# Review of Air-Coupled Transduction for Nondestructive Testing and Evaluation

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*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 (Lynnworth, 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).

**"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."**

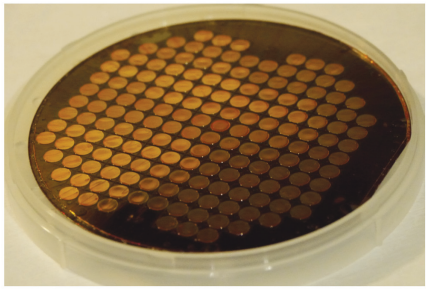
Alternatives to matching layers have been proposed to enhance the ultrasonic radiation of bulk piezoelectric transducers. Multiple ultrasonic horns obtained by chemical etching on a plate have been tested in the range of 20 to 100 kHz (Fletcher and Thwaites, 1992). Another strategy has been to reduce 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

elastic waves generated within the thickest portion of the wedge (or adjacent plate) by a bulk piezoelectric transducer propagate towards the wedge tip and never reflect back from it. In practice, the wedge tip has a finite thickness and reflects some of the energy back into the wedge. Despite this imperfection, power-law profiles provide a smooth impedance matching transition for the large-amplitude flexural waves observed in the thinnest region of the wedge (near the wedge tip), thus improving significantly the ultrasonic radiation in air. The experimental validation of this numerical 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 radically 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 varying surface profile of the back plate, the membrane is resting on point-like supports and small air gaps are formed beneath the membrane. Under a voltage signal, the membrane deforms and displaces the surrounding fluid, which generates ultrasonic waves. The transducer can also be used as a receiver under the reciprocal process. Capacitive ultrasonic transducers offer two advantages over piezoelectric transducers: 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 tension 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 micromachined 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 uncertainties in traditional capacitive ultrasonic transducers: in-plane tension and air-gap size. Additionally, the reduction of the membrane and air-gap sizes allows reaching higher frequencies, in the tens of MHz, which was not possible previously. A photograph of a CMUT array is depicted in Figure 1a. The operating principle of CMUTs is identical to that of traditional capacitive ultrasonic transducers. However, there are three practical 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 different 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 displacement 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).

(a)



(b)

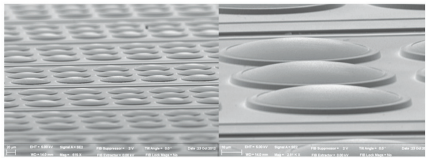


**Figure 1:** *Photographs of MUT arrays. (a) CMUT provided by Prof. Butrus (Pierre) Khuri-Yakub from Stanford University. (b) PMUT provided by Dr. Arman Hajati from FUJIFILM Dimatix.*

Piezoelectric micromachined ultrasonic transducers (PMUTs) are an alternative to CMUTs that still benefit from micro-fabrication techniques for miniaturization and precision 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 piezoelectric 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 specific point in air or on the surface of a sample (Azar et al., 2000). This allows reaching relatively high amplitude levels at the focal point compared to what a single-element transducer can generate.

The performance of a phased array is not only affected by transducer material and signal processing but also by its geometry. Initially, arrays were one-dimensional, which means that their elements were aligned along a linear axis and beams could be steered only in the plane formed by the axis of the array and the normal to the surfaces of the transducers. Simplification of the electronics and availability of cheaper hardware has spurred the development of two-dimensional arrays in which the elements are usually arranged in a checkerboard format. This added dimension allows three-dimensional steering. Annular arrays are the third type of arrays commonly encountered. They consist of a set of concentric rings with varying width so as to keep the surface area of each element constant. They allow the beam to be focused to different depths but only along the normal to the array surface passing through its center. One important aspect to consider when designing the array is the spacing between the elements. If the element spacing is larger than one half of a 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

