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13. ABSTRACT (Maximum 200 words) The objective of this project was to develop advanced non-contract instrumentation for nondestructive detection and characterization of critical flaws in aircraft structures as part of a timely quantitative nondestructive evaluation (QNDE) program. In the past several years, we have successfully developed several advanced ultrasonics NDE techniques that are relevant to the Air Force. This project was aimed at further development of advanced non-contact laser ultrasonic instrumentation for NDE so as to facilitate flaw detection and characterization. The sensing technique used is based on adaptive interferometry for non-contract detection of ultrasound. The generation of ultrasound is also by means of laser illumination. The advantages of using ultrasonic probe signals to interrogate the interiors of structures is well recognized. Non-contract laser ultrasonic NDE procedures, in addition: (1) provide increased speed of inspection; (ii) are amenable to quantitative interpretation since they are independent of coupling efficiency (iii) can be used on complex structures with curved surfaces; and (iv) can be configured (using optical fibers for instance) into very compact systems that can be used for remote inspection of hard-to-reach areas such as the interiors of fuel tanks inside wing-boxes. The technical findings are outlined in this report. The project findings offer great promise for the realization of rapid multiplexed two-mixing interferometric receivers for laser ultrasonic detection of flaws in aircraft structures.				
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NON-CONTACT ULTRASONIC DIAGNOSTIC SYSTEMS

AFOSR Award No.F49620-98-1-0285

Final Summary Technical Report

November 2001

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TABLE OF CONTENTS

Executive Summary	3
1. Introduction	5
2. Technical Findings	5
3. Future Directions: Preliminary Results on Laser Ultrasonic Phased-Arrays	12
4. Conclusion	18

EXECUTIVE SUMMARY

The objective of this project was to develop advanced non-contact instrumentation for nondestructive detection and characterization of critical flaws in aircraft structures as part of a timely quantitative nondestructive evaluation (QNDE) program. In the past several years, we have successfully developed several advanced ultrasonics NDE techniques that are relevant to the Air Force. This project was aimed at further development of advanced **non-contact laser ultrasonic instrumentation for NDE** so as to facilitate flaw detection and characterization. The sensing technique used is based on adaptive interferometry for non-contact detection of ultrasound. The generation of ultrasound is also by means of laser illumination. The advantages of using ultrasonic probe signals to interrogate the interiors of structures is well recognized. *Non-contact* laser ultrasonic NDE procedures, in addition: (i) provide increased speed of inspection; (ii) are amenable to quantitative interpretation since they are independent of coupling efficiency; (iii) can be used on complex structures with curved surfaces; and (iv) can be configured (using optical fibers for instance) into very compact systems that can be used for remote inspection of hard-to-reach areas such as the interiors of fuel tanks inside wing-boxes.

The technical findings are outlined in this report. The project findings offer great promise for the realization of rapid multiplexed two-mixing interferometric receivers for laser ultrasonic detection of flaws in aircraft structures.

Personnel Supported:

The following people were supported in part through this project:

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2. Todd W. Murray, Hemmo Tuovinen, and Sridhar Krishnaswamy, (2000), "Adaptive Optical Array Receivers for Detection of Surface Acoustic Waves," Applied Optics, vol. 39, No. 19, pp 3276-3284.
3. P. Fomitchov, Alex Kromine, Sridhar Krishnaswamy, J.D. Achenbach, (May 2000), "Sagnac-Type Fiber-Optic Array Sensor for Detection of Bulk Ultrasonic Waves," IEEE UFFC Transactions. Vol. 47, No.3, pp584-590.
4. P. Fomitchov, Sridhar Krishnaswamy, J.D. Achenbach, (July 2000), "Extrinsic and Intrinsic Fiber-Optic Sagnac Ultrasound Sensor," Optical Engineering, vol 39, No. 7, pp 1972-1984.
5. P.A. Fomitchov, Sridhar Krishnaswamy, and J.D. Achenbach, (1999), "Intrinsic Fiber-Optic Sagnac Ultrasound Sensor for Process Monitoring in Composite Structures," SPIE vol. 3589, pp 156-159.
6. P.F. Fomitchov, T. W. Murray and Sridhar Krishnaswamy, "Intrinsic Fiber-Optic Ultrasonic Sensor Array Using Multiplexed Two-Wave Mixing Interferometry," in Review of Progress in Quantitative Nondestructive Evaluation, ed. D.O. Thompson and D.E. Chimenti, vol. 21, AIP Conf. Proc
7. Y. Zhou, T. W. Murray, and Sridhar Krishnaswamy, "A Multiplexed Two-Wave Mixing Interferometer for Laser Ultrasonic Measurements of Material Anisotropy," in Review of Progress in Quantitative Nondestructive Evaluation, ed. D.O. Thompson and D.E. Chimenti, vol. 21, AIP Conf. Proc.
8. T.W. Murray, Z. Yi, and S. Krishnaswamy (2000), "Adaptive Optical Phased Array Interferometer for Acoustic Wave Detection," in Review of Progress in Quantitative Nondestructive Evaluation, ed. D.O. Thompson and D.E. Chimenti, vol. 20, AIP Conf. Proc..
9. Hemmo Tuovinen, T.W. Murray, and Sridhar Krishnaswamy, (1999), "Adaptive Array Receivers for Surface Acoustic Wave Detection," in Review of Progress in Quantitative Nondestructive Evaluation, ed. D.O. Thompson and D.E. Chimenti, vol. 19, AIP Conf. Proc.5098.
10. Hemmo Tuovinen, T.W. Murray, and Sridhar Krishnaswamy, (1999), "An Adaptive Laser-Array Receiver for Surface Ultrasonic Waves," in AIP Conf. Proc. 497, Ninth International Symposium on Nondestructive Characterization of Materials, ed. R.E. Green.

