EPN-104

LAMBDA TRANSDUCERS: THEIR FEATURES AND APPLICATIONS IN NONDESTRUCTIVE CHARACTERIZATION OF MATERIALS

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redefining
the limits of
ultrasound

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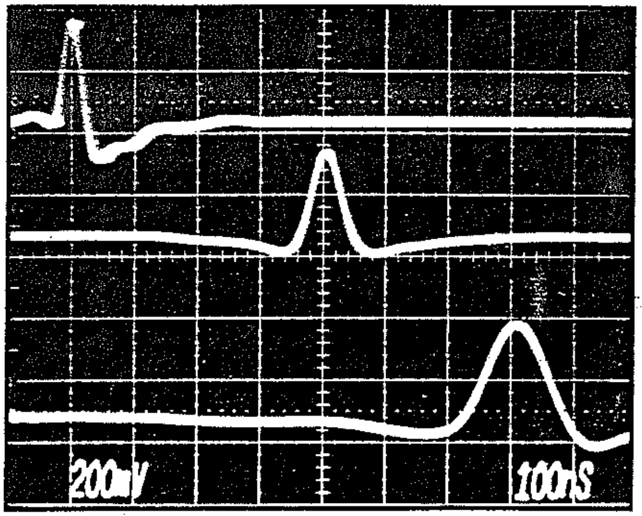
LAMBDA TRANSDUCERS

TOUCHING THE LIMITS OF PHYSICAL LAWS FOR MAXIMUM PRECISION AND ACCURACY IN NDT/NDE



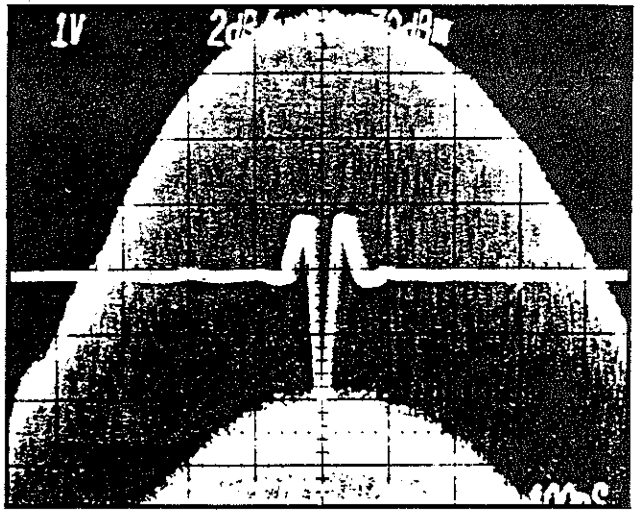


Fig. 1. Real time RF responses from LAMBDA transducers
TOP: A 10MHz LAMBDA; 50 nanosecond
MIDDLE: A 5MHz LAMBDA; 100 nanosecond
BOTTOM: A 3MHz LAMBDA; 200 nanosecond

Fig. 2. Typical real time and frequency analyses of a LAMBDA transducer
Peak frequency: 10MHz, Bandwidth center frequency: 10MHz
Bandwidth at -6dB points: 13MHz, Pulse width: 50 nanosecond

DEVELOPMENT OF LAMBDA TRANSDUCERS

One of the most criticial requirements in nondestructive testing (NDT) of materials is the NDT system's ability to detect the minutest flaws lying very close to the surfaces of the test materials. The critical detection element - the heart of any NDT system - is the transducer.

The need to improve on the conventional transducer design is most critical in near-surface flaw detection applications. The conventional transducer's pulse width (ringdown) obscures the resolution of acoustic signals from near-surface flaws. Even the best commercial transducers exhibit a minimum of 1.5 wavelengths pulse widths, which is much too long for many such applications.

Inspired by industry demand and the challenge of developing a superior transducer, ULTRAN independently initiated a major research project in 1977. The purpose of this project was to create a practical transducer design that would exhibit highly controlled pulse widths without excessively increasing the transducer frequency. Such a transducer would provide optimum resolution of even the tiniest near-surface defects in test materials for industry's most innovative NDT/NDE applications.

Careful research into piezoelectric development, geometrical acoustics, materials design, and the applications of advanced forming technologies has led to the development of a transducer that exhibits only a half-cycle (UNIPOLAR) rf impulse, and thus a drastically shortened pulse width. This exciting development represents nearly a 70% improvement over the best conventional transducer designs.

