A major challenge in the development of a full 2-D array is the large number of array elements. It is difficult to fabricate even a moderately sized 2-D array, and the high electrical impedance of the small elements often compromises imaging performance. We have designed a 2-D array that reduces these problems considerably. The array is fabricated by defining two linear array electrode patterns, one on each side of a 1-3 composite transducer substrate. The electrode pattern on the opposing surfaces are oriented at 90 degrees to one another, and the array is gently hemispherically curved to passively steer the ultrasound into a 3-D sector. One electrode pattern is used to define the transmit elements and the other the receive elements. To form an image the receive elements are grounded and a subset of the transmit elements are excited to focus the ultrasound in one plane. The transmit elements are then grounded and the signals from the receive elements are beamformed to focus the ultrasound in a perpendicular plane. The two-way beamformed signal is collected along the line formed by the intersection of the transmit and receive beams. Using parallel receive beamforming and by electronically scanning the transmit plane, real-time 3-D imaging can be realised. The major disadvantage of this approach is a loss in resolution and an increase in secondary lobes since the transmit and receive beams are focussing in perpendicular planes. To obtain a radiation pattern similar to a conventional array the aperture size must be doubled. However, even with this increase in the aperture, the total number of elements in a crossed electrode array is reduced by a factor of N/4 compared to a full 2-D array with NxN elements. The performance of the crossed electrode array was evaluated using a finite element model of the composite array structure and a numerical simulation of the two-way radiation pattern. The radiation pattern from a 4 MHz crossed electrode array with a radius of curvature of 11 cm, an electrode pitch of 300 µm, and 101 transmit and receive elements was investigated. The radiation pattern at a focal distance of 3 cm had a #6 dB width of 0.8 mm. Secondary lobes in the radiation pattern were suppressed by more than 60 dB.

Session: 4J
NONLINEAR IMAGING IN NDE
Chair: R. Gr. Maev
University of Windsor

4J-1  1:30 p.m.

EVALUATION OF NANOSCALE CRACKS BY LOW-PASS FILTER EFFECT IN NONLINEAR ULTRASOUND
K. YAMANAKA*¹, T. MIHARA¹, and T. TSUJI²,¹ Tohoku University, ²National Institute of Advanced Industrial Science and Technology.
Corresponding e-mail: yamanaka@material.tohoku.ac.jp

Among the nonlinear acoustics in solids, the most important one is to detect and evaluate a closed crack under residual stress with nanoscale opening, which is impossible by the linear ultrasound. Recently, elastic low-pass filtering effects
such as subharmonics and DC response are reported, in addition to higher harmonics. To analyze it, the asymmetric stiffness for tension and compression of a non-bonded crack is not enough but an effective mass is required. In this work we propose two models for simple but quantitative analysis based on concepts developed in the atomic force microscopy. The first model is an effective mass and spring placed in a force field of the Lenard-Jones potential including the extension to nanoscale sphere/plane or plane/plane pair. With appropriate parameters, the subharmonic generation is reproduced, including the dependence on the fundamental input amplitude and offset force representing the residual stress. The second model is the high-frequency limit where an averaged force per cycle applied by a crack plane to an effective mass of the counter crack plane is balanced with the restoring force of the spring, analogously to the ultrasonic force microscopy [1]. Both models reproduced our experimental finding that the subharmonic intensity first increased as the residual compression stress is reduced by applying a tensile stress, takes a maximum and then decreases as the offset compression is removed. [1] K. Yamanaka, H. Ogiso and O. Kolosov, Appl. Phys. Lett. 64 (1994) 178-180.

4J-2 1:45 p.m.

