Review of Air-Coupled Transduction for Nondestructive Testing and Evaluation

The future of nondestructive testing lies in the ability to efficiently generate waves in structures without contact.

Introduction

Nondestructive testing (NDT) of structures and mechanical parts is increasingly receiving attention as the need to monitor the health of aging infrastructure and quality controls on the manufacturing of mechanical parts is becoming more apparent. NDT is defined as using various tools, whether they be acoustic, electromagnetic, or thermally based, to inspect the structural integrity of these objects without damaging the object as a result of testing it. In the case of acoustic NDT techniques, a source transducer emits sound/vibrational waves into the structure under test and various techniques are then used to detect signatures of damage (such as micro or macro cracking, etc.).

In 1996, Delta Flight 1288 experienced engine failure when part of a fan hub entered the engine; this accident led to the death of two passengers. It was later determined that undetected micro-fractures missed during routine maintenance were the cause of the failure (Federal Aviation Administration, 2014). In 2002, a Boeing 747 operated by China Airlines catastrophically failed in flight, causing the death of 206 passengers and 19 crew members. The probable cause was the growth of incipient fractures, created during a previous noncritical accident that went undetected (Federal Aviation Administration, 2014). NDT techniques detected cracking and corrosion on the I-35W Mississippi River bridge in Minnesota prior to its collapse in 2007, yet measures were not taken to avoid the collapse that led to the deaths of 13 people (Wikipedia, 2014). In 2012, 16 workers at the Idaho National Laboratory were exposed to radioactive powder as a result of damaged stainless-steel cladding that housed the radioactive material (Associated Press, 2011). Each of these accidents, and many others, could likely have been avoided with the use of proper NDT techniques, along with appropriate intervention measures.

The vibration of solid structures for NDT, without contacting the structure, offers many advantages. As bonding between the source transducer and the structure is eliminated, along with the use of noncontact sensors (such as laser Doppler vibrometers and/or microphones), rapid imaging of large areas then becomes possible. Besides, it is not always desirable or feasible to use contact transducers on certain samples. The development of efficient air-coupled transducers, however, remains a challenge because of the large impedance contrast, by several orders of magnitude, between air and solids. Impedance is the product of the speed of sound and the density of the material or medium.
When there is a significant impedance change between two different media, in this case nearly 5 orders of magnitude difference between the face of the source transducer and the air, it is difficult to deliver energy into the air from the transducer’s motion. Practically, this means that only a fraction of the energy generated by the source will be transmitted into the air and then only a fraction will be transmitted to the structure. Essentially, nothing can be done about the impedance mismatch between the air and the structure under test. Fortunately, a number of approaches have been proposed to improve the transmission of energy from the source into the air. Noteworthy reviews on this topic include the paper of Green (2004) and the recent one of Chimenti (2014). Both focus on non-contact transduction devices while the latter also discusses the implementation of several NDT techniques. The present paper provides an overview of recent advances on the development of air-coupled transducers for NDT applications, with some new techniques that are not reported in either of the aforementioned papers, and a brief review of many traditional types of air-coupled transduction.