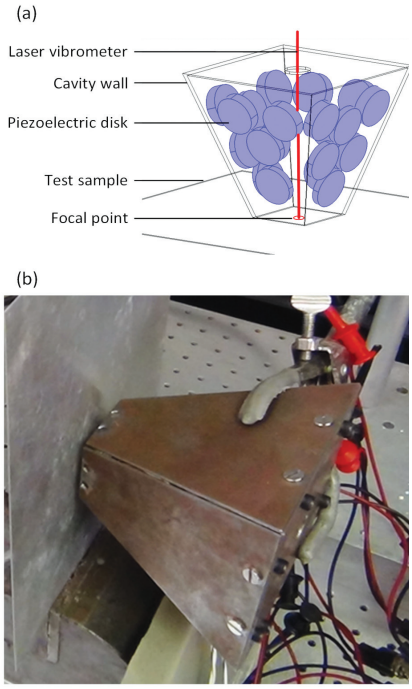



**Figure 2:** *The high-amplitude non-contact acoustic source based on reciprocal TR installed in front of a test sample: (a) drawing and (b) photograph of the experimental apparatus.*

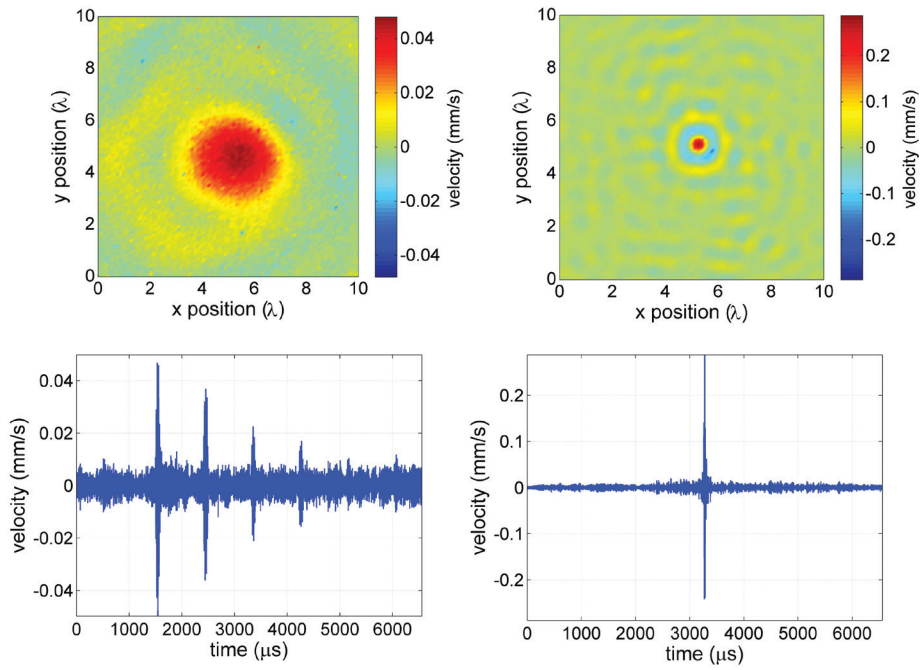



**Figure 3:** *Comparison of energy focusing on the surface of a thin metallic plate achieved with a Focused Ultrasound Transducer (left) and the TR non-contact source (right). Spatial extent of the focal spot in terms of wavelength (top) and time histories of the velocity at the focal point (bottom).*

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,

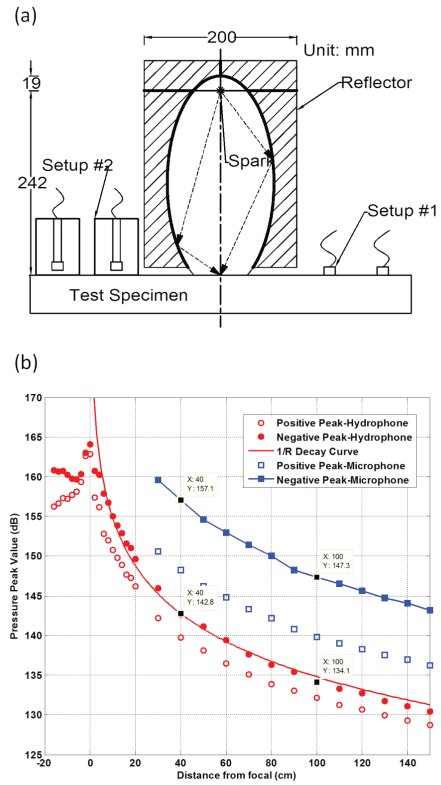



**Figure 4:** *(a) Schematic representation of the test setup including the spark source enclosed within the ellipsoidal reflector and (b) peak pressure amplitude versus distance along axis, measured by a hydrophone and a microphone. Hydrophone sensing was employed near the focus to enable measurement of high amplitudes without saturation (overloading).*

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.

