



New technologies for air-coupled ultrasonic transducers

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Abstract

Air-coupled ultrasonic testing (ACUT) has experienced rapid growth within the last years. It is especially well suited to inspection of lightweight structures consisting of composite materials and adhesive joints. Uniform coupling and easy maintenance are its advantages compared to contact technique. However, the impedance mismatch between the transducer and air poses a major challenge to the development of ACUT transducers. Commercially available air-coupled transducers consist of a piezocomposite material and matching layers. Their fabrication is difficult in handling and their signal-to-noise ratio sometimes not sufficient for various testing requirements. However, there are several innovative approaches using other materials and other physical principles to transmit and receive an ultrasonic pulse.

We present a review of the latest advances in research on air-coupled transducers for non-destructive testing, including previously unpublished results. We recognize two major directions as most promising: ferroelectrets and thermoacoustic transducers. Ferroelectrets are charged cellular polymers exhibiting piezoelectric properties. Their small acoustic impedance is matched to air better than matching layers applied in conventional air-coupled transducers. Applying bias voltage to a ferroelectret receiver is the latest development in this field, which increased the received signal by 12 to 15 dB. Thermoacoustic transducers use heat to initiate an ultrasonic wave, acting as transmitters. The working principle is known from nature as thunder and lightning: thermal energy of an electrically heated material, which can also be air, is converted into acoustic energy. Some thermoacoustic transmitters consist of a conductive layer with a thickness in the nanometer range deposited on a solid substrate. Another possibility is to use an electric spark. For the first time, measurements of the sound field of an electric spark up to 500 kHz were performed. Thermoacoustic transducers enable excitation of extremely broadband pulses while producing high pressure levels, which opens new possibilities for advanced signal processing.

1. Introduction

Since its beginnings in 1970s, air-coupled ultrasonic testing (ACUT) has experienced rapid growth as a non-destructive method to detect defects (1). Typical applications include inspection of lightweight structures consisting of composite materials like fibre-reinforced polymers or sandwich structures and metal adhesive joints. Compared to contact technique, it offers uniform coupling conditions and easier maintenance, since there is no running water. Some materials with sensitive surfaces, which would be damaged by a fluid couplant, are inspected with ACUT. However, the impedance

mismatch between any solid and air poses a major challenge to this technique. The signals are much smaller than with the contact technique, so that the sensitivity of air-coupled transducers is the main issue in their development. For this reason, commercially available air-coupled transducers consist of a piezocomposite material and matching layers matched to air. Their fabrication is difficult and their signal-to-noise ratio sometimes not sufficient for testing requirements of thicker probes or probes with higher damping. However, there are several innovative approaches using other materials and other physical principles to transmit and receive an ultrasonic pulse.

This contribution is a review of the latest advances in research on air-coupled transducers for non-destructive testing, including some previously unpublished results. Two major directions are recognised as most promising: transducers based on ferroelectrets and thermoacoustic transducers.

2. Ferroelectret transducers

2.1 The functioning principles

Ferroelectrets are charged cellular polymers exhibiting piezoelectric and pyroelectric properties (2)(3)(4). Typically, their cellular structure is strongly anisotropic, so that they are extremely soft in one direction, which is also the direction of their polarisation. Although they were named after ferroelectrics (or piezoelectric materials), the underlying mechanism of their piezoelectric properties is different. In ferroelectrets, the stress in the 3-direction reduces the dipole moments, so that the piezoelectric coefficient d_{33} is positive.

Most part of research on ferroelectrets was performed on cellular polypropylene. The manufacturing of this material begins with melting and foamization, followed by extrusion, cooling to the crystallization temperature, heating to the orientation temperature and finally biaxial orientation, which is responsible for the cellular structure (3). After this last step, the cellular polypropylene film is subjected to corona charging, so that ions are trapped at the cell walls, resulting in remanent polarization (5). This polarization leads to piezoelectric properties of ferroelectrets. They were named after ferroelectrics and electrets, because they unite their properties.