Conventional Non-Contact Sources

Most commonly, generation of ultrasonic waves inside a material through air is achieved with piezoelectric transducers that are manufactured from a bulk piece of ceramic. A piezoelectric material is characterized by its ability to convert electric energy into mechanical energy, and vice versa. The large impedance contrast between the piezoelectric material and air can be mitigated with resonant matching layers that are glued onto the surface of the transducer and that basically act as an impedance transition between the piezoelectric material and the air. Initial work on the design of such layers suggested a single layer with two characteristics: (1) a thickness of one quarter of a wavelength at the resonance frequency of the transducer so that a standing wave can be established across the layer; and (2) an impedance close to the geometrical mean of the impedances of the piezoelectric material and the medium the source is radiating into (Lynneworth, 1965). For air-coupled applications, the impedance of the matching layer should range between 0.001 and 0.1 MRayl (Haller et al., 1994). Many porous materials with impedances approaching this range, including cork and balsa wood, cannot be used as matching layers because they exhibit high attenuation, which deteriorates the performance of the transducer (Schiller et al., 1994; Stor-Pellinen et al., 1989). Practical materials for this application include silica aerogel (Krauss et al., 1994), silicone rubber loaded with micro-spheres (Yano et al., 1987), and porous membranes (Kelly et al., 2001). Most of these materials have impedances close to 0.1 MRayl and relatively low attenuation. Note that silica aerogel is limited to applications below 100 kHz because it does not lend itself to machining at the thickness that would be required for higher frequency applications. A detailed review of the materials used in the design of matching layers, including their attenuation, impedance, and performance, is given by Gómez Álvarez-Arenas (2004). The matching layer can also be created using micro-fabrication techniques (Haller et al., 1994) for operating frequencies approaching 1 MHz. The main disadvantage of using a single matching layer is the reduced bandwidth and the subsequent ringing of the transducer. To address this limitation, the use of multiple layers has been proposed, where the intermediate layers increase the bandwidth with a reduced effect on the sensitivity (Goll et al., 1975; Desilets et al., 1978).

Alternatives to matching layers have been proposed to enhance the ultrasonic radiation of bulk piezoelectric transducers. Multiple ultrasonic horns obtained by chemical etching on a plate have been tested in the range of 20 to 100 kHz (Fletcher and Thwaites, 1992). Another strategy has been to reduce the impedance of the active element through the use of composites made of ceramic pillars embedded in a uniform filler material (such as epoxy) matrix (Reilly and Hayward, 1991; Smith and Auld, 1991). The mechanical properties of the composite can be adjusted with the volume fraction of ceramic. Impedance matching has also been achieved by constraining a thin layer of air between the surface of the piezoelectric element and a thin polymer membrane or a perforated plate (Toda, 2002). Last, some recent numerical work has suggested the possibility of using wedges of power-law profiles to provide a gradual impedance matching (Remillieux et al., 2014). Ideally, for a perfect wedge tip with no thickness, these profiles ensure that the

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elastic waves generated within the thickest portion of the
diode (or adjacent plate) by a bulk piezoelectric transducer
propagate towards the diode tip and never reflect back from
it. In practice, the diode tip has a finite thickness and re-
ffects some of the energy back into the diode. Despite this
imperfection, power-law profiles provide a smooth imped-
ance matching transition for the large-amplitude flexural
waves observed in the thinnest region of the diode (near
the diode tip), thus improving significantly the ultrasonic
radiation in air. The experimental validation of this numeri-
cal work is underway.

Capacitive ultrasonic transducers are an alternative to bulk
piezoelectric transducers. They were introduced in the
1950s (Kuhl et al., 1954). Their principle of operation is radi-
cally different from that of piezoelectric transducers. They
typically consist of two components: (1) a fixed electrode - a
conducting back plate with a microscopically rough surface
of random profile; (2) an electrode allowed to deform - a
thin dielectric polymer membrane coated on one side with
a conducting layer and stretched over the back plate. A bias
voltage is applied so that the oppositely charged electrodes
attract. As a result, the membrane is stretched further and
remains in contact with the back plate. Because of the vary-
ing surface profile of the back plate, the membrane is rest-
ing on point-like supports and small air gaps are formed be-
neath the membrane. Under a voltage signal, the membrane
deforms and displaces the surrounding fluid, which gener-
ates ultrasonic waves. The transducer can also be used as a
receiver under the reciprocal process. Capacitive ultrasonic
transducers offer two advantages over piezoelectric trans-
ducers: a better impedance matching with air and a wider
bandwidth (Schindel, 1996). Their performance depends
mainly on the dimensions of the air gaps, the membrane
properties (such as density, dimensions), and the bias voltage
(Carr and Wykes, 1993). At high frequencies, such as above
1 MHz, it is not possible to control the size of the air gaps
beneath the membrane through traditional manufacturing
techniques. The subsequent variation of the membrane ten-
sion across its surface leads to reduced performance of the
transducer.