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- Invited presentation at the Optical Society of America Annual Meeting, Los Angeles, 2001.
- Invited presentation at the Ultrasonics Symposium, Delft, 2001.
- Presented papers at the Review of Progress in QNDE, 1999,2000, 2001.
- Presented a paper on the adaptive interferometer at the Ninth International Symposium on Materials Characterization, Sydney, July 1999.
- Presented a lecture at the Joint US-Korea IEEE-UFFC Workshop on Nondestructive Evaluation, Pusan, S. Korea, May 1999.
- Presented a series of lectures on Laser Ultrasonic Sensors at Oxford University, November 1998.
- Discussions with and demonstrations to various visitors to our labs. Ongoing discussions and collaboration with General Electric, Caterpillar, AlliedSignal on laser ultrasonics.
- Our work on phased array laser ultrasonic systems was highlighted in the article "Adaptive Optical Interferometers Speed Inspection" in SENSOR TECHNOLOGYALERT, July 21, 2000, John Wiley & Sons, Inc., New York, NY 10158.

I. INTRODUCTION

This project is concerned with laser ultrasonic diagnostic systems. Laser ultrasonics is expected to play a key role in structural diagnostics of aircraft structures. Lockheed Martin's recent successful bid for the JSF includes development of a state of the art laser ultrasonic inspection facility.

The objective of this project was to develop advanced non-contact instrumentation for nondestructive detection and characterization of critical flaws in aircraft structures as part of a timely quantitative nondestructive evaluation (QNDE) program. QNDE is an interdisciplinary process encompassing quantitative measurement techniques to identify and characterize flaws, coupled with measurement models to interpret and relate the data to considerations of structural integrity and remaining life time of a component. The complete QNDE process therefore requires drawing on the resources of sensor technology, fracture mechanics and materials science to obtain reliable estimates of remaining safe life for a structure given the flaw characteristics as measured by a reliable NDE tool.

The US Air Force has many old aircraft that form the backbone of the total operational force. A few of the older aircraft will be retired and replaced with new aircraft. However, for the most part, these replacements are a number of years away. Many of the aircraft have no planned replacements and are expected to remain in service a substantial number of additional years.

The Air Force fleet must operate under diverse and often severe environmental conditions, and the methods of QNDE will play an increasing role in the in-service monitoring and maintenance of the currently aging fleet as well as of future structural systems incorporating advanced composite materials and metals. New and improved techniques are needed to detect and characterize the severity of fatigue cracking and corrosion damage which can severely compromise the structural integrity and effective performance of Air Force systems. Many critical areas of aircraft structures such as the interiors of fuel tanks and interfaces in multi-layered components are not readily accessible for inspection using conventional NDE techniques. Improved methods for the timely detection and characterization of flaws are therefore needed to assess the safety of aging aircraft structures.

Under previous AFOSR-support, we have successfully developed several advanced ultrasonics NDE techniques that are relevant to the Air Force. This project further pursued the integrated development of advanced non-contact **laser ultrasonic** instrumentation for NDE so as to facilitate flaw detection and characterization. In the following sections, the main technical findings of this project are described in detail. This is followed by some preliminary results indicating the directions to pursue in the near future.

II. TECHNICAL FINDINGS

In this project, we developed laser ultrasonic receivers based on adaptive two-wave mixing in photorefractive crystals. The systems were configured for matched-filter detection of weak ultrasonic echoes from flaws. The sensitivity of optical detection of ultrasound needs to be improved in order to detect the typically weak scatter from small flaws such as cracks. The matched-filter optical arrangements utilizing distributed optical receivers that are described here can provide improved sensitivity, directionality to selectively discern flaw echoes, and temporal resolution.