Because of their predictable wavelength and frequency relationships, we decided to call our new transducer LAMBDA since the Greek symbol " λ " represents "wavelength". In fact, according to Bragg's law of diffraction which defines the maximum attainable resolution in terms of wavelength ($d_{min} = \lambda/2$), it is impossible to further improve a transducer's pulse width beyond that achieved by LAMBDA.

To the best of our knowledge, ULTRAN'S LAMBDA TRANSDUCERS ARE ACOUSTICALLY THE MOST ADVANCED TRANSDUCERS KNOWN.

In this catalog, we are pleased to outline acoustic and geometric characteristics and applications notes for this revolutionary ultrasonic development with emphasis on several practical applications of NDT and NDE of materials. We are also pleased to offer a variety of LAMBDA transducers for immersion and contact testing methods.

ADVANTAGES OF LAMBDA TRANSDUCERS

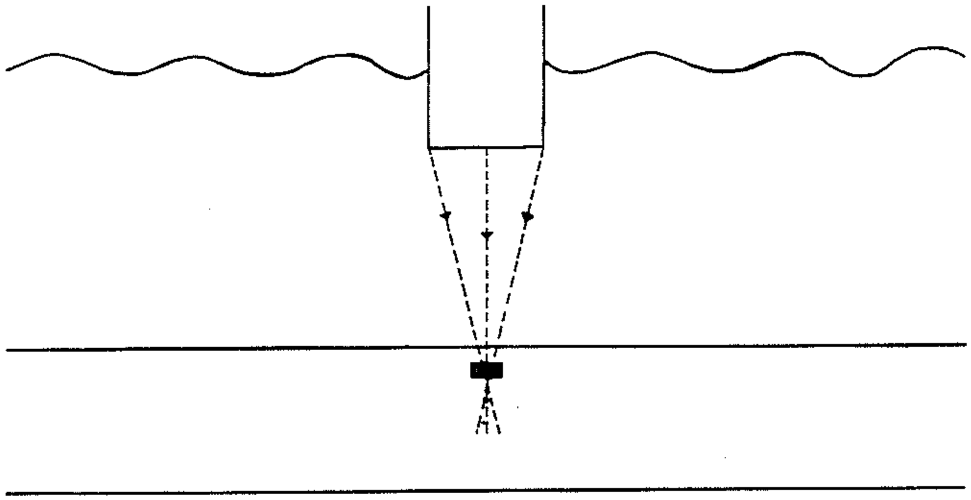
LAMBDA offers resolution enhancement, precise thickness gauging and dimensional analysis, detection of even the minutest defects, materials texture analysis, and much improved scanning speeds. A further advantage of LAMBDA transducers is their ability to assist a materials researcher in precise materials velocity and attenuation measurements as functions of varying frequency without requiring a large number of transducers. LAMBDA designs are highly suitable for the analysis and testing of metals, composites, plastics, rubbers, ceramics, glasses, and other advanced materials. ULTRAN invites your inquiries in order to further assist you in your innovative NDT/NDE applications.

ACOUSTIC QUALITIES AND USES

LAMBDA transducers typically emit broad bandwidth UNIPOLAR rf (radio frequency) impulses, the pulse widths of which correspond to half their wavelengths ($\lambda/2$). Pulse width is the time taken by ultrasound to rise from the state of rest to the maximum amplitude and finally back to the quiescent state. This is the rf envelope. The width of the rf envelope of LAMBDA transducers, or their pulse width, is one half cycle of the transducer's ringing (Figs. 1 and 2). For example, if one cycle of a transducer is completed in 100 nano seconds, then one cycle of a comparable LAMBDA transducer is completed in only 50 nano seconds. The LAMBDA transducer's frequency is not increased, instead its pulse width is cut down to the utmost limit, i.e., HALF CYCLE.

Because of their extremely broad frequency spectra, 100 to 300% of the peak frequency, (Fig. 2) LAMBDA transducers are used in the study of frequency dependence of ultrasound attenuation by material texture or defect size. Flat focused and delay line LAMBDA transducers also exhibit fairly well collimated ultrasonic beams even at greater depths in materials. This beam collimation feature can be directly applied to the improvement of mechanical indexing scans. For detailed description, see CHARACTERIZATION OF LAMBDA TRANSDUCERS, page 6.

For all practical purposes it is better to define transducers according to their acoustic characteristics, including real time rf response and its frequency components, when the primary concern is resolution. The majority of conventional transducers for high resolution applications ring for about one and one half wavelengths (1.5λ) at best. For example, one wavelength of a conventional 10MHz transducer in steel is 0.0235in, thus its 1.5λ is 0.035in; therefore, its practical resolution limit in steel is also 0.035in. However, a 10HMz LAMBDA has a pulse width corresponding to $\lambda/2$, 0.0117 in in steel, thus its resolution limit is about three times better than its conventional counterpart. The superiority of LAMBDA for resolution enhancement is obvious.