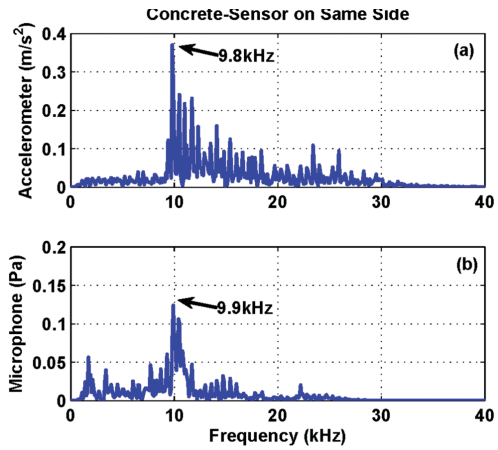


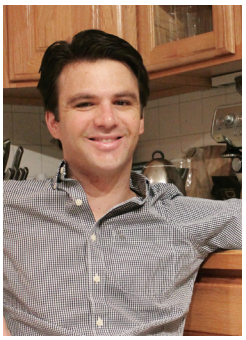

**Figure 5:** *Spectra showing the zero-group-velocity mode in a 25cm thick concrete plate measured using contact sensing and fully non-contact methods with spark-source excitation (Dai et al., 2013).*

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

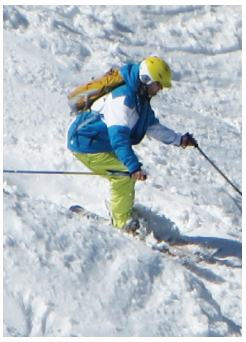
Nondestructive testing (NDT) is increasingly relied upon for monitoring aging infrastructure and for evaluating transportation structures. Air-coupled (non-contact) transduction allows rapid testing of these structures and thus increases the practicality of NDT implementation. Developments in the next 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.

## Biosketches



*Marcel Remillieux* is a post-doctoral research associate at Los Alamos National Laboratory. He is developing, implementing, and using numerical techniques to solve elastodynamic problems with applications to nondestructive testing. Between 2005 and 2012, he conducted research on NASA funded projects at Virginia Tech, where he received his M.S. and Ph.D. degrees in mechanical engineering. He also holds an Engineer Diploma in mechanical engineering from the Université de Technologie de Compiègne, France. During his undergraduate education, he was selected for a year-long exchange program with the University of Pennsylvania (Ivy League). Since that time, he has been mostly living in the United States and has been enjoying most of his vacations in France. In his free time, Marcel enjoys outdoor activities, skiing being his favorite, in New Mexico with his family.

*Brian Anderson* is a research scientist at Los Alamos National Laboratory (LANL) in the Geophysics Group where he develops new nonlinear acoustic techniques, using time reversal, for the nondestructive evaluation of mechanical parts and structures. He is an associate editor for the *Journal of the Acoustical Society of America*. Prior to coming to LANL, Brian spent 3 years as a visiting assistant professor at Brigham Young University (BYU) in the Dept. of Physics & Astronomy conducting research and teaching courses. He worked for three years as a postdoctoral research associate at LANL. He received a Ph.D. in Acoustics from the Pennsylvania State University in 2006 while working at the Applied Research Laboratory there. He received his M.S. and B.S. degrees in Physics from BYU. Brian enjoys GPS-based geocaching in his spare time with his three sons and his wife Angela.



*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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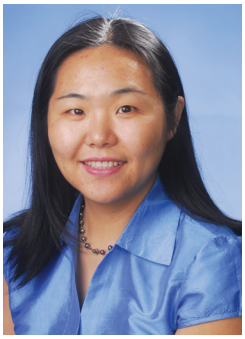

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## References

Achenbach, J. D. (2003). Reciprocity in Elastodynamics (Cambridge University Press, Cambridge, UK).

Akasheh, F., Myers, T., Fraser, J. D., Bose, S., and Bandyopadhyay, A. (2004). "Development of piezoelectric micromachined ultrasonic transducers," Sensors and Actuators A: Physical 111, 275–287.

Anderson, B. E., Griffa, M., Larmat, C., Ulrich, T. J., and Johnson, P. A. (2008). "Time Reversal," *Acoustics Today* 4, 5–16.