We have configured distributed optical receivers using both homodyne and heterodyne two-wave mixing holographic interferometers. Each of these set-ups has advantages and disadvantages in terms of sensitivity, simplicity of set-up, speed of adaptation to ambient noise, and the ability to provide direct absolute calibration. In both interferometer systems, a 6mm wide by 6mm high by 7mm thick BSO photorefractive

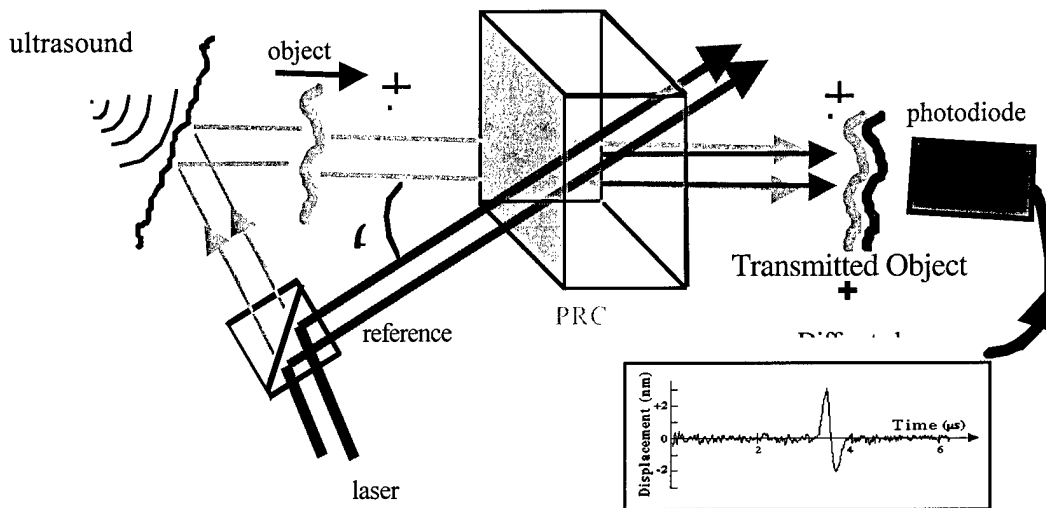


FIGURE 1: Adaptive holographic optical receiver setup

crystal was used with the crystal orientation such that the grating vector is along the [001] crystal axis. A sinusoidal electric field of 6 kV/cm at 3200 Hz was applied to enhance the diffraction efficiency. A schematic of the optical set up for the homodyne setup is shown in Fig.1. Both the homodyne and the heterodyne setups mentioned above can be configured as distributed optical receivers having various directionality and frequency response characteristics. These configurations are obtained by suitably modifying the spatial distribution of the detection laser

power (the object beam footprint) on the sample surface (Fig. 2A). For instance, by focussing the laser beam as a point on the object, an omni-directional broadband receiver is obtained. If the object beam footprint is a single line, the resulting receiver is primarily sensitive to SAWs propagating perpendicular to the line. By using a diffraction grating, the object beam footprint can be made to be a series of equally spaced points or lines. Such linear-array receivers are selectively sensitive to SAWs of a certain frequency and may be used advantageously if the SAW packet is known to be narrowband. A chirped array receiver can be configured using an object beam footprint that is a set of lines with linearly increasing spacing between the lines. In this case the receiver, when used to detect a matched chirped SAW packet, allows high temporal resolution to be maintained in the detection process while still distributing the detection laser power over the sample surface.

In general, the response of a distributed SAW receiver depends on the object beam footprint, the spatial distribution of the SAW packet, and the velocity of the SAW on the specimen. The specimen, for simplicity, is assumed to be isotropic. Let the optical power density function in the plane of the object surface be $P_o(x,y)$ as shown in Fig. 2B. Consider a planar SAW packet whose displacement field is given by:

$$u(x, y, t) = U(x \cos \theta + y \sin \theta - ct) \tag{1}$$

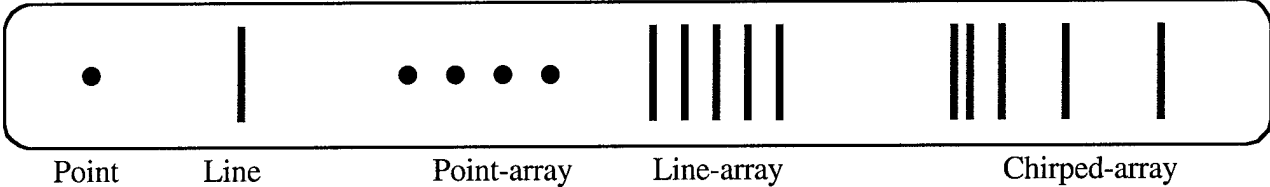


FIGURE 2A: Object-beam footprints for distributed optical receivers

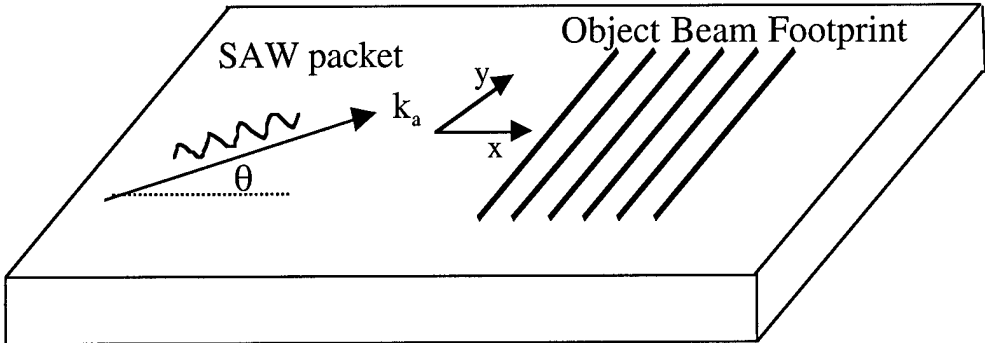


FIGURE 2B: Geometry of SAW packet and object beam footprint

where θ is the angle that the propagation vector makes with the x-axis, and c is the SAW wave-speed. We define the signal power, P_{sig} , as that part of the total collected laser power incident on the photodetector which contains information about the SAW displacement. Assuming linear detection of small displacements ($u \ll \lambda_o$), the signal power P_{sig} can be expressed (to within a constant factor) as:

$$P_{sig}(t) = k_o M \iint_S u(x, y, t) P_o(x, y) dx dy \quad (2)$$

Here the optical wave-number $k_o = 2\pi/\lambda_o$, λ_o is the optical wavelength, M is the modulation depth of the interference which is a fraction between zero and unity, and the integration is over the domain S which covers the object beam footprint. It should be noted that the signal power is therefore a convolution in the direction of the propagation vector of the SAW displacement signal with the object beam footprint.

Table 1 summarizes the response of several SAW receivers with various object beam footprints. In particular, note the following:

Point-focused SAW receiver: This is an omni-directional receiver (equally sensitive to ultrasound from all directions) whose higher frequency response rolls off depending on the spot size (Fig. 3). There is a tradeoff between sensitivity and frequency response because higher frequency response requires tighter focal spots, which in turn might necessitate decreasing the optical power in order not to damage the object.

Line-focused SAW receiver: As for the point-focused case, it is again essential to decrease the line-width x_o in order to have a broadband receiver. However, unlike for the point-focused case, it is now possible to keep the sensitivity high by keeping the total optical power high and distributing the light over the length L of the line receiver. An interesting feature of the line receiver is that it is highly directionally sensitive, especially as the length L increases or the frequency of the SAW increases. The "sinc" function response (Table 1) indicates that there will be signal roll off as the propagation direction of the SAW deviates from normal incidence. The extent of roll off, and consequently the extent of directionality of the line receiver, depends on the parameter $k_a L/2$, with higher frequency and consequently shorter wavelength ultrasonic signals experiencing a more rapid roll off. Figure 4 shows the experimental results that confirm this behavior.

TABLE 1: Response of Various Distributed Optical Receivers

Object Beam Footprint	Optical Matched Filter Receiver Response
<p><u>Point focussed:</u></p> $P_o(x, y) = P_o \exp\left(-\frac{x^2 + y^2}{r_o^2}\right)$	$P_{sig} = k_0 M . P_0 \pi r_o^2 . \exp\left(\frac{-k_a^2 r_o^2}{4}\right) . U \exp(-i\omega_a t)$
<p><u>Line focussed:</u></p> $P_o(x, y) = P_o \exp\left(-\frac{x^2}{x_o^2}\right),$ <p style="text-align: center;">($-L/2 \leq y \leq L/2$)</p>	$P_{sig} = k_0 M . P_0 \sqrt{\pi} L x_o . \exp\left(\frac{-k_a^2 x_o^2 \cos^2 \theta}{4}\right)$ $. \text{sinc}\left(\frac{k_a L \sin \theta}{2}\right) . U \exp(-i\omega_a t)$
<p><u>Line-array:</u></p> $P_o(x, y) = P_o \sum_{n=1}^N \delta(x - nd) . \exp\left(-\frac{x^2}{x_o^2}\right),$ <p style="text-align: center;">($-L/2 \leq y \leq L/2$)</p>	$P_{sig} = k_0 M . P_0 \sqrt{\pi} N L x_o . \exp\left(\frac{-k_a^2 x_o^2 \cos^2 \theta}{4}\right) . \text{sinc}\left(\frac{k_a L \sin \theta}{2}\right)$ $\cdot \left\{ \frac{\sin\left(N \frac{k_a d \cos \theta}{2}\right)}{N \sin\left(\frac{k_a d \cos \theta}{2}\right)} \right\} . U \exp(-i\omega_a t - \varphi)$
<p><u>Chirped-array:</u></p> $P_o(x, y) = P_o \left(\frac{1}{2}(1 + \text{sgn}(S(x)))\right),$ <p style="text-align: center;">($0 \leq x \leq T, -L/2 \leq y \leq L/2$)</p> <p>where $\text{sgn}(\psi) = \begin{cases} 1 & \psi > 0 \\ 0 & \psi = 0 \\ -1 & \psi < 0 \end{cases}$</p>	<p>Temporally well-defined (analytical expression too complicated to be presented compactly here). See Reference [14]</p>