CHARACTERIZATION OF LAMBDA TRANSDUCERS

To assist you with your applications development, we are pleased to present here a detailed performance analysis of this revolutionary technology. We have selected two LAMBDA transducers for this analysis, an unfocused type (0.5in diameter, 5.0MHz) and a focused type (0.5in diameter, 5.0MHz, and 3.0in point focal length). This analysis utilizes standard ASTM aluminum test blocks containing 0.046in (1mm) flat bottom holes (FBH) located from 0.062 to 6.0in (1.6 to 153mm) in the metal blocks. The following analyses describe distance amplitude relations in metal and ultrasonic beam geometry as a function of varying distances in the metal.

Distance Amplitude Relations

EXPERIMENTAL

ASTM aircraft quality aluminum test blocks containing 1mm FBHs were submerged in water and the distance from the transducer to the test block top surface was fixed at 1.5in (38mm) for each test block. Under these conditions, the transducer was traversed on all test blocks in order to obtain the maximum reflected amplitude from one test block, i.e., one corresponding to the first pressure maximum. After determining this, the instrument settings were fixed, the transducer was traversed on the rest of the test blocks, and reflected amplitudes from FBHs were measured on the oscilloscope and plotted against their respective metal travel distances.

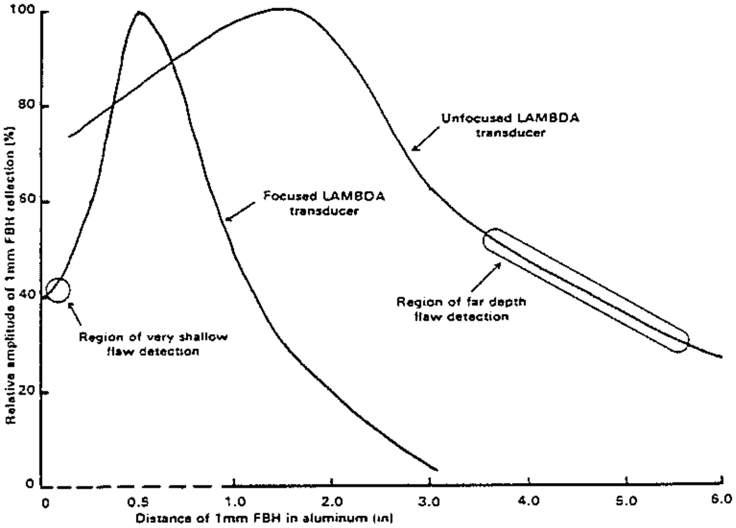


Fig. 3. Distance amplitude relations for 1mm FBH in aluminum
BLUE: Unfocused LAMBDA, 0.5in diameter, 5MHz
BLACK: Focused LAMBDA, 0.5in diameter, 5MHz, 3.0in point focal length

OBSERVATIONS AND RESULTS

Fig. 3 shows the plots for reflected amplitudes from 1mm FBHs as a function of metal travel distance for unfocused and focused LAMBDA transducers. The unfocused LAMBDA shows less than 40% amplitude reduction up to a distance of 3.0in (76mm) in aluminum. Furthermore, the same transducer is capable of penetrating and resolving simultaneously up to 6.0in (153mm) in metal without greatly affecting the reflected amplitudes of FBHs. These observations clearly indicate that the transducer has an extremely broad effective range in the test materials for flaw detection and penetration. Since the returning FBH reflections are fairly strong even from greater depths, an ultrasonic operator may be able to minimize or even eliminate the use of DAC or the time-corrected-gain devices.

The near surface detectability of the focused LAMBDA transducer is phenomenal. With this device, defects between 2 to 4mm can be detected at 0.030in (0.75mm) in most metals. Of course, a focused LAMBDA transducer does not have the depth of field equivalent to the unfocused type. The maximum effective range of the focused LAMBDA transducer shown here is from 0.030 to 3.0in (0.75 to 76mm) in most metals, while the range of its unfocused counterpart is from 0.075 to 6.0in (2 to 153mm).