The advent of micro-fabrication techniques led to the rapid
development, since the late 1980s, of capacitive microma-
chined ultrasonic transducers (CMUTs). The interested
reader is referred to the review of Khuri-Yakub and Oralkan
(2011) on this topic. Microfabrication techniques provide
control over the parameters for which there were uncertain-
ties in traditional capacitive ultrasonic transducers: in-
plane tension and air-gap size. Additionally, the reduc-
tion of the membrane and air-gap sizes allows reaching
higher frequencies, in the tens of MHz, which was not pos-
sible previously. A photograph of a CMUT array is de-
picted in Figure 1a.

Figure 1: Photographs of MUT arrays.
(a) CMUT provided by Prof. Butrus
(Pierre) Khuri-Yakub from Stanford
University. (b) PMUT provided by Dr.
Arman Hajati from FUJIFILM Dimatix.

The operating prin-
ciple of CMUTs is identical to that of traditional capacitive
ultrasonic transducers. However, there are three practical is-
issues with CMUTs: (1) the bias voltage must be close to the
collapse voltage to achieve the theoretical electromechanical
coupling, which is not possible given the current tolerances
in micro-fabrication techniques; (2) the design must be dif-
ferent for optimal transmitting and receiving operations:
a small air gap is required to increase sensitivity when the
CMUT is used as a receiver whereas the relatively large dis-
placement of the membrane in a transmitter requires a much
larger air gap; and (3) they have a small capacitance (large
electrical impedance), thus making their operation sensitive
to parasitic capacitances. To minimize the effect of parasitic
capacitance and to limit the potential of interference on the
cabling, the transmitter/receiver electronics should be kept
close to the CMUT elements (ideally integrated on a single
chip).

Piezoelectric micromachined ultrasonic transducers
(PMUTs) are an alternative to CMUTs that still benefit from
micro-fabrication techniques for miniaturization and preci-
sion control but do not need a conducting back plate to be
operated. A photograph of a PMUT array is shown in Figure
1b. Essentially, they consist of an electroded thin piezoelec-
tric film deposited on a (possibly multilayered) membrane
resonator, which is typically on the order of microns in
the thickness and tens of microns in the in-plane direction
(Akesheh et al., 2004). An electric field is applied across the
thickness of the piezoelectric film, which in turn induces
a deformation of the membrane according to its bending
modes. The piezoelectric film is used as an actuating element only while the ultrasonic radiation characteristics (such as operating frequency) are dictated by the membrane properties. Other advantages over CMUTs include: (1) a higher capacitance, which makes the transducer less vulnerable to parasitic capacitances and the use of coaxial cables possible; (2) lower power requirements due to the elimination of the bias voltage; and (3) lower sensitivity to fabrication accuracy. It is worth mentioning that PMUTs do not offer a perfect alternative to CMUTs as the deposition of a high quality thin piezoelectric film, free of defects, remains a challenge and therefore, an active topic of research. Defects in the thin film may include micro-cracks, pinholes, lattice misorientation, and non-uniform thickness.

Ultrasonic arrays of transducers have been increasingly preferred over single-element transducers because, when combined with appropriate signal processing techniques, they offer many attractive features, including some flexibility in the type of ultrasonic fields generated (such as plane waves, steered beams, and focused excitation) and better imaging capabilities. An extensive review on this topic for NDT applications, including transducer materials and array geometries, is given by Drinkwater and Wilcox (2006), with a particular focus on the phased array technology. The operation of phased arrays is based on the use of appropriate time delays between the signals applied to or received from the individual transducers. When parabolic delays are used, ultrasonic waves can be focused to a point-like geometrical source, a single wavelength (\(\lambda/2\)) at the operating frequency used for beam steering or focusing, then grating lobes will be generated. Grating lobes are essentially undesired side lobes resulting from the spatial under-sampling of periodically arranged elements. Usually, the \(\lambda/2\) limitation can be overcome by keeping the gap between the elements small while increasing the width of the element. As the element shape deviates from a point-like representation, its radiation becomes more directional and the contribution of the grating lobes is reduced but so is the range of angles at which beams can be steered.