**FAST ADAPTIVE MULTI-FREQUENCY ALL-OPTICAL SCANNING ACOUSTIC MICROSCOPE**

S. D. SHARPLES*, M. CLARK, N. A. MOHD ARIF, and M. G. SOMEKH, University of Nottingham.
Corresponding e-mail: steve.sharples@nottingham.ac.uk

A non-contact and completely damage-free instrument capable of rapid high resolution vector contrast imaging using surface acoustic waves—including Rayleigh and Lamb modes—is demonstrated. The laser source of the ultrasound generates around 30 pulses at 82MHz and harmonics thereof, and it is possible to image at several discrete frequencies—82MHz, 164MHz, 246MHz and above—simultaneously. Adaption of the spatial distribution of the excitation source to accommodate a wide range of materials and circumstances is trivial, since a spatial light modulator is used to produce an arbitrary distribution of incident optical energy. This is used to good effect in anisotropic materials with random grain structures, since the material microstructure perturbs the surface waves as they propagate on the material surface. The wavefront aberrations are detected by an acoustic wavefront sensor, and the excitation profile is adjusted to correct for the aberrations. This increases the accuracy and reliability of the measurements, and can increase the usable frequency range or propagation distance for a given material.

The adaptable source enables the instrument to be used for purposes other than linear surface wave detection and c-scan imaging; for instance, the SAW phase velocity of anisotropic crystals may be determined by wavenumber spectroscopy achieved by adapting the source k-vector and finding the peak in excitation. Also, there is considerable interest in nonlinear and harmonic detection and imaging, and the adaptable source may be used to suppress the harmonics.
naturally present in the excitation source. This is important for harmonic imaging, where it is necessary to ensure that the relatively weak harmonics generated by the nonlinear material properties are not swamped by those present in the source.

We would like to acknowledge the support of Rolls Royce PLC, and the UK Engineering and Physical Sciences Research Council (EPSRC).

4J-3  2:00 p.m.  
(Invited)  
NEW DEVELOPMENTS IN NONLINEAR ELASTIC WAVE NDT AND NDE  
P. A. JOHNSON*1, A. SUTIN2, and J. TENCATE1, 1Los Alamos National Laboratory, 2Stevens Institute of Technology.  
Corresponding e-mail: paj@lanl.gov

The nonlinear acoustic response of materials (i.e., generation of higher harmonics, amplitude-dependent resonance frequency shift, and modulation between waves of differing frequencies), is much more sensitive to the presence of damage than the linear response such as the signal damping or sound speed variation. We present an overview of three nonlinear wave methods that can be used for crack and damage detection: Nonlinear Time Reverse Acoustics (NLTRA), Nonlinear Wave Modulation Spectroscopy (NWMS) and Slow Dynamics (SD).

NLTRA: Nonlinear acoustic, non-destructive evaluation methods demonstrate extremely high sensitivity to the presence of cracks. Time Reverse Acoustics (TRA) methods provide the ability to focus acoustic energy to any point in a solid. In combination, we are applying the focusing properties of nonlinear TRA and the nonlinear properties of cracks to infer their existence. This paper presents the first observation that we are aware of applying nonlinear TRA (NLTRA) to determine whether or not damage is present in a material.

NWMS is based on applying an ultrasonic probe signal modulated by a low frequency vibration, i.e., nonlinear mixing of the probe and impact signal. The modulation manifests itself as side-band components in the spectrum of the received ultrasonic signal.

SD are manifest by an alteration in the material dissipation and elastic modulus after application of relatively strong acoustic wave, that slowly recover in time (103-104 seconds) to their equilibrium values. The method of Slow Dynamics is based on applying a pure tone probe signal near an eigenmode of a sample. When the sample is disturbed by a larger amplitude signal, the eigenmode shifts, changing the probe-wave amplitude and inducing slow dynamics. Such a change in amplitude only occurs in damaged materials. The method is simple and fast to apply but only works well when the material dissipation is low.

Work supported by Institutional Support at Los Alamos, and the Department of Energy Office of Basic Energy Research
HIGH RESOLUTION MAPPING OF NONLINEAR MHZ ULTRASONIC FIELDS USING A SCANNED SCATTERER

P. KACZKOWSKI*1, B. CUNITZ1, V. KHOKHLOVA2, and O. SAPOZHNIKOVA2,
1University of Washington, Seattle WA, USA, 2Moscow State University, Moscow, Russia.
Corresponding e-mail: peter@apl.washington.edu

BACKGROUND: Conventional mapping of high intensity fields produced by focused transducers is performed by mechanically scanning a hydrophone through the field. Unfortunately, repeated measurements at typical medical HIFU levels risk damaging the hydrophone by heating or cavitation, even when very short pulses are used. Furthermore, the resolution of the field map is limited to the size of the active area of the hydrophone, typically on the order of 0.5 mm and large compared to many wavelengths of interest. We show that a 2 MHz HIFU field can be measured in water and with high spatial resolution by placing a small scatterer in the field and sensing the scattered wave off to the side with a sensitive hydrophone from a safe distance.