Ultrasonic Beam Geometry

EXPERIMENTAL

As in the case of distance-amplitude relations, the distance from each standard ASTM aluminum test block to the transducer face was fixed at 1.5in in water. The transducer was aligned and traversed over the FBH in each test block in order to obtain its maximum (100%) reflected amplitude. Then the transducer was moved laterally across the FBH in order to obtain 70% of the maximum amplitude value. From there on, the transducer was indexed at 0.005in intervals and traversed laterally in the other direction until the 70% point was again reached. The distance between the two points (70% to 70%) is the effective width of the ultrasonic beam at a given point (FBH) in the test block. These observations were made for varying FBH depths on all test blocks.

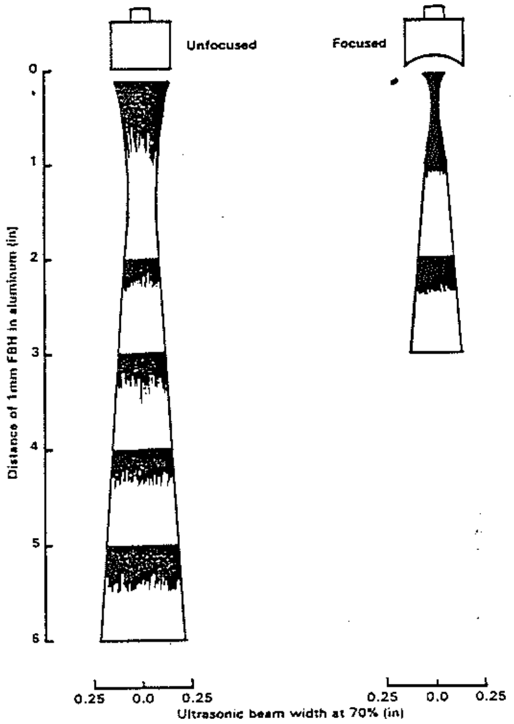


Fig. 4. Width of ultrasonic beam measured across 1mm FBH as a function of distance in aluminum
BLUE: Unfocused LAMBDA, 0.5in diameter, 5MHz
BLACK: Focused LAMBDA, 0.5in diameter, 5MHz, 3.0in point focal length

OBSERVATIONS AND RESULTS

Fig. 4 shows the measured widths of ultrasonic beams from focused and unfocused LAMBDA transducers by utilizing 1mm FBHs as reflecting targets in aluminum test blocks. Along the vertical axis of this plot (Fig. 4) is the distance of the FBHs from the top surfaces of the test blocks; the horizontal axis shows the measured values of the ultrasonic beam widths at the 70% points described above. This method of beam plotting produces a "visual image" of the shape and size of the ultrasonic beam within the test materials, and is called composite ultrasonic beam geometry.

The unfocused LAMBDA exhibits a fairly broad collimated ultrasonic beam in metal, measured up to 6.0in (153mm). On each test block, the width and shape of the beam were highly symmetrical and geometrically uniform across the transducer face. Besides the apparent beam collimation of unfocused LAMBDA transducers, we observed a near absence of side-lobing phenomenon as well as virtual elimination of the deleterious near zone maximas and minimas.

Conventional transducer designs generally possess strong near field maximas and minimas as well as well defined side lobes at the transducer ends. Recently, attempts have been made to modify ultrasonic beam geometries (R. V. Murphy, in Materials Evaluation, vol.39, March 1981). These methods utilize extraneous geometrical shapes that are physically mounted on the active transducer faces. While the results of this research are good, the transducer devices so produced are mechanically fragile and acoustically weak due to the introduction of unwanted interfaces in such designs. LAMBDA transducers have no such weaknesses, and their acoustic design is absolutely optimum.

The focused LAMBDA transducers exhibit highly sharp focal points, thus making them suitable for extremely close-surface resolution and detection of even the minutest defects. Focused LAMBDA transducers are virtually devoid of near field effects and free from the side-lobing phenomenon. The beam symmetry and geometrical uniformity of these devices are unparalleled in conventional transducer designs.

General Conclusions About LAMBDA Transducers

Here we have cited the analysis of only two LAMBDA transducers. In our studies of other LAMBDA transducers we have consistently observed similar results that varied in magnitude only, depending upon the transducer dimensions, frequencies, etc. In summary, the LAMBDA design, a genuine breakthrough in transducer technology, has the following advanced performance features:

- * Highly controlled pulse widths, corresponding to half the wavelength (λ /2),
- * Ultrasonic beam collimation,
- * Virtual elimination of the side-lobing phenomenon,
- * Near absence of the deleterious effects of near field (Fresnel Zone),
- * Moderate acoustic sensitivity, and
- * Highly symmetrical and geometrically uniform ultrasonic beams.

