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Real-time dual-channel ultrasonic system for inspection of aircraft structures

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Abstract

Ultrasonic inspection techniques have a proven record of applications during manufacturing and maintenance of metallic and composite aircraft structures. A-scan, B-scan, and C-scan modalities of ultrasonic imaging are deployed as independent evaluation tools by many researchers and NDI practitioners. However, modern manufacturing and maintenance procedures require real-time three-dimensional information about the condition of multi-layered structures. This kind of information can only be provided when several ultrasonic scanning modalities are combined.

In this paper, we will present an integrated dual-channel system for real-time three-dimensional evaluation of large area aircraft structures. The structure to be imaged is insonified using either a piezoelectric transducer or a laser-based acoustic generator. The receiver system consists of two integrated data acquisition channels that are utilized for concurrent in-plane and in-depth real-time evaluation of structures. High resolution imaging ("horizontal") channel with an ultrasonic CCD camera presents large (1square inch) real-time planar (X-Y plane) images of the structures while another ("vertical") acquisition channel analyzes in-depth (Z-axis) ultrasonic scans presenting data in an A-scan format. Applications of the dual-channel real-time ultrasonic imaging system on metallic and composite aircraft structures will be presented.

Keywords: ultrasonic imaging, composite structures

1. INTRODUCTION

Ultrasound has been widely used as an imaging technique for nondestructive evaluation and inspection, and ultrasonic NDI methods have an impressive record of applications on metallic and composite structures. Traditional ultrasonic imaging techniques are typically point-by-point inspection systems coupled with a scanning device. In this paper we describe an ultrasonic imaging system[1] which is combined with an A-scan ultrasonic system to provide depth information in addition to large area imaging at video rates. The system provides high-resolution and easy-to-interpret images of the structure of an investigated object. The imaging system can be used on complex geometries such as curved and/or rough surfaces, it can be configured to work in either two-sided (through-transmission) or single-side (pulse-echo) inspection, and it significantly decreases the inspection time over conventional ultrasonic C-scan techniques. The following components constitute the principal parts of the imaging system: a large-area ultrasonic source and a commercially available large-area ultrasonic CCD camera. Depending on the configuration employed, the ultrasonic transducer providing the insonification for the imaging system is either piezoelectric or laser-based. The various designs and applicability considerations are discussed. Laser-based generation of ultrasound is a well-known non-contact technique that has been previously employed in nondestructive investigation. Non-contact generation is essential in cases when contact with the specimen is not possible. The fundamentals of how pulsed-laser energy is converted into acoustic waves have been widely investigated [2].

In this paper, we report the latest developments and applications of this imaging system. The applications include imaging of various artificial defects placed in metallic blocks, unidirectional and woven composite laminates.

2. IMAGING CHANNEL

The "horizontal" imaging channel of the dual-channel inspection system is based on the high-resolution ultrasonic imaging system, AcoustoCam, manufactured by Imperium Inc[1]. The key component of this system is a two-dimensional 12×12 mm CCD chip, which has 120×120 piezoelectric sensing elements used to sense the incoming ultrasonic pressure distribution. A lens system is designed and built in front of the chip to collect the incoming ultrasonic signal, and provides the ability of focusing and imaging at different depth of the testing object to this system. The chip and the lens system are immersed in water that is encapsulated in a cylindrical tube. The electronic system connected to the chip gates the detected ultrasonic signal according to the traveling time, creates a real-time video of the feature, which is then finally transferred to a TV or a computer for monitoring and recording.

System diagrams of the AcoustoCam in through-transmission and pulse-echo modes are shown in Figure 1. In through-transmission mode, the feature is insonified by the PZT transducer directly. In pulse-echo mode, the ultrasonic signal from the PZT transducer is directed by a beamsplitter to insonify the feature within the test object.