Cellular polypropylene has a thickness between 50 and 100 μm , an acoustic impedance about $0.03 \times 10^6 \text{ Pa}\cdot\text{s/m}$ at frequencies around 250 kHz and a piezoelectric constant d_{33} around 200 pC/N. Its Young modulus c_{33} is strongly frequency-dependent, so that d_{33} and the acoustic impedance are frequency dependent too (6)(7). A study of their viscoelastic properties revealed that the Young modulus of cellular polypropylene with the product name HS06-20-BR by company EMFIT varies from 0.04 to 0.8 MPa in the frequency range from 0.3 Hz to 300 kHz, which was well modelled by Cole-Cole relation describing viscoelastic materials (7).

The thickness change of a ferroelectret transmitter is described by the relation

$$\Delta h_t = \frac{\varepsilon}{2c_{33}h} V_t^2 + \frac{\varepsilon V_0}{c_{33}h} V_t, \quad (1)$$

where ε is the permittivity of the ferroelectret, c_{33} its Young modulus in thickness direction, h its thickness, V_0 its internal voltage caused by polarization and V_t the excitation voltage (2)(3). The first of the two terms describes the thickness change due to electrostatic force (the functioning principle of a capacitive loudspeaker) and the second term the piezoelectric properties. However, it should be considered that the elasticity is frequency-dependent, so that the thickness change depends on the time behaviour of the excitation signal, which is not considered in Equation (1). When the same ferroelectret transducer is used as a receiver, the generated voltage can be described by the equation

$$\Delta V = V_0 \frac{\Delta h}{h}, \quad (2)$$

where V_0 is the internal voltage and Δh the thickness change of the receiver. This equation also describes capacitive microphones, with V_0 standing for external bias voltage.

2.2 Transducers based on ferroelectrets

Typically ferroelectret films are glued on an electrode, while the other electrode is deposited at the other surface (8)(9). The electrode deposition is performed using electron beam evaporation, evaporating layers of aluminium, gold or titanium with a thickness between 10 and 500 nm. The extraordinary flexibility of thin ferroelectret films enables cylindrical and even spherical focusing, which combined with high-voltage excitation creates sound pressure levels above 140 dB (10). When excited with square pulses of 1800 V, ferroelectret transducers with a diameter of 19 mm and a resonance frequency between 200 and 300 kHz produce much higher signals than the commercial transducers, leading to an increase of the signal-to-noise ratio by 20 dB. These transducers were successfully applied to inspection of adhesive joints and CFRP (carbon-fiber-reinforced plastic) plates, detecting inserts of 1 mm size within joints and plates with a total thickness of about 4 mm. Applying additional bias voltage increases the signal additionally by 12 to 15 dB, which is described later in this section. Stacking several layers together decreases the resonance frequency with some loss of sensitivity (9)(11)(12).

Since the ferroelectret film is glued onto one of the electrodes, various transducer geometries can be easily created by structuring that electrode, while the electrode deposited at the other side of the ferroelectret may be continuously connected. Not only phased array probes can be easily produced this way (13), but also a twin transducer with the transmitter and the receiver placed at the same piece of ferroelectret film. Two concentric electrodes were placed on the same circuit board, which was spherically focussed with curvature radius of 50 mm. As shown in Figure 1(a), the inner electrode was a circle with a varied diameter and the outer electrode a ring around that circle with an outer diameter of 27 mm. A ferroelectret film HS06-20-BR by company EMFIT was glued onto the circuit board and deposited with 100 nm aluminium using electron beam evaporation, applying the technology earlier developed for focusing ferroelectret transducers (10). This is why the structure of the electrodes and the division into the transmitting and the receiving part is not visible (see Figure 1(b)). The sound field of this transducer was evaluated by using the reflection from a circular rod, as illustrated in

Figure 2(a). This rod with a 6 mm diameter was moved in the sound field of the transducer and the reflected signal was recorded and evaluated as a C-Scan, as seen in Figure 2(b). The sound field resembles a sound field of a circular focussing transducer. The 6dB focal size depends on the size of the receiver, which is the circular electrode in the middle. For the receiver diameter of 8, 10 and 12 mm the following focal sizes were measured: 6.5, 3.1 and 3.7 respectively.