NDT/NDE WITH LAMBDA TRANSDUCERS

Because of their unique and highly desirable characteristics, LAMBDA transducers outperform their conventional counterparts by more than a factor of three in many nondestructive testing applications. For example, if you have been using a broad bandwidth 15MHz transducer in your applications, you can now achieve better resolution and efficient materials penetration by using a lower frequency 5MHz LAMBDA transducer.

In order to make the optimum use of LAMBDA technology, we suggest that you use a broad frequency bandwidth combination of pulser and receiver. This configuration should complement the exceptionally broad frequency bandwidths of LAMBDA transducers. The following sections outline a number of routine and special NDT/NDE applications utilizing LAMBDA transducers.

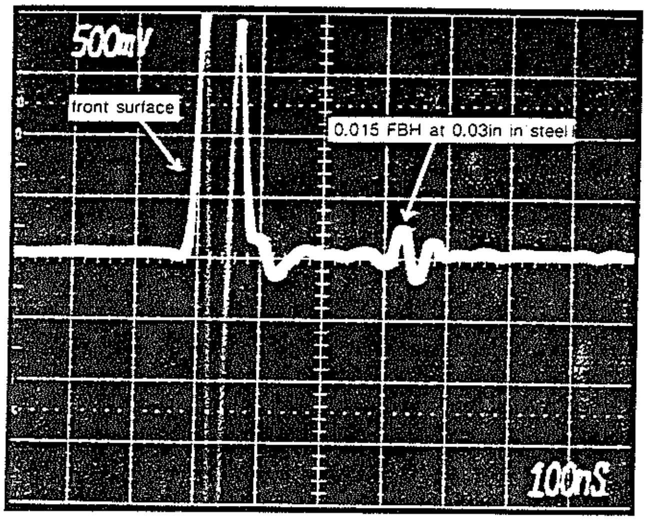


Fig. 5. Real time RF oscilloscope trace from 0.015in FBH at 0.030in in steel. Vertical scale: 500mv/div; Horizontal scale: 100ns/div with 0.25in diameter, 10MHz, 0.75in point focus LAMBDA transducer

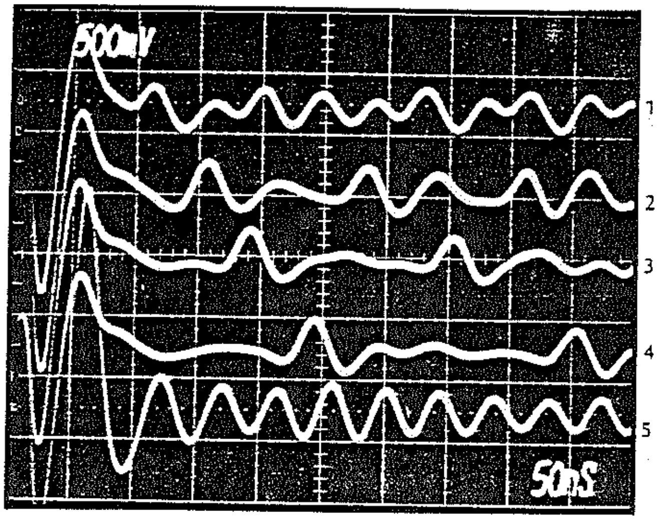


Fig. 6 Multi-exposure oscilloscope traces of real time RF responses from a variety of steel foils with 0.25in diameter, 10MHz, 0.75in point focus LAMBDA transducer
1. 100% separation of surfaces of a 0.010in steel foil
2. 100% separation of surfaces of a 0.015in steel foil
3. 100% separation of surfaces of a 0.020in steel plate
4. 100% separation of surfaces of a 0.025in steel plate
5. 100% separation of surfaces of a 0.004in steel foil measured from second multiple.

Close Surface Defect Detection And Resolution

The maximum resolution of a LAMBDA transducer for a given material generally corresponds to λ/2. In steel, for example, 5MHz and 10MHz LAMBDA transducers resolve at 0.025in and 0.012in respectively. This characteristic, in conjunction with the highly sharp and well-defined geometry of the ultrasonic beam, makes a LAMBDA transducer well suited for the detection of even the minutest flaws occuring close to the test surfaces.

Fig. 5 is such an example. It shows clear detection of a 0.015in (0.40mm) diameter flat bottom hole at 0.030in (0.76mm) in steel by a 10MHz LAMBDA transducer. Note the presence of ample time between the front surface and the defect reflections for even closer surface testing (Fig. 5).