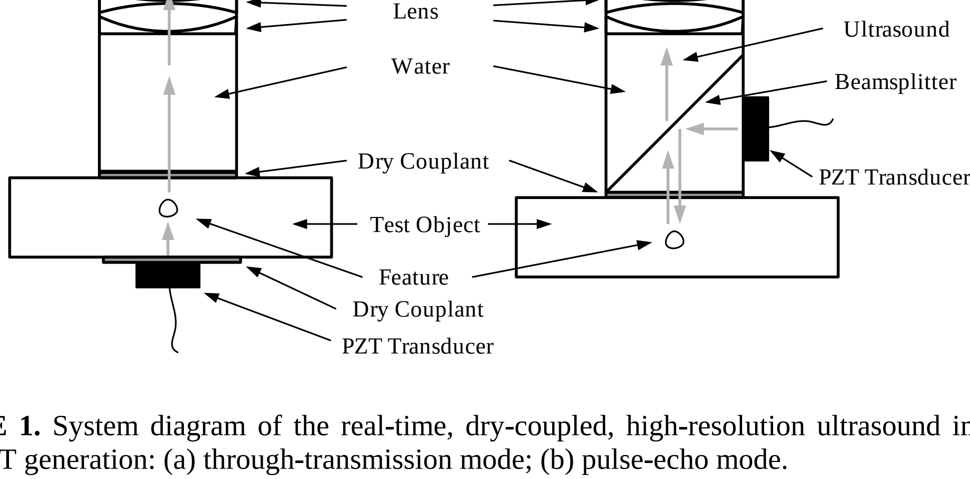


FIGURE 1. System diagram of the real-time, dry-coupled, high-resolution ultrasound imaging system using PZT generation: (a) through-transmission mode; (b) pulse-echo mode.

The signal from the feature is collected by the lens system to create an image on the CCD chip of the camera. A polymer dry couplant is used here to couple the ultrasound between the test object and the camera.

The vertical position of the imaging/inspection plane inside the test object can be controlled by two components of the imaging camera. One of the components, the lens system, provides transfer of the ultrasonic field from the inspection plane to the surface of the CCD sensing chip. Lens-based focusing of the imaging system at a specific depth range results in better sharpness of the acquired images. It can also increase or decrease the “field of view”/inspection area of the camera. However, as any other lens system, Acoustocam’s lenses have substantial focal depth collecting ultrasonic signals in front and behind the selected imaging/inspection plane. Those signals are received by the CCD chip and displayed concurrently with the signals from the inspection plane. This creates artifacts and “noise” on the ultrasonic images.

The depth position of the imaging/inspection plane can be controlled more effectively by another imaging camera component, namely a so-called electronic “time-gating” module. This module selects a “time window” when the CCD chip is open to receive ultrasonic images. Both front and back edges of the “time-window” are adjusted making it possible to control depth position of the inspection plane inside material as well as thickness of the time/depth “slice”. Obviously, proper positioning of narrow time-windows can remove “out-of-plane” signals from the acquired images and, subsequently, will result in better image quality.

However, comprehensive ultrasonic inspections of aircraft structures with variable thickness and unknown depth of flaws would require continuous repositioning of the narrow time-windows to provide 100% coverage of the inspection area. Development of the continuously “refocused” system for real-time imaging could be quite complex and expensive.

3. A-SCAN ACQUISITION CHANNEL

Continuous repositioning of the imaging plane can be replaced by another inspection procedure where the image acquisition channel is guided by the flaw detection channel. This channel collects and analyzes ultrasonic data presenting them in the A-scan format. Without any defect indications, the “horizontal” imaging channel remains focused at the pre-selected depth. Any ultrasonic signal that can be qualified by the “vertical” flaw detection channel as a defect indication will trigger real-time automatic refocusing of the imaging channel and acquisition of the high-resolution defect images at the depth of the flaw indication. Such an integrated dual-channel inspection system (Fig. 2) can effectively detect flaws, displaying information in the traditional A-scan format while simultaneously providing guidance for repositioning of the high-resolution imaging channel.

