



Novel air-coupled ultrasonic transducer combining the thermoacoustic with the piezoelectric effect

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Abstract. In recent years, there has been an increasing industrial demand for one-sided inspection of various structures by means of air-coupled ultrasonic technique. Lightweight structures based on carbon-fibre-reinforced polymers may have very complex shapes, making air-coupled transmission difficult or even impossible. The inspection of concrete structures is another example where one-sided inspection is required.

To address these challenges a new type of transducer for air-coupled pulse-echo inspection was developed, which unites two principles: thermoacoustic emission and piezoelectric reception. The thermoacoustic emitter is a titanium electrode with a thickness of several tens of nanometer. This electrode was deposited onto charged cellular polypropylene, which serves as a piezoelectric receiver. The thermoacoustic transmission is based on a transformation of the thermal energy of an electrically heated electrode into the acoustic energy of an ultrasonic wave. Thermoacoustic emitters provide resonance-free behaviour and thus extremely broadband pulses. Charged cellular polypropylene is piezoelectric due to the polarization of its cells and it is well matched to air, with a Young modulus in the order of magnitude of MPa. In this contribution we present some pulse-echo measurements with the first prototypes of the combined thermoacoustic-piezoelectric transducer.

1. The Need for Air-Coupled Pulse-Echo Ultrasonic Inspection

Increasingly complex shapes of lightweight structures pose new challenges to non-destructive testing. Various structures based on carbon-fibre-reinforced plastic (CFRP) and glued joints allow only one-sided access, for example, car bodies. Most concrete structures also have to be inspected from one side. Inexpensive and contact-free alternatives to conventional ultrasonic testing are being explored, like thermographic (TT) and air-coupled ultrasonic testing (ACUT). While the former has the advantage of one-sided access to the inspected object, the latter is well established only as through transmission technique, where two-sided accessibility is required [1].

ACUT with pulse-echo technique or a dual-element probe is particularly challenging. Piezoelectric (PE) transducers are basically damped mass-spring systems, which show post-ringing of the transducer and hence a long decay time of generated



acoustic signals. The acoustic impedance of a test piece is typically four orders of magnitude larger than that of air. This enormous impedance mismatch is responsible for a very long and strong surface reflection overshadowing any useful signal from the inside, so that conventional air-coupled pulse-echo technique is not used for volume inspection. For this reason there is a need to increase both the sensitivity of transducers and their bandwidth. Thermoacoustic (TA) emitters have proven to be a good solution, when a large bandwidth is needed [2]. In this contribution, we first report about various TA emitters applied to non-destructive materials testing, and then we present a new type of air-coupled ultrasonic transducer for pulse-echo inspection, which unites two principles: TA emission and piezoelectric reception.

2. Thermoacoustic Air-Coupled Ultrasonic Transmitter

Electro-thermoacoustic air-coupled ultrasonic transmitter consists either of free-standing electrically conductive films or wires, or of electrically conductive films on solid substrates [3][4]. The sound waves emerge while current is applied, due to transfer of thermal energy to the adjacent gas particles. After switching off of the electric current, the transmitter surface cools down and the energy of the adjacent gas particles returns to that of the initial state. Therefore, a TA emitter displays no post-ringing and can be applied as a broadband airborne ultrasound source [2][3][5].

Figure 1 illustrates schematically the functioning principle of TA transmitters and their broadband spectrum. The TA transmitter used for these measurements was the combined TA-PE transducer described in Section 3. It was prepared with a 100 nm thick titanium electrode deposited on cellular polypropylene. This transmitter was excited with a saw-tooth signal and the sound pressure was measured using laser Doppler vibrometer and a polyethylene membrane at 4 cm from the transmitter, in a way described in [5]. Thermoacoustically generated sound pressure follows almost exactly the shape of the electrical excitation pulse. This makes it possible to generate nearly arbitrarily shaped acoustic signals without post-ringing [2][3][5].

Planar piezoelectric transmitters exhibit so-called natural focusing, which arises from the interference of the narrow-band sound wave. The sound field of a planar TA transmitter is not focused if it is excited with a short pulse, but it can be focused by curving the electrically conductive film or the substrate carrying it. A circularly shaped and spherically focussed TA transducer with concentric electrodes was constructed (Fig. 3(a)).