Associated Press, Idaho lab accident may stem from damaged container, Internet, last viewed May 8, 2014, http://examiner-enterprise.com/sections/news/nation/idaho-lab-accident-may-stem-damaged-container.html.

Azar, L., Shi, Y., and Wooh, S.-C. (2000). "Beam focusing behavior of linear phased arrays," NDT & E International 33, 189–198.

Bhardwaj, M. C. "Ultrasonic transducer for high transduction in gases and method for non-contact ultrasound transmission into solid materials," US Patent #6,311,573, November 6, 2001.

Carr, H., and Wykes, C. (1993). "Diagnostic measurements in capacitive transducers" Ultrasonics 31, 13–20

Cès, M., Clorennec, D., Royer, D., and Prada, C. (2011) "Edge resonance and zero group velocity Lamb modes in a free elastic plate," *Journal of the Acoustical Society of America* 130, 689–694.

Chimenti, D. E. (2014). "Review of air-coupled ultrasonic materials characterization," Ultrasonics, in press.

Cooper, J. A., Dewhurst, R. J., Moody, S., and Palmer, S. B. (1984). "High-voltage spark discharge source as an ultrasonic generator," IEE Proceedings A. Physical Science, Measurement and Instrumentation, Management and Education, Reviews 131, 275–281.

Dai, X., Zhu, J., and Haberman, M. R. (2013). "A focused electric spark source for non-contact stress wave excitation in solids," *Journal of the Acoustical Society of America* 134, EL513–EL519.

Desilets, C. S., Fraser, J. D., and Kino, G. S. (1978). "The design of efficient broad-band piezoelectric transducers," IEEE Transactions on Sonics and Ultrasonics 25, 115–125.

Drinkwater, B. W., and Wilcox, P. D. (2006). "Ultrasonic arrays for non-destructive evaluation: A review," NDT & E International 39, 525–541.

Federal Aviation Administration, Lessons learned from airplane accidents, Internet, last viewed May 8, 2014, http://lessonslearned.faa.gov/ll_main.cfm?TabID=3&CategoryID=7&LLID=60.

Federal Aviation Administration, Lessons learned from airplane accidents, Internet, last viewed May 8, 2014, http://lessonslearned.faa.gov/ll_main.cfm?TabID=3&CategoryID=7&LLID=6.

Fink, M. (1992). "Time reversal of ultrasonic fields – Part I: Basic principles," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 39, 555–566.

Fletcher, N. H., and Thwaites, S. (1992). "Multi-horn matching plate for ultrasonic transducers," Ultrasonics 30, 67–75.

Gauster, W. B. (1971). "Effect of heating rate in thermoelastic stress production," Journal of the Mechanics and Physics of Solids 19, 137–145.

Gibson, A., and Popovics, J. S. (2005) "Lamb wave basis for impact-echo method analysis," Journal of Engineering Mechanics 131, 438–443.

Goll, J. H., and Auld, B. A. (1975). "Multilayer impedance matching schemes for broadbanding of water loaded piezoelectric transducers and high Q electric resonators," IEEE Transactions on Sonics and Ultrasonics 22, 52–53.

Gómez Álvarez-Arenas, T. E. (2004). "Acoustic impedance matching of piezoelectric transducers to the air," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 51, 624–633.

Green Jr., R. E. (2004). "Non-contact ultrasonic techniques" Ultrasonics 42, 9–16.

Haller, M. I., and Khuri-Yakub, B. T. (1994). "Micromachined 1–3 composites for ultrasonic air transducers," Review of Scientific Instruments 65, 2095–2098.

Krauss, O., Gerlach, R., and Fricke, J. (1994). "Experimental and theoretical investigations of SiO2-aerogel matched piezo-transducers," Ultrasonics 32, 217–222.

Hamilton, M. F. (1993). "Transient axial solution for the reflection of a spherical wave from a concave ellipsoidal mirror," *Journal of the Acoustical Society of America* 93, 1256–1266.

Holland, S. D., and Chimenti, D. E. (2004) "High contrast air-coupled acoustic imaging with zero group velocity Lamb modes," Ultrasonics 42, 957–960.

Kelly, S. P., Hayward, G., and Gómez, T. E. (2001). "An air-coupled ultrasonic matching layer employing half wavelength cavity resonance," Proceedings IEEE Ultrasonic Symposium, 965–968.