The A-scan channel includes a commercial miniature ultrasonic data acquisition instrument and a Windows-based instrument control and data processing software. The ultrasonic data acquisition instrument is a combination pulser/receiver and high-speed analog to digital converter for a computer USB port. The instrument generates electrical pulses that are transmitted by the transmitting ultrasonic PZT transducer (Fig. 3), receives the echoes from the specimen using a receiving PVDF transducer, and converts the ultrasonic pulse back into the electrical signal that is then processed by the on-board receiver and analog-to-digital converter. This generation/acquisition process is entirely adjustable by user-configurable properties including: pulse voltage, pulse width, pulse/echo or through transmission mode, receiver gain, rectification, sampling rate, trigger

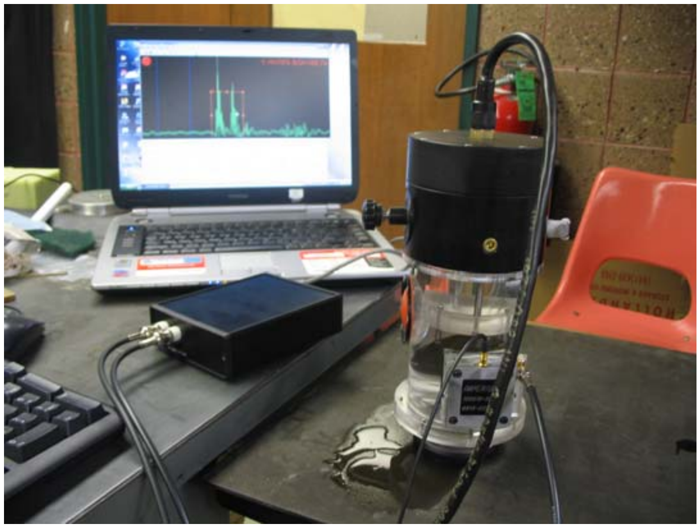


FIGURE 2. Integrated dual-channel inspection system.

source (internal or external), trigger delay, and gate settings. One of the unique features of the miniature ultrasonic instrument is the on-board DSP from Texas Instruments. It is capable of processing data at high speeds for real time peak detection, data compression, spray marker control, as well as factory process control and feedback. Another benefit of the DSP is that the device can also run in standalone operation mode as a remote pulser/receiver and data processing system. When used in standalone operation mode the device does not need to be connected to a computer. The device can remember the stored configuration and operate independently, powered either by an AC adapter or optional battery pack. It is capable of providing feedback through the internal speaker and digital I/O pins to indicate flaws or measurements outside of the specified thickness range.

Special custom software was developed to control the integrated dual-channel system. This software serves as a real-time interface to the miniature ultrasonic instrument, provides a method to control the desired settings of the device, displays data in the A-scan format.