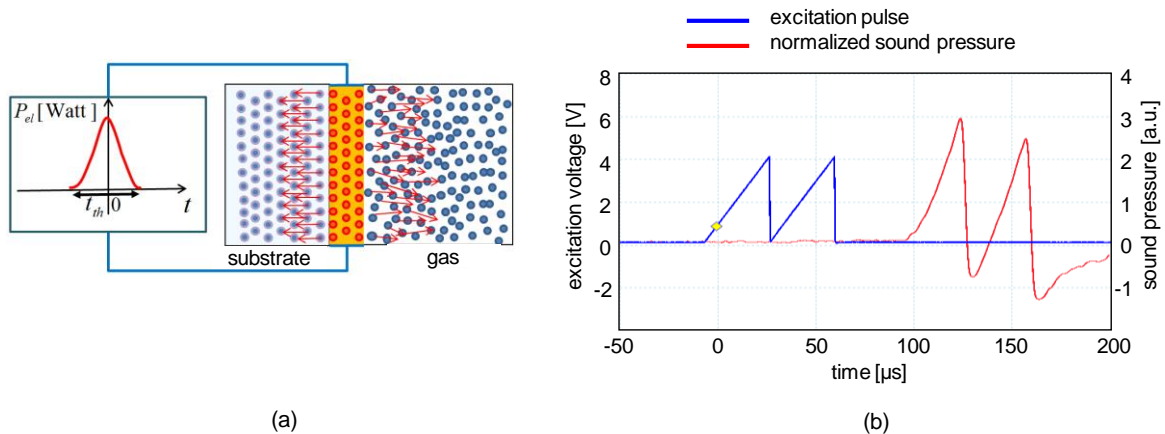


Fig. 1. (a) Schematic representation of the thermoacoustic principle and (b) a measurement of the thermoacoustically excited sound pressure.

Spherically curved glass substrate with a curvature radius of 55 mm was coated with 200 nm thick indium-tin-oxide (ITO) using plasma coating process. This ITO layer with an aperture of 50 mm served as an electrically conductive film. Using this transmitter and a focussing piezoelectric receiver based on cellular polypropylene [6][7] it was possible to inspect a 4 mm thick 0/90° CFRP plate in through transmission technique and to detect step wedge inserts as narrow as 1 mm (Fig. 2) [3]. To the best of the authors' knowledge, this is the first successful application of TA emitters in ultrasonic non-destructive testing.

The same TA transmitter was applied in a configuration which enables one-sided access to a test piece. The TA transmitter was combined with a laser Doppler vibrometer (LDV) as a broadband receiver, as illustrated in Fig. 3, so that the laser vibrometer