Line-array SAW receiver: These are narrowband receivers sensitive to only a set of discrete ultrasound bands centered around $f_n = nc/(d \cos \theta)$, $n = 1, 2, 3, \dots$. The array can therefore be *tuned* to receive a desired frequency by appropriately choosing the line spacing ‘d’. The normalized magnitude of the frequency response of the array receiver is plotted in Fig. 5 for arrays of size

$N=1,3,9$. The plot is for the case of normal incidence and for a line width of $50\ \mu\text{m}$, velocity of $3000\ \text{m/s}$, and line spacing of $600\ \mu\text{m}$. The response of a single line ($N=1$, no array) shows the high frequency roll off attributable to the finite width of the lines. With additional number of elements in the array, the receiver response becomes increasingly narrowband centered around the array frequencies. It is seen that the amplitude of the SAW packets at the array frequencies is enhanced over that from a single line in direct proportion to the number of lines in the array (assuming uniform power density P_0 over all lines in the array). Figure 6 shows experimental results for a line-array receiver that confirm the expected response.

Chirped SAW receiver: The major advantage of using a chirped receiver (where the line spacing increases linearly from one end) over a narrowband receiver is that the matched filter output is compressed into a narrow spike leading to increased temporal resolution of the detection system. This concept is illustrated in Fig. 7. Figure 7a shows both a linear frequency modulated tone burst and a narrowband tone burst. Fig. 7b shows the respective signal outputs for matched displacement fields and receiver functions. The peak signal amplitude is identical but the chirp signal envelope is significantly compressed while the narrowband signal has drawbacks in that ambiguities exist at multiples of the signal period (at the sidelobes) and difficulties may arise when detecting multiple closely spaced signals. One additional feature of the chirp receiver is that the asymmetry of the receiver makes it primarily sensitive to chirp signals propagating in a particular direction as opposed to narrowband line array receivers which are equally sensitive to waves propagating in either direction along the normal to the lines. Figure 8 shows the experimental results for a chirped receiver created using a transmission mask with the desired chirp array. Fig. 8A shows the arrival of two wave packets with the first packet corresponding to the direct signal and the second corresponding to a reflection from the sample edge. The direct signal correlates well with the receiver and gives the characteristic pulse compressed signal predicted (see Fig. 7B for comparison). The reflected signal is 180° out of phase with respect to the direct signal (flipped) and thus does not correlate with the receiver. By rotating the receiver mask 180° , correlation with the reflected signal can be achieved as is illustrated in Fig. 8B. Chirped receivers therefore not only allow for better temporal resolution than narrow-band receivers but also offer an added degree of directionality.

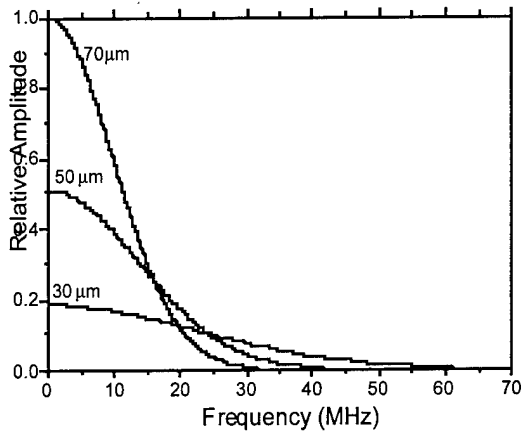


Figure 3: Frequency response of point-focused SAW receiver drops with spot size. From damage considerations, the optical power density is kept constant resulting in decreased sensitivity for higher bandwidth receivers.