Another conventional technique for non-contact transduction is based on the thermoelastic effect. White (1963) demonstrated that the thermal expansion resulting from transient heating on the surface of a solid generates elastic waves within the solid, which is referred to as the thermoelastic effect. Pulsed lasers are commonly used for this purpose since they can create a focused excitation in space and time. The amplitude of the excitation is related to the energy density. If it becomes too large, material ablation may occur as a result of the melting and evaporation of the material in the area targeted by the laser. The effect of the heating rate was studied by Gauster (1971). The depth of the damage is on the order of a few microns. This may not be acceptable in some NDT applications. In this case, the pulsed laser should be operated within the thermoelastic regime, such as below the threshold of ablation. Typically, for NDT applications, the pulse duration approaches 10 ns, which provides a broadband perturbation with frequency content up to 100 MHz (Viertl, 1980). Pulsed lasers have been used to excite different types of waves in structures. Despite many advantages, the operation of a pulsed laser requires high power and appropriate safety measures to be taken. Therefore, it does not have the same practicality as air-coupled sources.

**Time Reversal Acoustic Non-Contact Excitation**

A high amplitude acoustic source has been developed at the Los Alamos National Laboratory (LANL) using the principle of reciprocal time reversal (TR) to focus energy in time and space on the surface of a sample without contact (Le Bas et al., 2013). A prototype of this source is depicted in Figure 2. The hardware essentially consists of a hollow cavity enclosed by thin metallic walls onto which some piezoelectric transducers are glued. The size(s) of the transducers will
determine the optimal operating frequencies of the source. The cavity creates a diffusely scattered wave field inside and contains an opening to allow a progressive emission of the scattered waves. The cavity has two holes in order to shine a laser vibrometer through it. The elastic response recorded by the laser at a point on the surface of the test sample is used to calibrate the source to focus energy at that point, as will be described below. The larger hole at the top of the pyramid is also the main sound transmission path from the source to the sample. Note that, in a TR experiment, scattering is beneficial to the ability of focusing energy in time and space because each reflection acts as a virtual source. In other words, a TR experiment can be conducted successfully with only one transducer as long as the medium is highly reverberant and weakly dissipative. This is clearly an advantage over phased arrays where scattering would deteriorate the performance of the array.

A standard TR experiment in a reverberant medium consists of two steps that can be briefly summarized as follows (Anderson et al., 2008). In the first step, or forward propagation, a known signal is emitted from a source at a point A while a receiver is recording the signal at a point B. The received signal is the convolution of the impulse response between points A and B with the source signal. This impulse response is rather complex due to the multiple propagation paths within the bounded medium. In the second step, or backward propagation, the received signal is reversed in time and remitted from point B. The invariance of the wave equation implies that the various broadcasts of energy from each virtual source will coalesce at point A, where the original source signal will be reconstructed (Fink, 1992). There are some imperfections in this reconstruction process, mainly because the directional information of the energy received in the forward signals is not typically used, attenuation that exists in a realistic system, and a limited (as opposed to infinite) acquisition time of the forward-propagation signal is used. It is possible to interchange the source and the receiver positions thanks to the principle of spatial reciprocity (Achenbach, 2003). In the backward-propagation step of a reciprocal TR experiment, the received signal is remitted from the source point A and coalesces at the receiver point B.
Experiments were conducted on a thin metallic plate (Figure 2) and the performance of the LANL source was compared to that of a commercially available Focused Ultrasound Transducer (FUT) that makes use of impedance matching layers and some geometry optimization. Figure 3 shows the velocity fields on the plate at an instant in time and the signals recorded at the focal point location. One advantage of the LANL source is the ability to generate only one distinct large amplitude pulse of energy whereas the FUT repeatedly produces pulses of energy due to the multiple reflections between the surface of the FUT and that of the test sample. The size of the focal spot is approximately five times smaller with the LANL source than with the FUT. Last, the LANL source also offers a significant gain of amplitude, in this case a factor eight times. Note that this gain was obtained with a prototype device that was not optimized in any way and that was built for the purpose of demonstrating that the concept was working. Optimization studies are under way. In particular, the effects of the wall thickness, layout of the transducers, and shape of the cavity are investigated. An additional gain of amplitude is expected from an optimized device.

