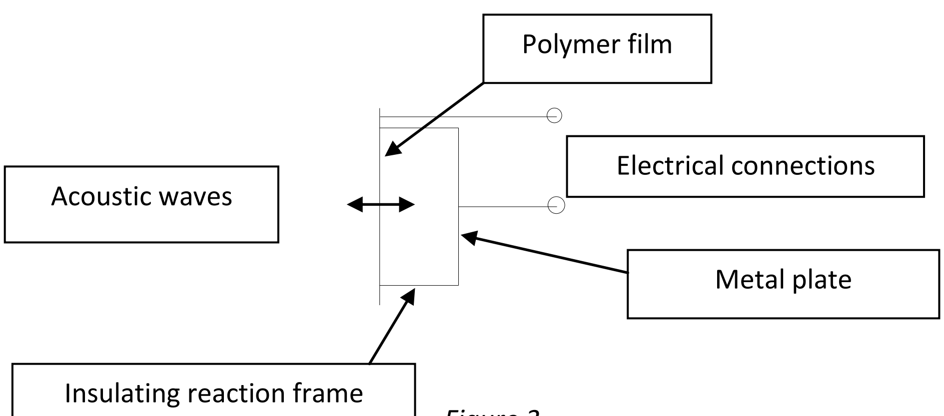

Figure 3

Sketch of an electrostatic transducer. The two electrical terminals are connected to a polarizing voltage and also to either a source of modulation (case of a transmitter) or to a high impedance amplifier (case of a microphone).

C. Sources of high power CW ultrasound

A source of CW ultrasound is generally a resonating structure with a high mechanical quality factor (Q). It is pumped with mechanical energy by an active electromechanical device at its resonating frequency. In high power applications the design objective is to maximise the amplitude of vibration. If mechanical energy leaks through the support-frame then the amplitude is reduced but, by supporting the system at a node, losses are kept to a minimum (see figure 4). The Langévin design is a popular transmitter using nodal support, which also benefits from axial symmetry, allowing an axial screw to pull the vibrating components tightly into compression. Some materials used in electromechanical devices are brittle, fracturing in tension but a static, axial compression force prevents tension developing in the device making it longer-lasting and capable of working at higher amplitude. At resonance the two ends of the vibrating cylinder are anti-nodes, with a node at the centre, making the cylinder a half a wavelength long. The frequency of resonance can be calculated knowing the speed of sound in the materials. Langévin resonators are used in sonar transmitters, inkjet printers and sieve agitators.

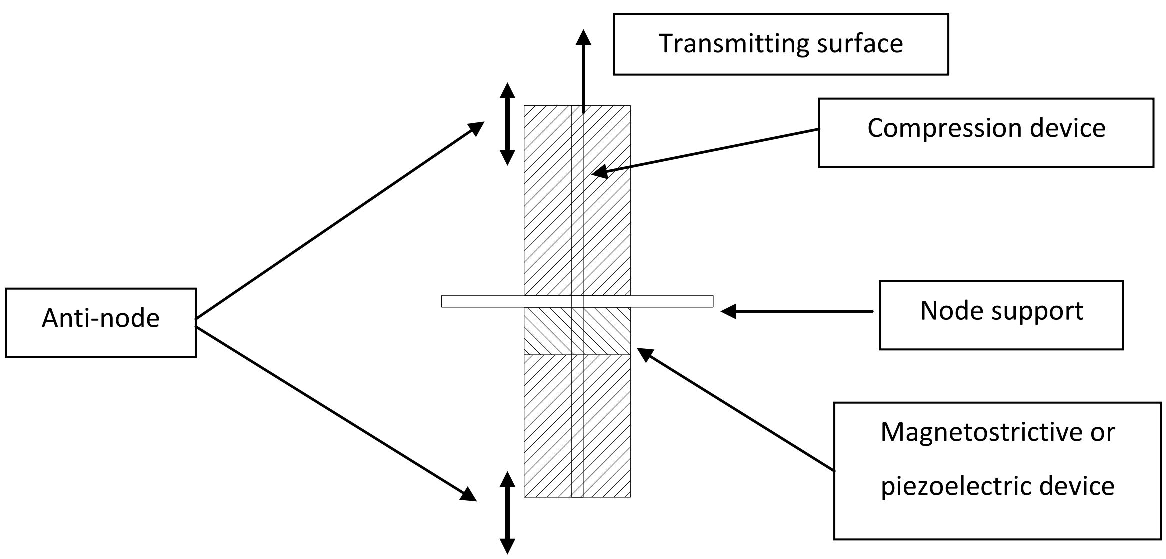

Figure 4

Sketch of a CW ultrasound source. The important feature is that the entire system vibrates so that the support is a node (minimum vibration level) and the two ends are anti-nodes (maximum vibration level).

D. Transducer arrays.

An array is a collection of two or more transducer elements working in concert. An array can be used by transmitting the same signal from the elements but with different time delays that change the direction of propagation of the transmitted wavefront or focus it. Arrays offer considerable flexibility in beam-forming, with no moving parts and high speed scanning.