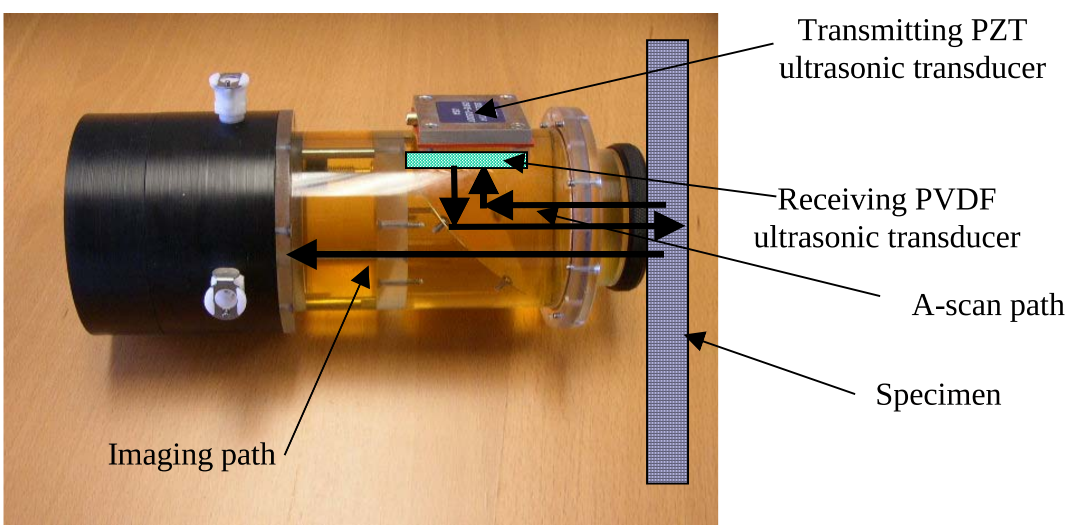


FIGURE 3. Transmitting/receiving configuration of the A-scan and imaging channels.

The flaw signal data are transferred in real-time to the imaging channel, repositioning the front edge of the time-gating electronic system and, in-turn, refocusing the imaging plane as necessary.

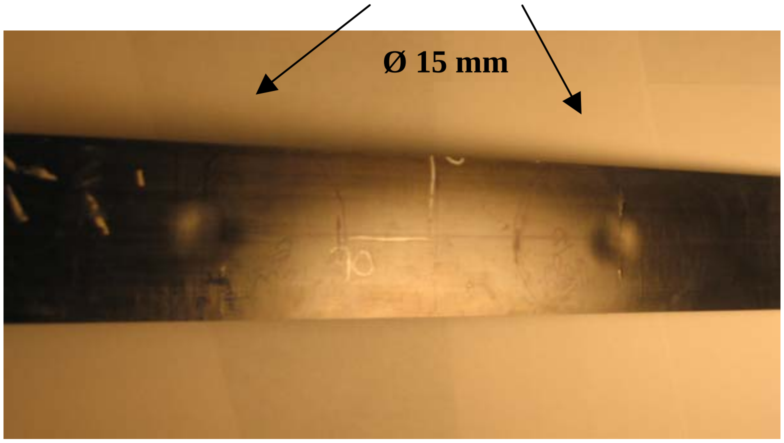


FIGURE 4 Composite coupon with two damaged areas from the low-velocity impacts.

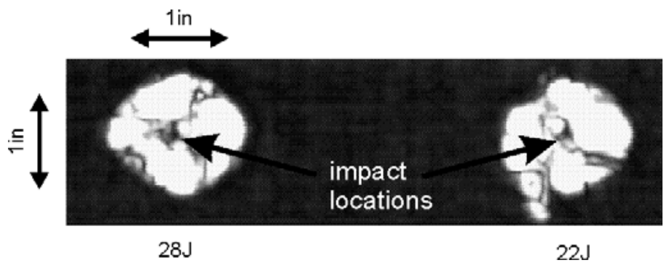
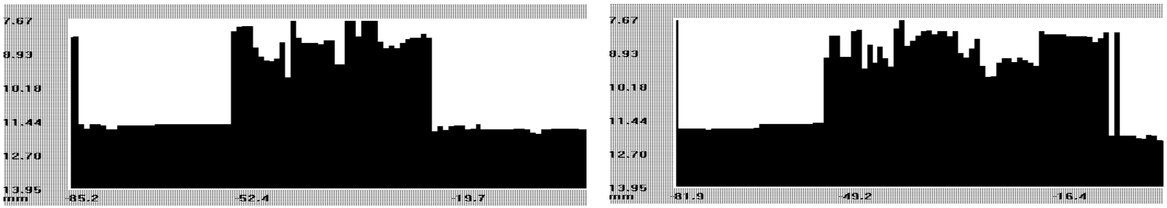


FIGURE 5. C-scan of the impacted cross-ply coupon in the damaged area (two hit-points with the energy of 28 J and 22J).