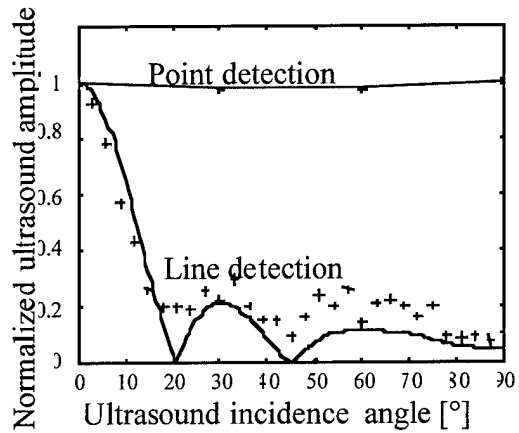


Figure 4: Results demonstrating directional sensitivity of the line-probe interferometer. Points are experimental data, and lines are best theoretical curve fit. For comparison, results for a point-receiver are also shown, demonstrating their omnidirectionality.

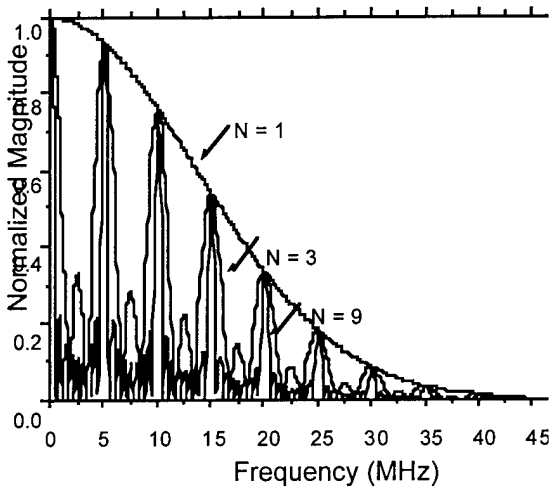


Figure 5: Frequency response of line-array receivers. Note that the response becomes increasingly narrowband with increasing of elements.

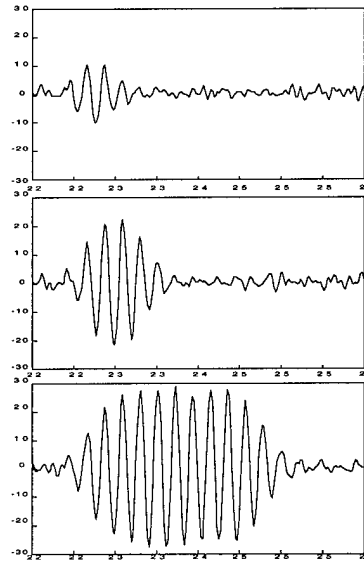


Figure 6: Experimental results for 5MHz toneburst detected using 1, 3 and 5 lines respectively.

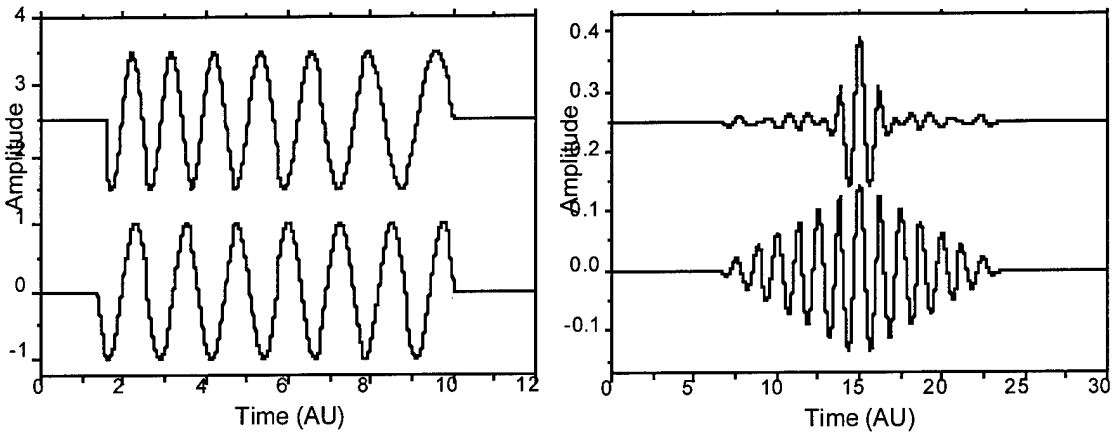


Figure 7A: Theoretical chirped and narrowband wavepacket. **7B** matched filter output showing time compression of chirped signal.