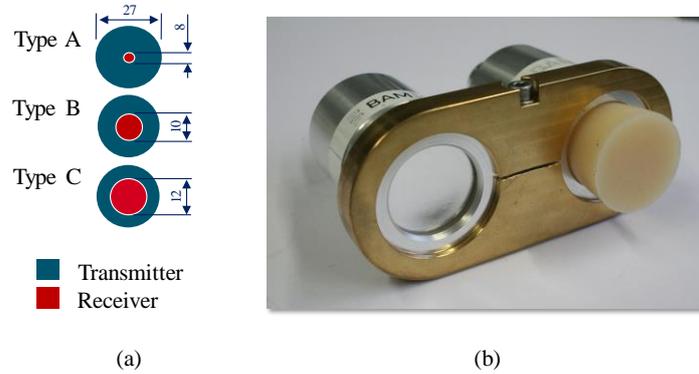


Figure 1. (a) The layout of the electrodes and (b) a photograph of the ferroelectric twin probe. The electric units for the transmitter and for the receiver are placed in separate housings.

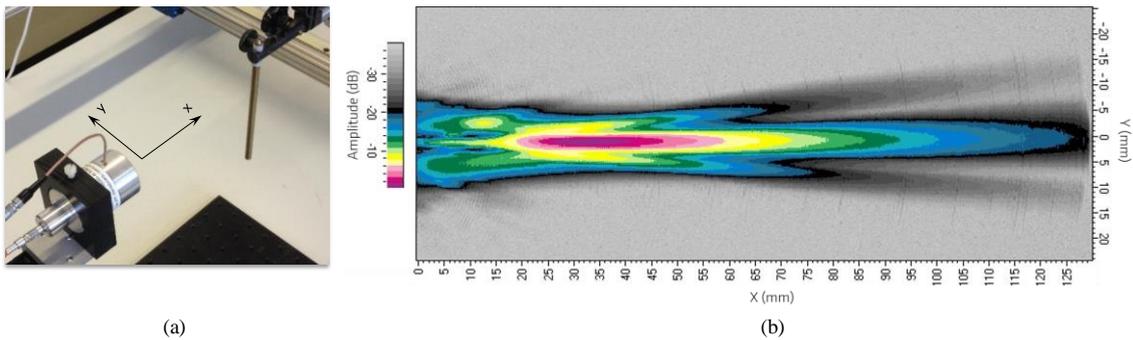


Figure 2. The sound field of the twin probe Type B recorded as a C-Scan of the reflection from a circular rod with a diameter 6 mm. The transducer was positioned at $x = -9$ mm, $y = 0$ while the rod was moved. (a) The experimental setup and (b) the resulting C-Scan.

If ferroelectrets are understood as capacitive microphones with an internal bias voltage V_0 , then the next natural thought is to apply additional bias voltage to increase their sensitivity (8). Ferroelectret receivers with no additional bias voltage were constructed and built consisting of two modules: one containing the deposited ferroelectret and the other containing a pre-amplifier (10). An additional module was constructed that provided bias voltage V_{DC} from -2000 to +2000 V (8). When this bias voltage module was connected and +2000 V applied, the received voltage increased by 12 to 15 dB, while the noise increased by only 1 dB. This was a result of an experiment with a through transmission of air, where the received peak-to-peak signal was evaluated against varying bias voltage as shown in Figure 3(a).