4. ULTRASONIC IMAGING OF COMPOSITE LAMINATES

Coupons 40x300 mm were cut from a cross-ply specimen 4.6 mm thick, with the 300 mm side parallel to the fiber direction of the first layer (Fig. 4). Low-velocity impact damage was introduced by a specially designed impactor with a 25 mm radius steel ball tip. The energy of the impact was based on the mass and height of the impactor. A guiding rail was used to control the location of the impact with an estimated precision of 2 mm. On one of the composite coupons, the impact was applied at the same point 30 consecutive times with a constant energy of 22 J. The experiment was repeated with the impact energy of 28 J. Several ultrasonic evaluation techniques were deployed to inspect the damaged areas. First, a C-scan image of the damaged coupon was acquired in the immersion tank. This C-scan is shown in Fig. 5. Next, the coupon was inspected using B-scan module of the ultrasonic flaw detector EPOCH III and the integrated real-time A-scan/imaging system developed by Northwestern University and Imperium, Inc. B-scan images of the impact points are presented in Fig. 6a, b. Both B-scans show variable depth of the damaged/delaminated composite layers. This fact demonstrates importance of the real-time guidance system for proper vertical positioning of the imaging plane. For large damaged areas, timely repositioning of the imaging plane will substantially improve the image quality. Another important observation from the B-scan images is related to the size of the impacts. Visible indications of both the damaged areas are approximately 15 mm in diameter. The same impacted points measured by ultrasonic B-scan techniques show much larger (more than twice) cross-sectional diameter of the delaminated areas. This means that the internal damage in composite laminates from the low-velocity impacts could significantly exceed visible surface damage. It also means that visual inspection cannot be considered as an adequate inspection procedure for such cases. Real-time ultrasonic images acquired using the integrated inspection system have also demonstrated quite large areas of the internal damage (Fig. 7).



a **b**

FIGURE 6. B-scan images of the damaged areas from low-velocity impacts of energy 22J (a) and 28J (b).