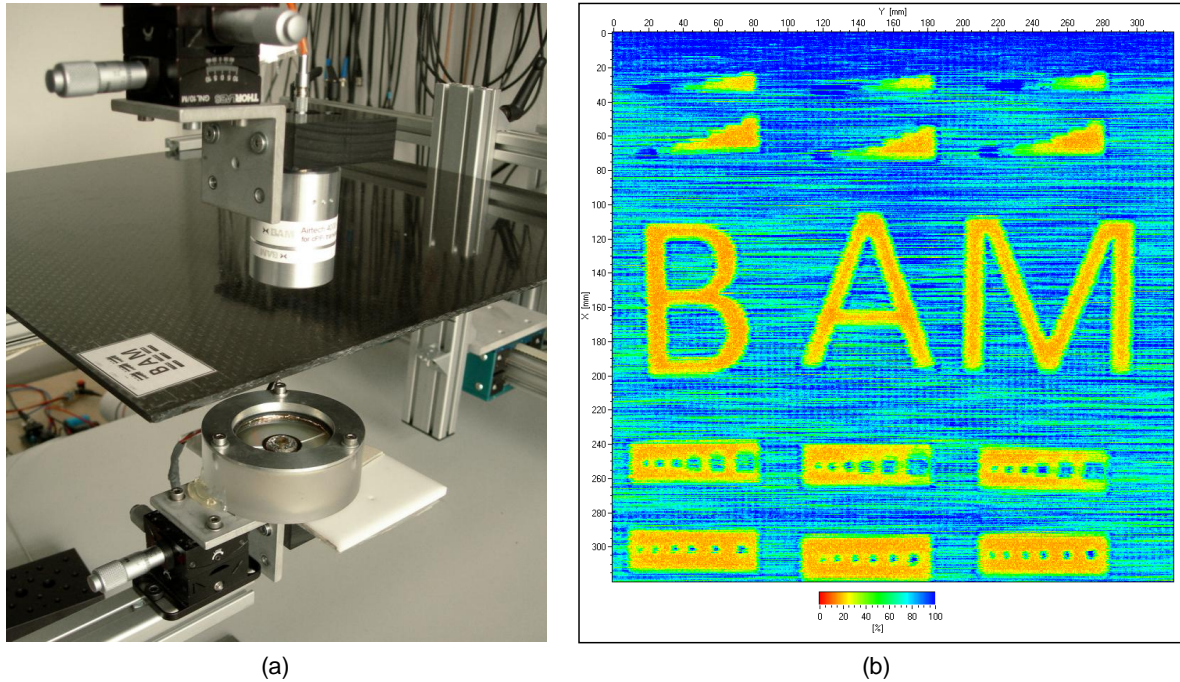


Fig. 2. (a) Setup for a through transmission with a thermoacoustic transmitter (bottom) and a piezoelectric receiver (top) and (b) the corresponding C-Scan.

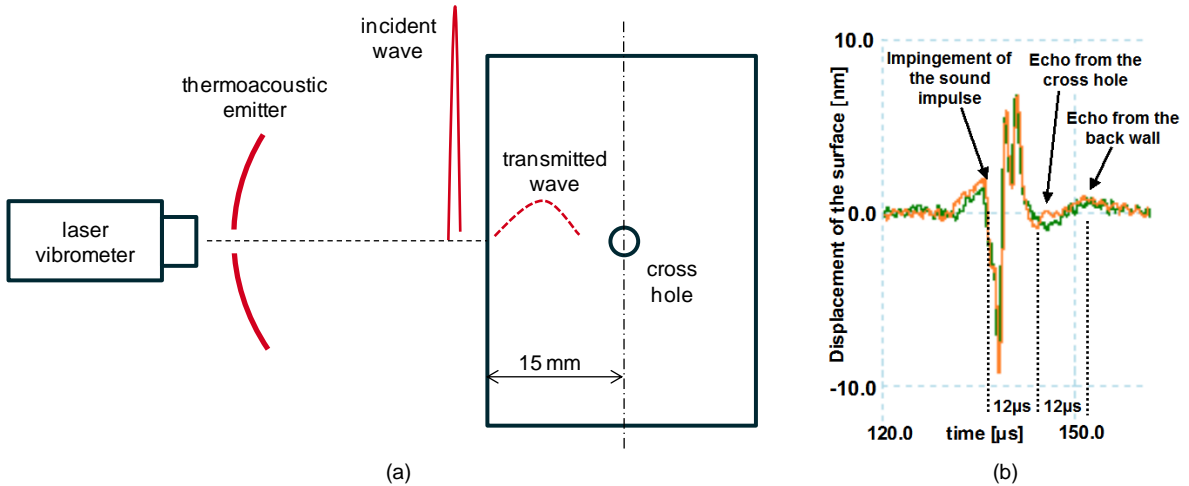


Fig. 3. (a) Setup for an inspection with a focussing thermoacoustic transmitter and a laser vibrometer as a receiver. (b) The orange curve is the signal over the cross hole and the green curve the signal over the intact region.

measured the displacement velocity of the block surface at the beam index. The test piece was a Plexiglas block with a 3 mm cross hole at 15 mm depth. The transmitter was excited with single excitation pulses of 1.5 μ s duration and 20 kW power. Fig. 3 (b) compares the displacements of the Plexiglas block surface measured by a laser vibrometer. The signals were measured over a cross hole of 3 mm diameter located approximately in 1.5 cm depth (orange curve) and 2 cm beside the cross hole at an intact region (green curve). Both time-signals are averaged over 256 measurements. The difference of the two signals indicates the presence of the cross hole in the test piece, which would not be possible with conventional air-coupled transducers and one-sided access due to post-ringing of piezoelectric transducers.