Dimensional Analysis And Thickness Gauging

The dimensional analysis and thickness (thinness) gauging of tubes, pipes, and flat materials requires not only very high resolution, but also NDT system accuracy. Accuracy of the system is directly related to the cleanliness of the transducer's real time response, or its waveform. In such applications the proper use of LAMBDA transducers can enable an ultrasonic operator to achieve accuracies in excess of 10^{-5}in, with resolution equal to λ/2. Fig. 6 shows the results from a 10MHz LAMBDA transducer on steel foils ranging in thickness from 0.004 to 0.025in (0.10 to 0.63mm).

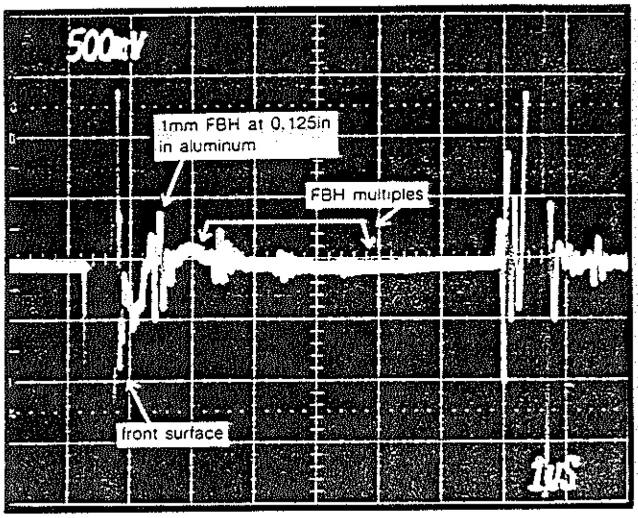


Fig. 7. Real time RF oscilloscope trace of 1mm FBH at 0.125in in aluminum with an unfocused LAMBDA, 0.5in diameter, 5MHz.

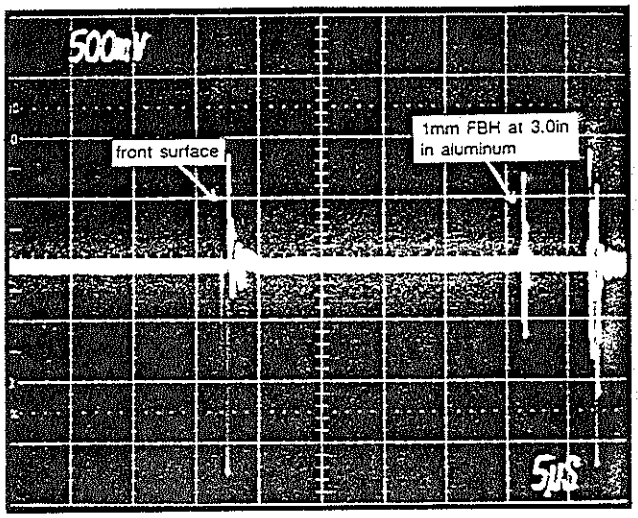


Fig. 8. Real time RF oscilloscope trace of 1mm FBH at 3.0in in aluminum with an unfocused LAMBDA, 0.5in diameter, 5MHz.

Flaw Detection With An Unfocused LAMBDA

The beam collimation effects of the unfocused LAMBDA are startling. It is because of this characteristic that we are able to detect flaws in materials ranging from very close to their surfaces to much deeper areas. Please see the CHARACTERIZATION OF LAMBDA TRANSDUCERS (Page 6) for geometrical details. Fig. 7 and 8 respectively show the indications from 0.047in (1mm) flat bottom holes located at 0.125in (3mm) and 3.0in (76mm) in aluminum. This analysis utilized a 5MHz, 0.5in diameter LAMBDA transducer.

Flaw Detection With A Focused LAMBDA

A focused ultrasonic beam from a LAMBDA transducer optimizes nondestructive testing of materials to the fullest extent for near surface resolution of flaws. Fig. 9 and 10 respectively show the indications from 0.047in (1mm) FBHs located at 0.050in (1.3mm) and 1.0in (25mm) in steel. In Fig. 9, note the availability of ample time between the front surface and the FBH reflections for further increment of resolution. As expected, the focused LAMBDA transducer does not have a depth of field comparable to its unfocused partner. This analysis utilized a 5MHz, 0.5in diameter, 3.0in point focused LAMBDA transducer.