E. Steering and focussing

Figure 5 shows groups of single wavefronts emerging from a linear array of elements. Where the wavefronts overlap with the same phase there is constructive interference but elsewhere the interference is destructive (not shown in the figure). It is common to space elements periodically, with a distance between centers of $\lambda/2$. This gives a good balance between source strength and beam quality. If elements are separated by more than $\lambda/2$ then there will be aliasing, called grating-lobes in this instance, in any wavefronts focussed down as small as λ, meaning that the full potential for axial and lateral resolution available at the operating frequency is not achieved.

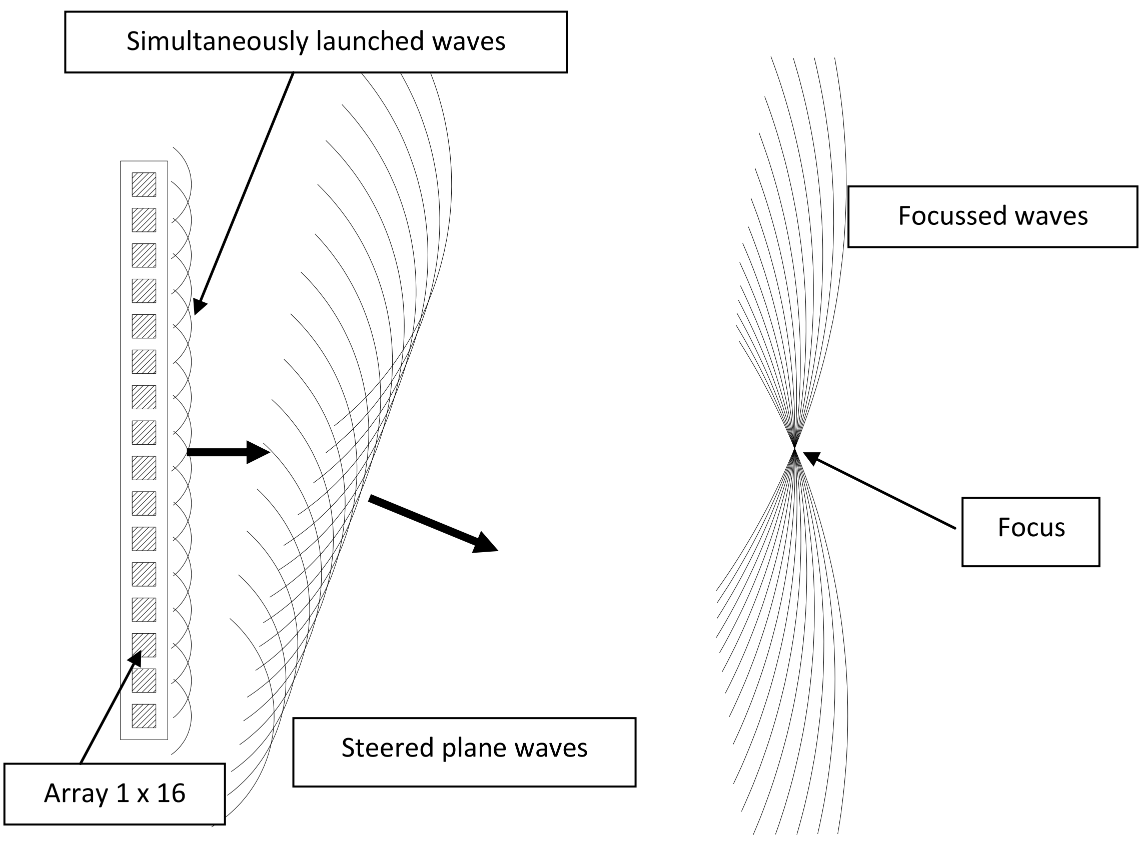

Figure 5

Sketch to illustrate how an ultrasonic beam can be steered and focussed using an array of transmitters.

The same principles, of successive time delays and superposition of signals, can be applied to signals received by the array. A disadvantage is that a considerable amount of signal processing must be done. Beam-forming of received signals can be used to simulate the effect of an ultrasonic lens and beam-forming can provide better quality images than a lens, which is a further benefit of using arrays.

F. Time-reversal mirrors

Arrays can also be used in a self-adaptive imaging mode called time-reversal mirrors. Firstly, a single impulse is transmitted simultaneously from all the elements in an array and the same elements are used for receiving. Then the received signals are simply time-reversed and re-transmitted from the same elements. The elements are used again to collect a second set of signals, which is used for making a compound B-mode scan or C-mode scan. Time-reversal mirroring automatically adapts the transmitted signals to the test sample, providing an image of any scatterers there.

G. Two dimensional arrays

An array with elements distributed over two dimensions gives beam control in three dimensions. Arrays with 64 x 64 (4096) elements have been built but it is not feasible to transmit and receive from all the elements, instead only 128 receivers and 128 transmitters might typically be used in what is known as a sparse array. Since there are more than 256 elements available it is possible to use different elements as transmitter and receivers but there are a very large number of ways of choosing the elements, too many for all of them to be evaluated in a reasonable time. Computer simulations can select configurations that give good performance. Two dimensional arrays allow arbitrary cross-sectional images to be created rapidly, giving better performance for medical imaging.

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