3. Transducer Combining the Thermoacoustic with the Piezoelectric Effect

A new type of air-coupled ultrasonic probe combining the principle of TA transmission with piezoelectric (PE) reception of ultrasonic pulses has been constructed and tested (Fig. 4). The receiving function is provided by a PE transducer based on cellular polypropylene (cPP). Charged cPP is piezoelectric due to the polarization of its cells and it is well matched to air, with a Young modulus about 1 MPa at frequencies around 300 kHz, which is a typical resonance frequency of a cPP transducer. The outgoing signal of the cPP transducer is amplified with a low-noise preamplifier matched to the extremely high output impedance of the transducer, which is between 1 and 10 M Ω . In our thermoacoustic-piezoelectric transducer, the outer electrode of the piezoelectric receiver serves as the electrically conductive film of the thermoacoustic transmitter, so that the cPP film has two functions: as a PE receiver and as a substrate for the TA transmitter. The transmitting outer electrode with an area 20x20 mm is a 100 nm thick layer of titanium deposited to the cPP film by means of electron beam evaporation. The electrical excitation signals were provided by an external sending unit. The cPP film was previously glued to a spherically curved surface carrying the other electrode. This technological process of focussing was described in [6] and [7].

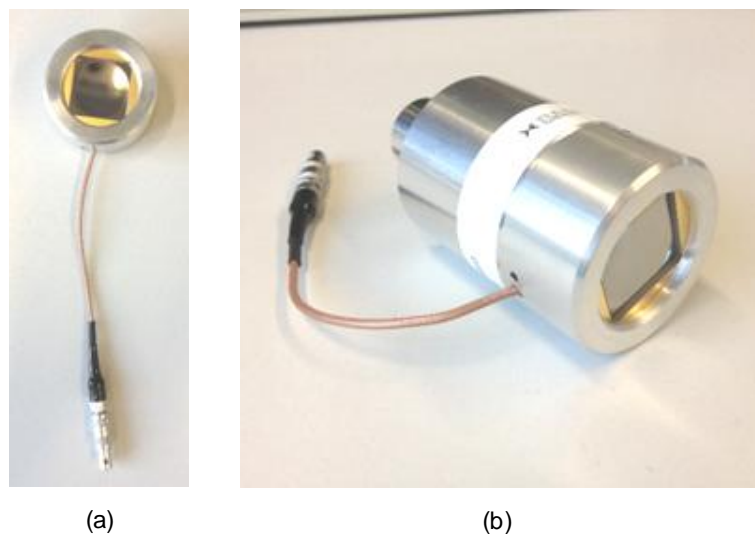


Fig. 4. (a) Thermoacoustic-piezoelectric transducer, (b) attached to a preamplifier. The cable provides connection to an external sending unit.

A pulse-echo measurement on a step wedge was performed to reconstruct the contour of this test piece (Figures 5 and 6). The transducer was excited with 53 V square pulses with a pulse repetition frequency (PRF) of about 200 Hz. The time of flight as well as the signal height was evaluated. Using the time of flight, flat-bottom holes with 4 mm or larger diameter were detected, while the holes with 2 mm diameter were not detected. In C-Scans even the smallest holes with a 1 mm diameter were detected. The 1 mm high steps were clearly distinguishable on the time-of-flight image. Experiments on further prototypes are necessary to investigate the abilities and the limits of this type of transducer.