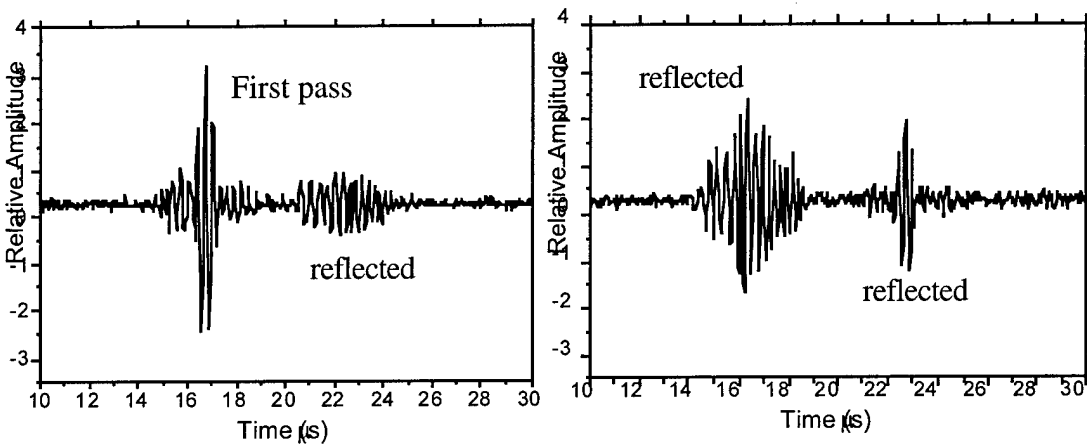


Figure 8A: Experimental results. First pass signal is matched with chirped SAW packet whereas the back reflected signal is not. **8B** correlation with the back reflected signal is obtained by reversing the object beam footprint.

III. FUTURE DIRECTIONS - Preliminary Results On Laser Ultrasonic Phased-Arrays:

Our laser ultrasonic multiplexed detector can be made significantly more useful by the addition of a photo-detector array. In this case, each point or line on the surface can be imaged on to a *separate* detector. This preserves the *phase* information from each point for subsequent processing. The receiver can then be focused in a given direction by use of appropriate electronic delays between photo-detector outputs or via digital processing. The major advantage of such a

system is that it can be used in ultrasonic imaging applications to obtain flaw maps both for bulk and surface acoustic waves. Cracks in engine components and airframes as well as corrosion in the interior of structures can be effectively imaged. The system can also be used to demodulate phase-encoded signals from fiber-optic sensor arrays that form part of a health monitoring network in smart structures. These are the aspects that will be pursued in this proposed project.

In the following sections, we first describe A proposed fiber-optic laser ultrasonic array diagnostic system that uses multiplexed two-wave mixing. We then outline the major components of the proposed work including applications to laser ultrasonic phased-arrays for rapid NDE of aircraft structures and fiber-optic ultrasonic sensor arrays for health monitoring of smart structures.

3.1 Multiplexed Laser Ultrasonic Array System: The proposed fiber-optic laser ultrasonic array system is shown schematically in Figure 9A,B. Light from a laser source is coupled into a bundle of optical fibers (single or multi-mode) to form a single reference and several sampling beams as shown in Figure 9A. (This part of the system can eventually be replaced by 1xN fiber couplers.) The reference beam is piped directly to the multiplexed two-wave mixing demodulator shown in Fig. 9B. The sampling fibers can be used either *extrinsically* or *intrinsically*. In the *extrinsic* mode, these just pipe the light to the surface of a test specimen, and the scattered light from each point is collected by another set of multi-mode fibers which then take the light to the demodulating unit shown in Fig. 9B. In the *intrinsic* mode, the sampling fibers themselves act as sensors, and directly pipe the light to the demodulation unit.

The demodulation unit consists of the same set of optics as in the system described in section II, except that now the beams along each of the signal beam directions is imaged onto separate photodetector elements. This creates a true interferometric array by the process of multiplexed two-wave mixing in the PRC.