A physical model explaining this result can be obtained by expanding Equation (2), so that the bias voltage consists of ferroelectret internal voltage and additional DC voltage:

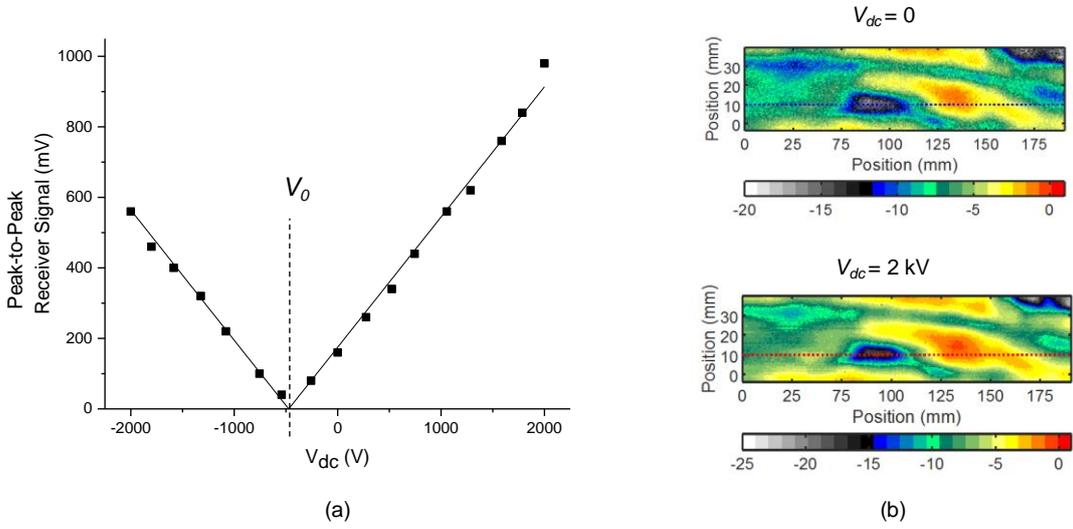


Figure 3. (a) The influence of additional bias voltage on the sensitivity of the ferroelectret receiver. V_0 is the internal voltage of the ferroelectret receiver and V_{dc} the additional bias voltage. (b) C-Scan of spruce timber with a thickness 35 mm with and without additional bias voltage, with a colour scale in dB.

$$\Delta V = (V_0 + V_{DC}) \frac{\Delta h}{h} . \quad (3)$$

The intercept gives an estimate of the internal voltage V_0 of the evaluated single-layer transducer, which is around 500 V. Inspection of spruce timber in Figure 3(b) gives an example how the application of additional bias voltage increases the signal-to-noise ratio.

3. Thermoacoustic transducers

We all know the natural phenomenon called thunder and lightning well from our daily life. The electrical discharge of the charged cloud particles causes a rapid change in the temperature gradient, which generates the rumble of thunder. Due to the short and strong excitation, the pressure of the fluid is increased and propagates as shock wave front, travelling kilometres until it vanishes. Various observations of thermoacoustically induced acoustic oscillations have been reported over time. Byron Higgins wrote the first scientific article about this phenomenon when he described the generation of sound during glass blowing process (14). Plasma speakers make use of thermoacoustic effect to reproduce audible sound with limited power.

One of the types of thermoacoustic transducers consist of a deposited conductive layer based on fused silica. Since the conductive layer acts as a regular conductor, electrical energy is dissipated and converted to heat by Joule's heating. This heat is responsible for an increase of the pressure, which is how an acoustic wave is initiated. The heat is proportional to the electrical power, so that a sine-wave electric excitation leads to an acoustical signal with the double frequency. Such transducers were already applied in

non-destructive testing. A thermoacoustic transmitter was combined with a ferroelectret receiver to inspect a 4 mm thick CFRP test piece (15).