Last, it is worth mentioning that the spot size (measured as full width at half maximum) achieved by a TR mirror in the far field cannot be smaller than half a wavelength as a consequence of the diffraction limit. Sub-wavelength components of the acoustic field cannot be recovered by TR in the far field of a homogeneous medium because they are carried by evanescent waves, which decay exponentially with the distance from the source. The diffraction limit can be overcome by using, for instance, a distribution of scatterers with specific sizes in the near field of the source, to achieve sub-wavelength focusing (Lerosey et al., 2007). Evanescent waves convert to propagating waves as they diffract off the scatterers.

**Focused Electric Spark Source**

Focusing can also be achieved by appropriately tuning the shape of the transducer: usually with an ellipsoidal shape. This strategy has been used for bulk piezoelectric transducers that are combined with impedance matching layers (Bhardwaj, 2001), with capacitive ultrasonic transducers (Song et al., 2006), and spark sources (Dai et al., 2013). The performance of the first type of focused transducer has been discussed in the previous section, in comparison with that of the LANL source (TR mirror). The second type of focused transducer can achieve diffraction-limited focusing, like the TR mirror. The third type is discussed in more details below, since it is a new apparatus that is neither based on bulk piezoelectric transducers nor capacitive ultrasound transducers.

Recent efforts at The University of Texas (UT) at Austin have been focused on the generation of high amplitude air-borne acoustic signals for non-contact excitation of wave motion in concrete slabs to aid in the rapid inspection of the nation’s infrastructure (Dai et al., 2013). The non-contact air-coupled NDT device devised by UT is schematized in Figure 4 and consists of a spark generator and an ellipsoidal focusing mirror. The spark generator consists of two electrodes separated by a small air gap which is collocated with the near focus of the ellipsoidal reflector. A high electric potential is generated across the electrodes of the spark generator by charging a large capacitor that is electrically in parallel with the electrodes. Discharge occurs when the electric field between the electrodes reaches a critical level and the ensuing spark creates a rapid and intense heating of the air resulting in a high amplitude acoustic disturbance that spreads outward with nearly omnidirectional directivity. This transient wave spherically diverges from the near focus until it encounters the ellipsoidal reflector, when it is then reflected and re-directed back to the far focus. The reflected wavefront
converges at the far focus where the amplitude is proportional to the time-derivative of the spark-generated signal and some gain factor related to the geometry of the reflector (Hamilton, 1993). Because the spark-generated wave has a very short rise-time, and thus a high temporal derivative, the peak pressures at the far focus are very high and thus capable of generating elastic waves in the sample to be interrogated. In-air peak pressures as high as 180 dB re 20 μPa at the far-focus have been measured (Dai et al., 2013).

It is important to point out that the use of spark-generated signals to generate high amplitude acoustic waves is nothing new. Indeed, Wright and Blackstock (1997) used spark-generated signals to study on-axis wave field resulting from spark-generated air-borne N-waves that were focused by an ellipsoidal reflector. Further, use of a spark discharges for ultrasonic NDT has also been explored with some success (Cooper et al., 1984; Korolev et al., 1987). Those discharges result in intense, transient, and localized heating at the surface of the sample and a subsequent high frequency ultrasonic signal with amplitudes similar to those generated by pulsed lasers. This approach proved to be somewhat problematic, however, because numerous spark discharges on the surface of the interrogated sample resulted in damage due to ablation and thus alternative configurations were investigated.