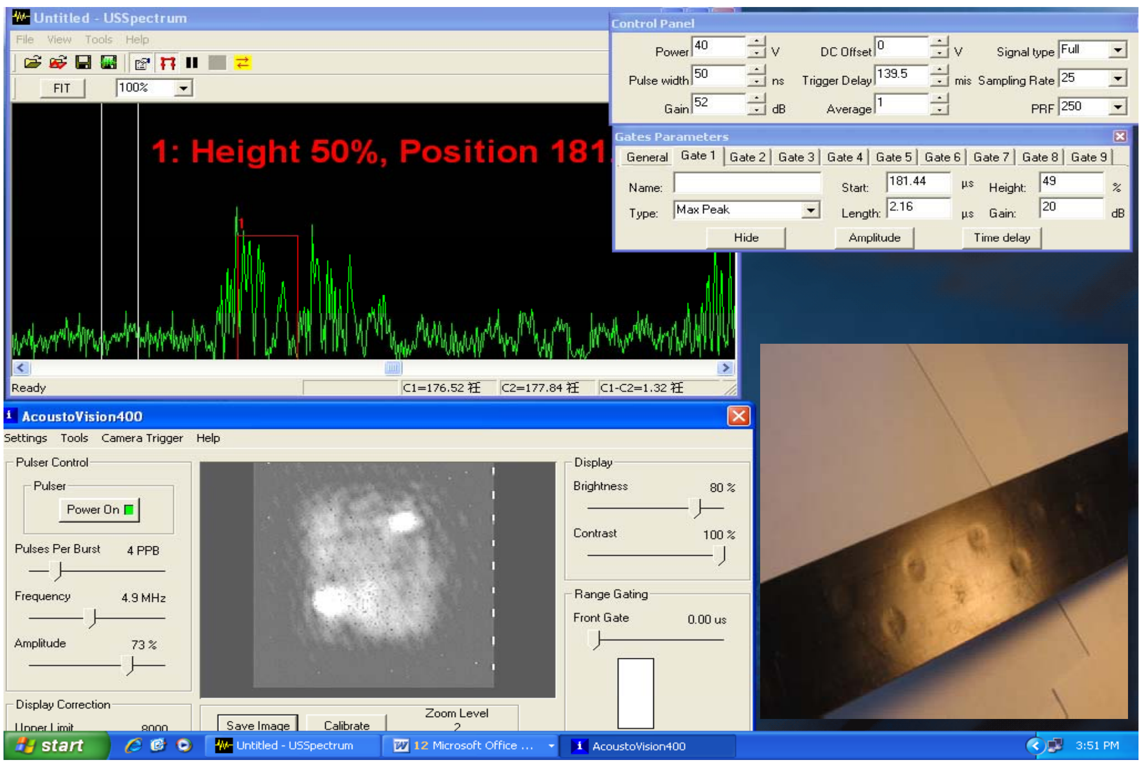


FIGURE 7. Real-time ultrasonic A-scan and image of the damaged area from low-velocity impact of energy 28J.

5. LASER ACOUSTOCAM IMAGING:

The advantages of laser-based generation of ultrasound are well known and have been investigated in detail by many researchers. Principal aspects include the non-contact characteristic of the technique and the adaptability to hostile working environments and complex geometries. These advantages represented an initial incentive for our work to implement a laser-based source for the imaging system. The three different configurations used so far in the development process are shown in Fig. 8. In all cases, the ultrasound is produced within a constrained absorption-expansion (CAE) layer, heated by an expanded laser beam. For the fabrication of the CAE layer, several methods were considered. CAE layers composed of carbon particles (size 2 μm) and a constrictive matrix of transparent silicone were used for the images included in this paper. The details of the CAE layers fabrication and performance are given elsewhere [3]. Since the silicon matrix is a soft material, this CAE layer works as a dry couplant as well.

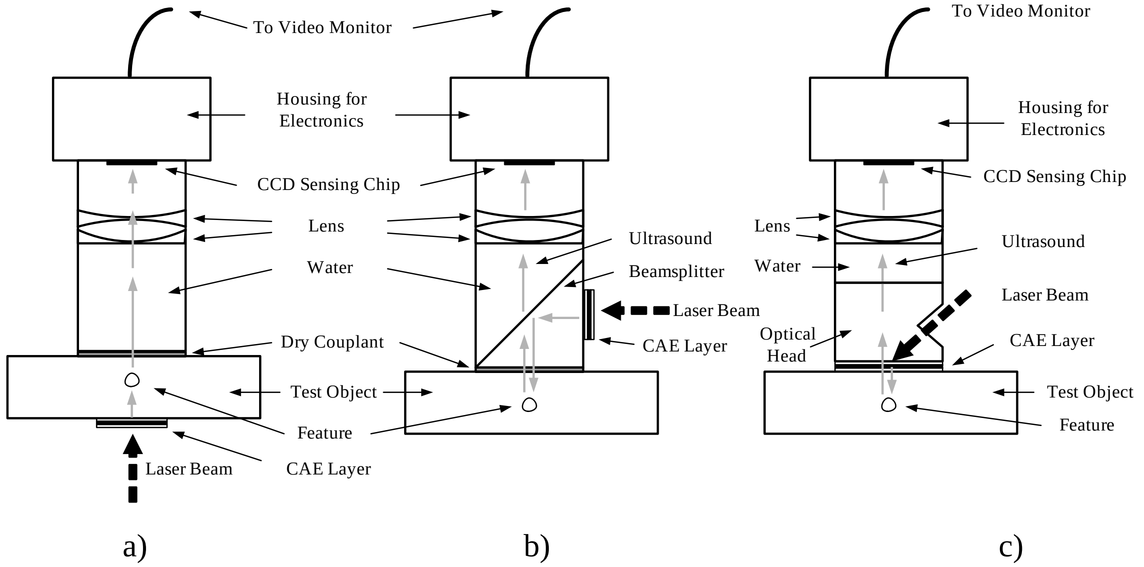


Figure 8: Ultrasonic imaging system diagram using laser-based ultrasound generation: a) pulse-echo mode with beamsplitter, b) through-transmission mode with beamsplitter, and c) pulse-echo mode using an optical head.