Khuri-Yakub, B. T., and Oralkan, Ö. (2011). "Capacitive micromachined ultrasonic transducers for medical imaging and therapy," Journal of Micromechanics and Microengineering: Structures, Devices, and Systems 21, 055004–055014.

Korolev, S. V., Krasil'nikov, V. A., and Krylov, V. V. (1987). "Mechanism of sound generation in a solid by a spark discharge near the surface," Soviet Physics – Acoustics 33, 451–452.

Korolev, S. V., and Krylov, V. V. (1988). "Efficient excitation of Rayleigh waves by a strong shock wave initiated by a spark in air," Soviet Technical Physics Letters 14, 843–845.

Krylov, V. V. (1992). "On the theory of surface acoustic wave generation by electric spark discharge," Journal of Physics D: Applied Physics 25, 155–161.

Kuhl, W., Schodder, G. R., and Schröder, F.-K. (1954). "Condenser transmitters and microphones with solid dielectric for airborne ultrasonics," Acustica 4, 519–532.

Le Bas, P.-Y., Ulrich, T. J., Anderson, B. E., and Esplin, J. J. (2013). "A high amplitude, time reversal acoustic non-contact excitation (trance)," *Journal of the Acoustical Society of America* 134, EL52–EL56.

Lerosey, G., de Rosny, J., Tourin, A., and Fink, M. (2007). "Focusing beyond the diffraction limit with far-field time reversal," Science 315, 1120–1122.

Lynnworth, L. C. (1965). "Ultrasonic impedance matching from solid to gas," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 12, 37–48.

Prada, C., Clorennec, D., and Royer, D. (2008) "Local vibration of an elastic plate and zero-group velocity Lamb modes," *Journal of the Acoustical Society of America* 124, 203–212.

Reilly, D., and Hayward, G. (1991). "Through air transmission for ultrasonic non-destructive testing," Proceedings IEEE Ultrasonic Symposium, 763–766.

Remillieux, M. C., Anderson, B. E., Le Bas, P.-Y., and Ulrich, T. J. (2014). "Improving the air coupling of bulk piezoelectric transducers with wedges of power-law profiles: A numerical study," Ultrasonics 54, 1409–1416.

Sansalone, M., and Carino, N. J. (1986). "Impact echo: A method for flaw detection in concrete using transient stress waves," Report No. NBSIR86-3452, National Bureau of Standards, Gaithersburg, MD.

Schiller S., Hsieh, C.-K., Chou, C.-H., and Khuri-Yakub, B. T. (1990). "Novel high-frequency air transducers," Review of Progress in Quantitative Nondestructive Evaluation 9, 795–798.

Schindel, D. W., Hutchins, D. A., and Grandia, W. A. (1996). "Capacitive and piezoelectric air-coupled transducers for resonant ultrasonic inspection," Ultrasonics 34, 621–627.

Smith, W. A., and Auld, B. A. (1991). "Modeling 1–3 composite piezoelectrics: Thickness-mode oscillations," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 38, 40–47.

Song., J., Chimenti, D. E., and Holland, S. D. (2006). "Spherically focused capacitive-film, air-coupled ultrasonic transducer," *Journal of the Acoustical Society of America* 119, EL1–EL6.

Stor-Pellinen, J., Oksanen, M., Vuohelainen, R., Rantala, J., Hartikainen, J., and Luukkala, M. (1989). "Photoacoustic inspection of matching layers of ultrasonic air-coupled transducers," Proceedings IEEE Ultrasonic Symposium, 665–668.

Toda, M. (2002). "New type of matching layer for air-coupled ultrasonic transducers," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 49, 972–979.

Viertl, J. R. M. (1980). "Frequency spectrum of laser-generated ultrasonic waves," Journal of Applied Physics 51, 805–807.

White, R. M. (1963). "Generation of elastic waves by transient surface heating," Journal of Applied Physics 34, 3559–3564.

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Wikipedia, I-35W Mississippi River bridge, Internet, last viewed May 8, 2014, http://en.wikipedia.org/wiki/I-35W_Mississippi_River_bridge.

Wright, W. M., and Blackstock, D. T. (1997). "Focusing of N waves in air by an ellipsoidal reflector," *Journal of the Acoustical Society of America* 102, 741–746.

Yano, T., Tone, M., and Fukumoto, A. (1987). "Range finding and surface characterization using high-frequency air transducers," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 34, 232–236.