Another possibility is to use gas discharges (electric spark or arc). As described, the most familiar natural phenomena are lightning and thunder. Gas discharges excite a wideband acoustic signal. For this paper, measurements of this excitation on electric spark discharges up to 500 kHz were performed. Two significant effects affect the acoustic excitation: a) the electrodynamic and b) the thermoacoustic effect. The electrodynamic influence relies on the production of charged particles and the body force caused by the electric field acting on these. We can neglect the electrodynamic influence compared with the thermoacoustic one, because the recombination processes between ions and other chemical compounds in air (e.g. carbon monoxide CO and atmospheric methane CH₄) dominate. Since the applied electrical field accelerates the charged particles, they interact with neutral particles inside the volume. Elastic and inelastic collisions between charged (electrons, ions) particles and neutral molecules of the gas mixture cause the temperature increase. Depending on the kind of discharge, the thermal change can be continuous (arc) or limited in time (spark).

We investigated the acoustic emission of gas discharges using a prototype as shown in Figure 4, with 1 mm distance between the electrodes, applying the sound particle velocimetry method described in (15). For the pulse-shaped emission initiated with 7.5 kV pulses, frequency components in a broad frequency range were observed. Figure 5 illustrates the characteristics of these acoustic emissions. The recorded signal is not perfectly broadband, but it consists of several resonance frequencies with different amplitudes. Due to the nature of the gas discharges, the acoustic response is strongly dependent on the environmental settings. However, we could reproduce similar characteristics over a period of one year without any modifications on the experimental setup, using the same prototypes. Several types of gas discharges were tested and an electric spark could produce a maximum sound pressure level of about 137 dB (Figure 5), which is comparable to commercial transducers.

The electric spark discharge generates pressure variation, which tends to be non-linear. Figure 5 shows the sound pressure level over distance emitted by an electric spark discharge. The non-linear behaviour dominates for distances below 400 mm and consists of two dominating effects, which both were observed experimentally (16): a) the wave-steering and b) the acoustic saturation. Wave-steering describes the change of the signal shape depending on the distance from the source, whereas higher harmonics in the acoustic spectrum appear. The acoustic saturation is caused by the streaming processes of the fluid. For low-intensity acoustic excitations, the influence of streaming processes is very weak and can be neglected. For high-intensity acoustics, they consume energy and must be considered. The distance independence of the sound pressure level of spherical waves apparently contradicts the conservation of energy, but it can be fully explained by the convective terms and the presence of wave-steering. The depicted effect is called acoustic saturation and was observed by various authors (16). In non-linear regime, the energy is contained in higher harmonics.

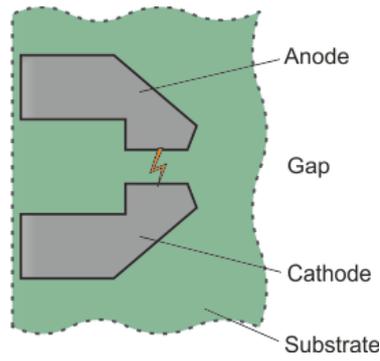


Figure 4. Schematic representation of the initiation of an electric spark.