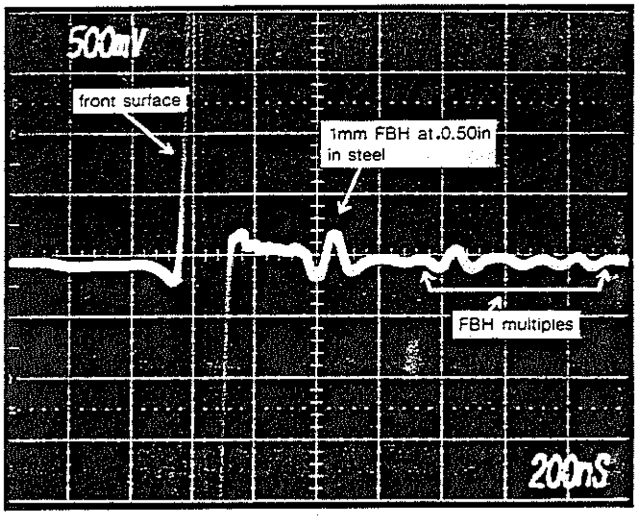


Fig. 9. Real time RF oscilloscope trace of 0.047in FBH at 0.050in in steel with a focused LAMBDA, 0.5in diameter, 5MHz, 3.0in point focal length

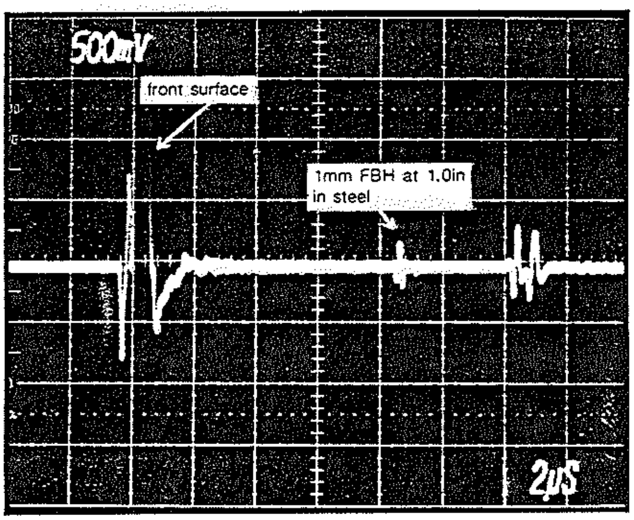


Fig. 10. Real time RF oscilloscope trace of 0.047in FBH at 1.0in in steel with a focused LAMBDA, 0.5in diameter, 5MHz, 3.0in point focal length

Characterization Of Composite And Low Impedance Materials

A frequent assumption is that high sensitivity transducers are suitable for the analysis of low acoustic impedance materials, such as composites, plastics, rubbers, and tires. This assumption is based upon the ultrasound attenuation by low impedance materials, therefore the need for higher ultrasonic sensitivity or loop gain. In our work at ULTRAN we have discovered that broad bandwidth, moderate sensitivity transducers give better results on a majority of low impedance materials. With LAMBDA transducers we are able to isolate detailed texture information from the layered low impedance materials. We believe LAMBDA transducers are more suitable for composite-types because these materials attenuate only the high frequency components while responding to LAMBDA's enormous lower frequency range. See Fig. 2 for spectral details.

Fig. 11 is a multi-exposure oscilloscope image of a graphite reinforced, epoxy-based composite. The total thickness of this material is 0.054in (1.4mm); the thickness of individual laminate varies from 0.008 to 0.014in (0.2 to 0.35mm). The top and bottom traces in Fig. 11 seem to be defect free; indications between the top and bottom surfaces show the presence of several lamina. The remaining traces show the effects of the impact damage on this material; note their relationships with individual laminate positions. The transducer used for this analysis was a 10MHz, 0.25in diameter, 0.75in point focused LAMBDA.

Characterization Of Ceramics And Other Brittle Materials

The majority of technical ceramic materials (dense alumina, silicon carbide, tungsten carbide, silicon nitride, zirconia, beryllia, fusion cast materials, etc.) have extremely high sound velocities, and correspondingly high wavelengths at a given frequency. Therefore, higher frequency and very short pulse width transducers are needed to test or analyze such materials. These transducer features provide high resolution as well as the detection of micron-size pores in ceramics. Here the importance of LAMBDA is self-evident. For an example, we have investigated, a dense alumina plate (V_l = 3.85 x 10^5in/s or 9.8 x 10^5cm/s) with a 10MHz, 0.25in diameter, 0.75in point focal length LAMBDA transducer. Fig. 12 shows a multi-exposure oscilloscope image of traces from six different points in this material. All the small and large reflections succeeding the top surface (indication at left of Fig. 12) are the indications from minute pores in this material. The location of these pores with reference to the top surface are from 0.038 to 0.17in (0.96 to 4.3mm) in alumina.