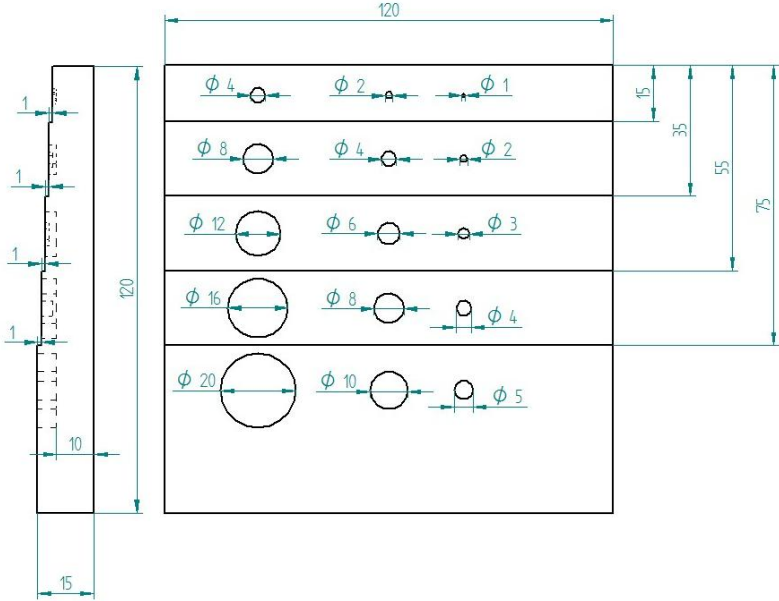


Fig. 5. Step wedge test piece containing flat-bottom holes.

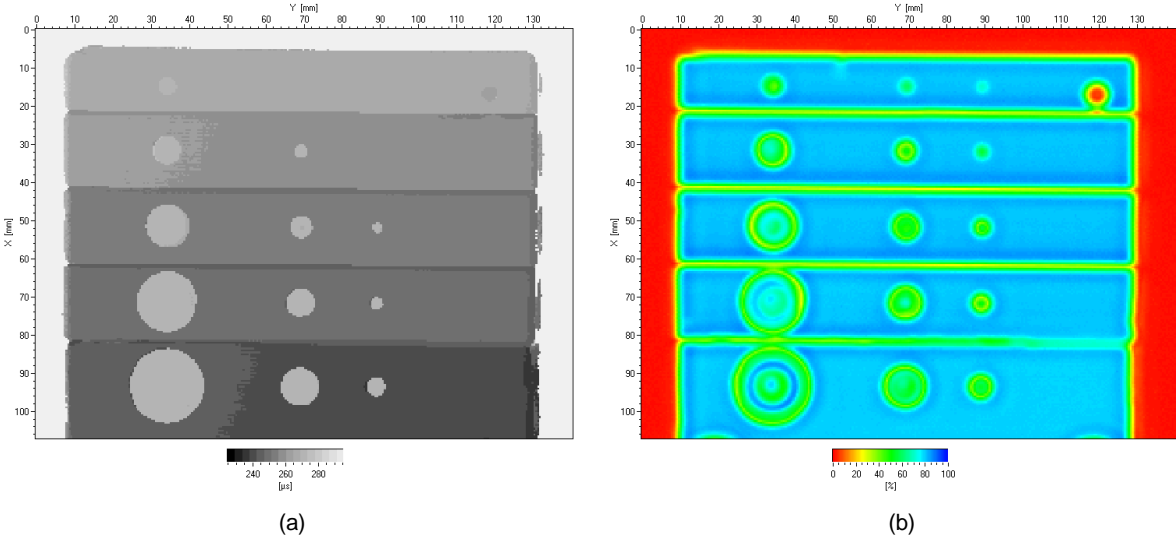


Fig. 6. (a) Time of flight and (b) C-Scan on a step wedge with flat-bottom holes using the thermoacoustic-piezoelectric transducer.

4. Conclusions

In this contribution we presented some new thermoacoustic (TA) air-coupled ultrasonic transmitters and demonstrated their applications in non-destructive testing. For the first time, a TA transmitter consisting of an electrically conducting film made of ITO and a glass substrate was successfully applied for a through transmission inspection of a CFRP plate. Additionally, a configuration of a TA transmitter and a laser vibrometer as a receiver was applied for inspection with one-sided access. The measurement results demonstrate the applicability of TA transmitter as a new tool for non-contact airborne ultrasound inspection with one-sided access.

Beyond this, a new type of air-coupled ultrasonic transducer was constructed, which unites a TA transmitter and a cPP-based PE receiver. The first measurements with these probes suitable for test objects with one-side accessibility show promising results. Measurements on a step wedge profile show that flat-bottom holes with 4 mm diameter can be detected using the evaluation of the time of flight and 1 mm holes using C-Scans. Thermoacoustic transmitters have the advantage of an extremely large bandwidth compared to conventional air-coupled ultrasound transducers, which makes them suitable for many different applications. Experiments on further prototypes are necessary to investigate the capabilities and the limits of this new type of ultrasonic transducer.

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