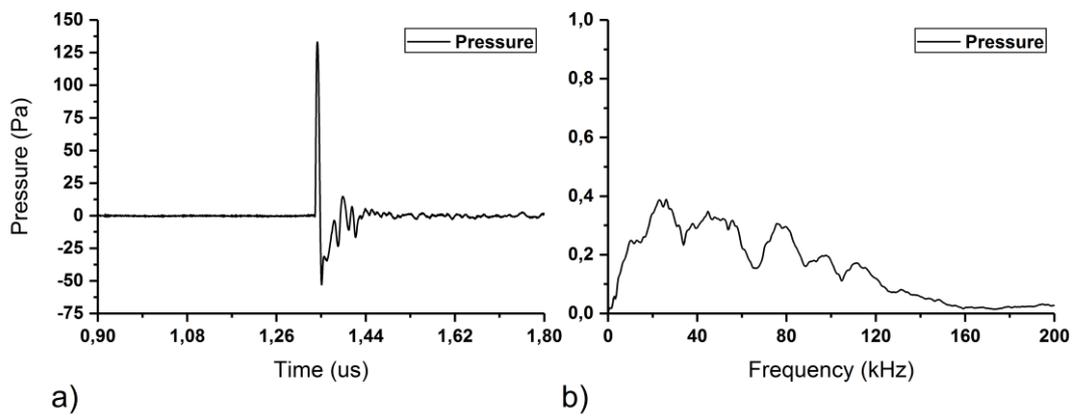


Figure 5. (a) Measured acoustic excitation of a gas discharge and (b) the corresponding Fourier transformed. The acoustic signal was recorded at 440 mm distance from the source.

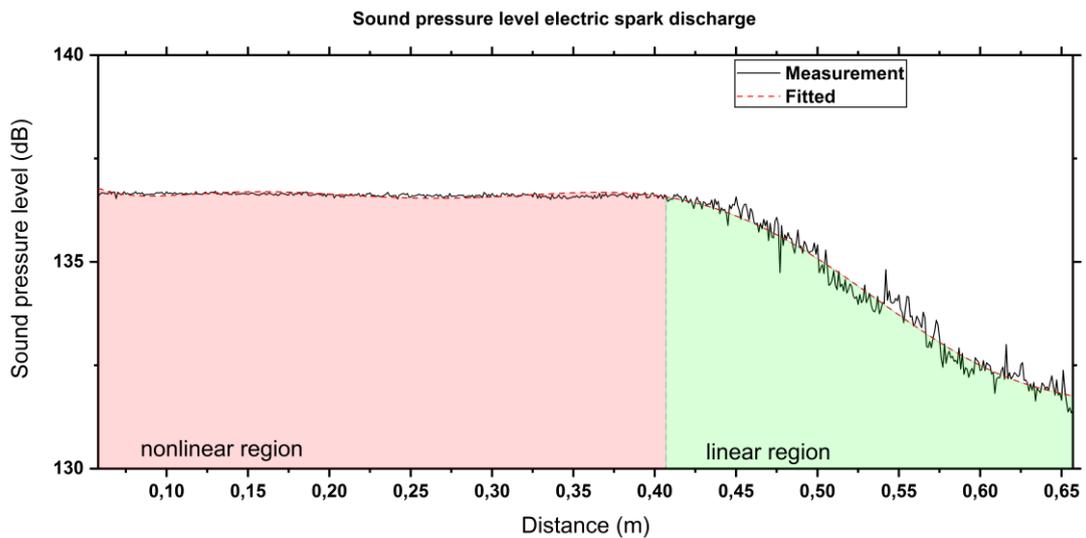


Figure 6. Sound pressure level over distance of an electric spark discharge.

4. Conclusions

Cellular polypropylene is a ferroelectret material offering new possibilities for the construction of air-coupled transducers. It can be easily formed, bended and structured, so that various apertures are possible. A recent innovation is a twin probe with a transmitter and a receiver placed on the same ferroelectret film. For common frequencies for air-coupled ultrasonic testing, it offers sensitivity 20 dB higher than transducers based on piezoceramics. If additional bias voltage is applied to the receiver, the sensitivity increases further by 12 to 15 dB. This makes it the most sensitive ultrasonic transmission system for non-destructive testing available. Ferroelectret transducers open new possibilities for the inspection of components with high signal losses. Beyond non-destructive testing, other applications are possible, where highly sensitive microphones in ultrasonic range are required.

The newest generation of thermoacoustic transmitters offer extremely high bandwidth and sound pressure levels comparable to conventional air-coupled transducers. Combined with other types of receivers, they are being considered for ultrasonic inspection. With their broad bandwidth they potentially offer more information about the inspected object, which would broaden the application field of air-coupled ultrasonic testing.

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