APPROACH: We fabricated tapered rods of steel and glass with tip diameters between 0.5 mm and 0.01 mm. One tip is mounted toward the source in a rigid frame that also holds two hydrophones: a 1 cm diameter 5 MHz focused PZT element directed at the scatterer and located to the side of the source, and one 0.5 mm active diameter PVDF needle hydrophone used for calibration. The rigid frame ensures that the Greens function between the scatterer and the PZT hydrophone remains constant, and can be calibrated at low power by repositioning the frame and using the reference broadband PVDF hydrophone. Field mapping is done over a broad frequency band by processing the averaged scattered pressure waveform acquired at each location using 3-10 pulses. Field maps are compared to nonlinear computations using a KZK equation method.

RESULTS: Using a 0.05 mm glass tip the SNR is about 25 dB at 2 MHz, and 20 dB at 8 MHz; the sub-wavelength scatterer size helps equalize power over frequency. Experimental field maps of the fundamental, 2nd, 3rd, and 4th harmonic fields plotted on a linear color scale are nearly indistinguishable from numerical simulations.

CONCLUSIONS: This simple method can be used to measure MHz range HIFU fields (including harmonics) at full power, in water or other fluids without risk of damage to the hydrophone. Tapered glass tips are effective and inexpensive to manufacture, and tend to suppress cavitation due to their surface properties.

Support provided by the U.S. Army Medical Research Acquisition Activity under terms of Agreement No. DAMD17-00-2-0063.
FOCUSING OF ULTRASOUND IN COMPOSITE MEDIUM USING TIME REVERSAL ACOUSTICS

A. SUTIN and A. SARVAZIAN*, Artann Laboratories.
Corresponding e-mail: armen@artannlabs.com

The concept of Time Reversal Acoustics (TRA) developed by M. Fink and colleagues provides elegant possibilities of both temporal and spatial concentrating of acoustic energy in inhomogeneous composite media. Furthermore, numerous reflections from boundaries, which distort focusing in conventional ultrasound focusing systems and are viewed as a significant technical hurdle, lead to the improvement of the focusing ability of TRA system. TRA takes advantage of this usually undesirable process. We explored possibilities of making use of these advantages of TRA focusing of ultrasonic waves in several complex systems such as composite tissue models and focusing through human skull model. We developed a compact electronic unit for TRA applications which provides receiving, digitizing, storing, time reversing and transmitting acoustic signals in a wide frequency range from 0.01 to 10 MHz. A simple TRA focusing system comprising a plane piezoceramic transducer attached to an external resonator such as an aluminum block which was acoustically coupled to the tested model system has been used. It was shown that for high Q resonators the diameter of the focal spot at the level of #3dB can be less than a half of wavelength. In focusing through a significantly attenuating media such as skull model, the TRA focusing efficacy decreases but still remains at the level hardly achievable by the conventional ultrasound focusing systems: the diameter of the focal area at the half-power-bandwidth level was about 2 wavelength for the frequency of 500 kHz. It is shown that TRA system can provide efficient focusing of acoustic signals of arbitrary waveforms (short r.f pulses, amplitude-modulated tone burst signal, tone burst signal with Gaussian envelope). In many medical and industrial applications the important factor is the average acoustic energy delivered to the chosen point. We investigated the regime of overlapping TRA signals when the time between radiated TRA signals is much less than the duration of the single radiated signal. We obtained efficient TRA focusing for pulse repetition frequency up to 10 KHz for the r.f. pulses with the carrier frequency of 500 kHz and with 16 overlapping TRA signals.

This work was supported in part by the NIA NIH grant 1 R21 EB001548-01