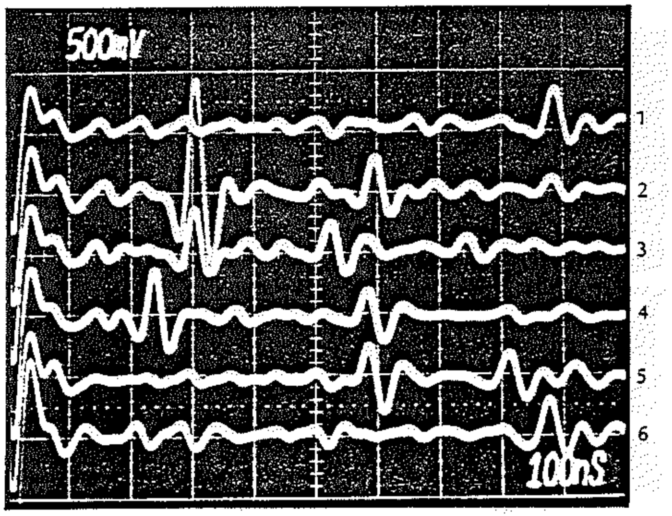


Fig. 11. Multi-exposure oscilloscope traces from a number of points in a graphite fiber reinforced epoxy-based laminate. Total laminate thickness 0.054in, individual lamina vary from 0.008 to 0.014in in thickness.
1 & 6: Believed to be defect free parts of the laminate. Small internal reflections are the indications of various lamina.
2 to 5: Indications from impact damage in the laminate composite.

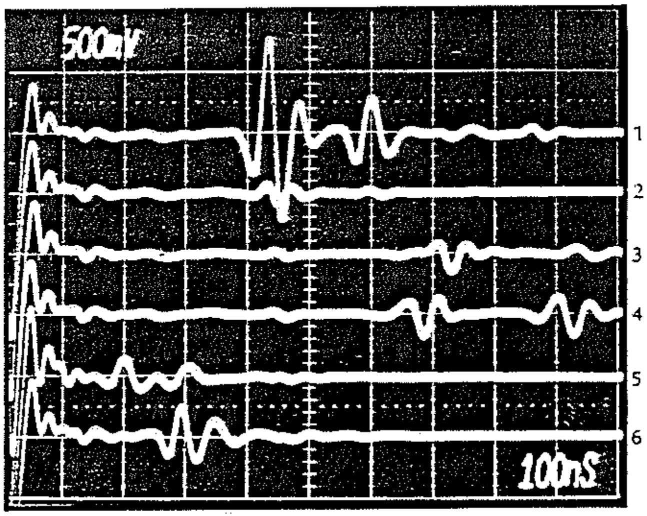


Fig. 12. Multi-exposure oscilloscope traces from a number of points in a 0.25in thick plate of dense alumina ceramic
1 to 6: Internal reflections are indications from large to micron size pores located at 0.038 to 0.17in from the top surface of the ceramic.

Materials Research With LAMBDA Technology

LAMBDA technology offers unique acoustic and geometrical features which are well suited to the needs of a materials researcher whose primary goal is to characterize materials nondestructively. The ultimate aim of ultrasonic nondestructive testing is not merely to detect the presence of overt defects in materials, but also to develop relationships based upon ultrasound-material interaction in order to characterize the conditions that cause the materials to fail.

There are three basic properties that can be measured by ultrasound: velocity of sound, attenuation of ultrasound, and spectral frequency characteristics of the reflected or transmitted signals. Accurate measurement of these properties is absolutely essential for meaningful materials research. A LAMBDA transducer's highly controlled pulse width ($\lambda/2$) allows precise and accurate measurement of ultrasound velocities. Because of their exceptionally broad frequency spectra, LAMBDA transducers provide data on the frequency dependence of ultrasound attenuation upon the surface and internal structure (texture - intergranular relationships) of materials. LAMBDA transducers also provide easier data collection and more meaningful data for deconvolution studies of materials by spectral analysis. Lambda technology eliminates the need for the expensive computer hardware and software which are necessary to artificially modify the acoustic characteristics of conventional transducers.

The availability of a very large number of frequencies in each LAMBDA transducer is the cornerstone of materials research with these devices. The ultimate objective of this research is failure prevention in all structural applications of materials, whether they are used in aircrafts, satellites, nuclear plants, bridges, railroads, or automotive industries. We believe that LAMBDA technology can enhance both qualitative and quantitative aspects of nondestructive materials characterization. ULTRAN solicits inquiries on such subjects from interested parties.