Krylov and colleagues later investigated the use of air-borne acoustic waves generated by in-air sparks with some encouraging results for generating elastic wave motion in aluminum. Their studies included un-focused (Krylov, 1992) and spherically focused air-borne waves (Korolev and Krylov, 1988). Each of those had drawbacks which apparently discouraged further study. Curiously, no results were ever reported by Krylov and colleagues that employed an ellipsoidal reflector paired with spark-generated acoustic waves which enables wave focusing without requiring collocation of the source and focus points.

The ultrasonic source developed at UT has been used for impact-echo testing in concrete plates. This technique (impact-echo) consists of impulsively loading the surface of the plate, usually via contact such as a hammer blow, and recording the out-of-plane motion. The spectrum of the response contains a peak corresponding to the impact-echo frequency, which is proportional to the compressional wave speed in the material and inversely proportional to the sample thickness (Sansalone and Carino, 1986). Recent analysis has shown that these impact-echo frequencies are associated with zero-group-velocity (ZGV) Lamb modes that represent localized wave motion with non-zero phase velocity but zero group velocity and have high excitability (Gibson and Popovics, 2005; Prada et al., 2008). Because these modes have zero-group velocity, they represent wave motion that is trapped near the source point and thus is long lived and relatively easy to detect.

Theoretical and experimental work at UT shows that the focused spark-generated air-borne signal has a sufficiently small spot size on the air-solid interface that broadband surface waves can be generated in concrete and detected using accelerometers on the surface (contact sensing) or microphones positioned close to the surface (non-contact sensing), as seen in Figure 5 for the case of a 25 cm thick concrete plate. The results clearly show that a spark-generated signal focused by an ellipsoidal reflector enables fully air-coupled interrogation of the surface of a specimen with high acoustic impedance. Other work exploiting the properties of ZGV modes was based on the use of traditional air-coupled ultrasonic transducers (Holland and Chimenti, 2004) and pulsed laser excitation (Cès et al., 2011).

**Conclusion**

Nondestructive testing (NDT) is increasingly relied upon for monitoring aging infrastructure and for evaluating transportation structures. Air-coupled (non-contact) transduction allows rapid testing of these structures and thus increases the practicality of NDT implementation. Developments in the next generation of air coupled sources, that utilize time-reversal focusing or a focused electric spark source, will provide more reliable excitation with higher amplitudes and allow the use of advanced NDT techniques.
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TJ Ulrich has been conducting research using time reversal and nonlinear elasticity at Los Alamos National Laboratory (LANL) for the past 10 years, first as a post-doc and now as a research scientist. During this time he has developed many international collaborations and enjoys traveling the world to work on various topics on acoustics, nondestructive evaluation, and materials characterization. Prior to coming to LANL, TJ attended the University of Nevada, Reno where he obtained degrees in Materials Science and Engineering (B.S.) and Physics (M.S. and Ph.D.). His current research focus is developing the next generation of acoustic tools for nondestructive evaluation of mechanical parts and structures, specifically for nuclear energy applications, as well as geophysical exploration tools and techniques for the oil and gas industry. When at all possible you can find TJ at his home away from home on the slopes of Taos Ski Valley with his family or down in town enjoying the blue corn and green chile.

Pierre-Yves Le Bas is currently a research scientist at Los Alamos National Laboratory. He obtained his Ph.D. in acoustics from the University of Le Havre, France in 2004. Pierre-Yves was one of the experimentalists in a European project called AERONEWS where he developed NDE techniques combining Time Reversal and nonlinear elasticity during a post-doc at KU Leuven, Belgium. His work includes the use of nonlinear acoustic techniques for nondestructive evaluation and borehole imaging. He is a certified LabVIEW architect for developing experimental systems. Pierre-Yves enjoys mentoring the Los Alamos High School FIRST robotics team, project Y.

Biosketches continued on next page.
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References