5.1 Imaging of defects in Aluminum blocks using a laser-based ultrasonic source

As a proof of concept, we started with a variation of the original PZT-configuration. A CAE layer was mounted in the place of the PZT transducer, as shown in Fig. 8a. A Continuum SureLite I-20 Nd:YAG laser, with output at 1064nm wavelength and 5ns pulse width, was used to excite the ultrasound in the CAE layer. The energy of the laser beam was approximately 80mJ and the beam was expanded to a diameter of 1 inch. This test was intended as a simple feasibility study for incorporating the laser-based source into the imaging system. Images of surface defects on aluminum blocks with flat-bottomed holes (sometimes in the shape of letters) were recorded. These images are displayed in Fig 9.

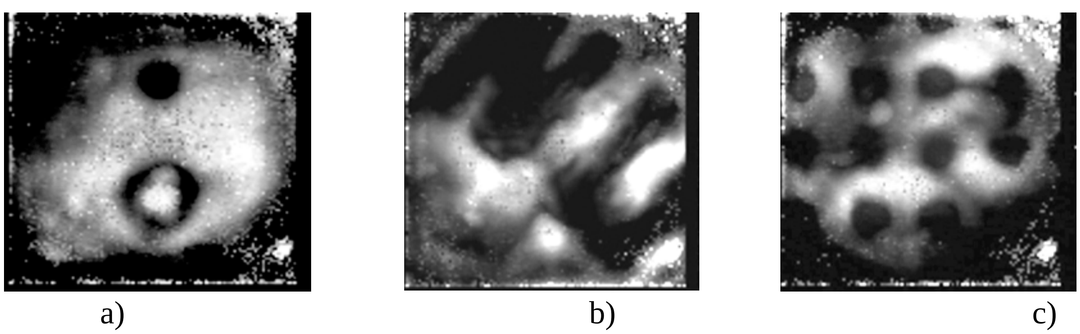


Figure 9: Images of subsurface defects in pulse-echo mode with a laser-based ultrasonic source.

5.2 Imaging of defects in composite laminates using a laser-based ultrasonic source

As mentioned before, an important application of the imaging system is to identify defects in composite materials. Another step towards the development of the imaging system using the laser-based source was to image pillow inserts (representing delaminations) in a unidirectional composite panel. The imaging system is configured in through-transmission mode, as shown in Fig.8a. The CAE layer was placed directly on the composite panel. The camera was attached to the other side of the panel to acquire the image. Wet couplant was used to couple the camera to the panel. The image obtained is shown in Fig. 10.

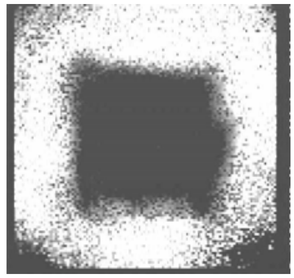


Figure 10: Image of a square-pillow defect in a unidirectional composite pannel, using a laser-based ultrasonic source and in through-transmission.

6. CONCLUSIONS:

The salient points of this paper are:

1. A dual-mode ultrasonic system using a large area imaging system and combined with an A-scan system for depth information has been developed.
2. The ultrasonic source can be either conventional piezoelectric transducers or laser-based generation.
3. The system has been demonstrated on a number of metallic and composite specimens.

ACKNOWLEDGEMENTS

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REFERENCES

1. Imperium Inc., Silver Spring, MD, USA, http://www.imperiuminc.com.
2. C. B. Scruby and L. E. Drain, *Laser Ultrasonics*, publisher, Adam Hilger, Bristol, 1990.
3. G. Petculescu, Y. Zhou, I. Komsky, and S. Krishnaswamy, “Laser-Generated Ultrasonic Source For A Real-Time Dry-Contact Imaging System,” American Institute of Physics, vol. 24, ed. D.O. Thompson and D.E. Chimenti, 2005.