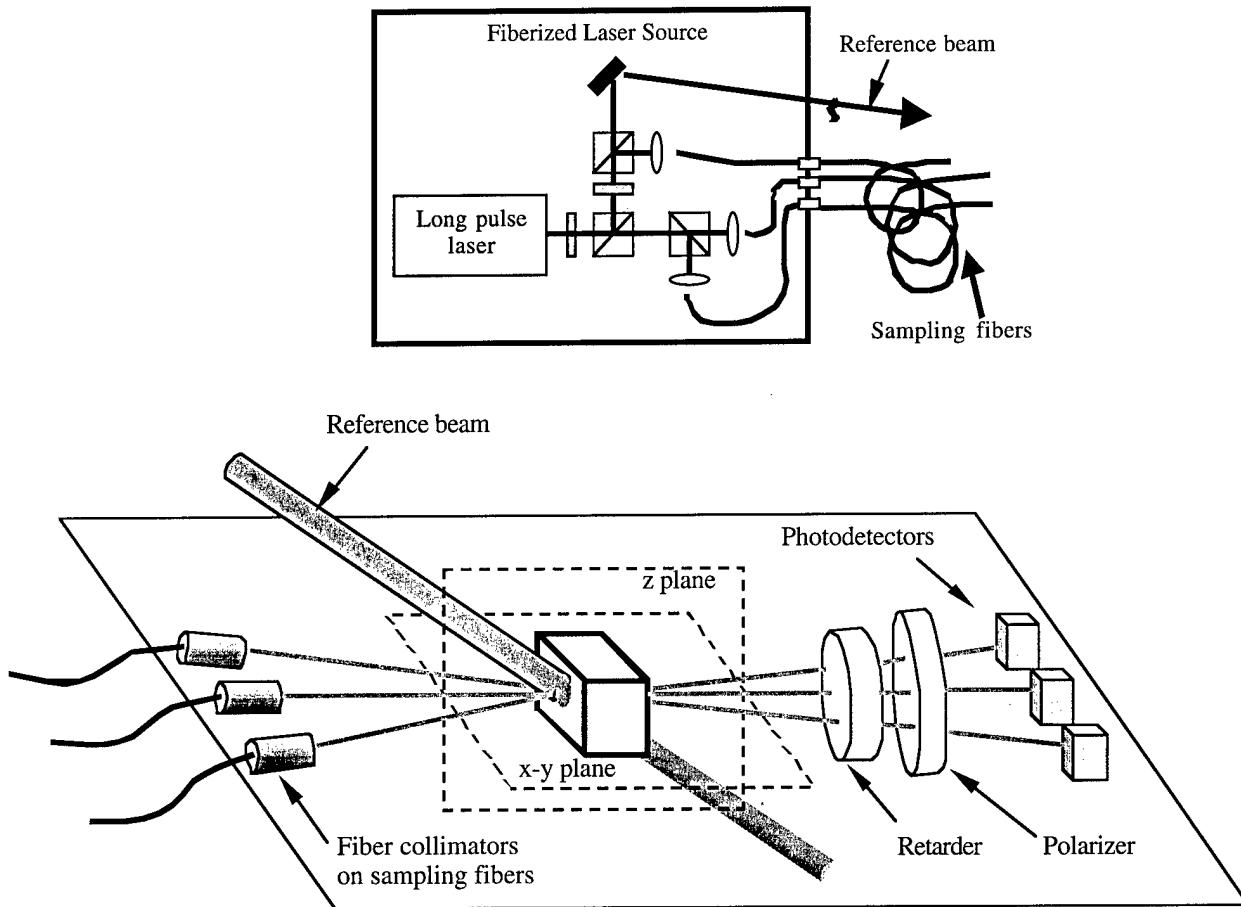


Figure 9: A. Fiberized laser source coupling light into N-sampling fibers; B. multiplexed two-wave mixing demodulation unit (only 3 sampling fibers are shown).

3.2 Laser Ultrasonic Phased-Array for Rapid NDE of Structures: Ultrasonic phased arrays are typically constructed using multi-element contact transducers and, in general, provide both transmit and receive focusing capabilities. These systems have seen widespread use in both nondestructive evaluation (NDE) and medical ultrasonics. Ultrasonic phased arrays using lasers for generation and detection are desirable because they are non-contact, have a small footprint and can be used on awkward geometries and at high temperature. Furthermore, optical phased array detection can be used for high frequency applications where high resolution imaging is required, but the array element spacing has to be small. This is critical for detecting small cracks, for instance. Although some progress has been made, the fabrication of high-frequency contact

transducer arrays with array element spacing in the micrometer range presents significant challenges. Using optical arrays, the element size can be precisely controlled down to the micrometer range using a focusing lens. The signal-to-noise ratio (SNR) and spatial resolution of the detection system can be enhanced through post-processing using, for example, the synthetic aperture focusing technique. Additionally, unlike with contact transducer systems, the element spacing in the array can be dynamically controlled with optical receivers.

To date, full-fledged laser-based ultrasonic phased array systems have not been demonstrated. Phased array laser generation systems, using a series of appropriately timed and spaced laser pulses, have been shown to focus and directionally steer thermoelastically generated ultrasound. On the detection side, however, ultrasonic data has only been collected by scanning a single point over the surface of the object under inspection. *In order to increase the speed of inspection, a multi-element optical receiver such as the one described in section 3.1 is required.* The array receiver can be focused to any point by appropriate digital or analog phase shifting of the detected signals. Although scanning may still be required when using multiplexed interferometers to inspect large area components, array detection has the potential to significantly reduce inspection time by a factor of ten or better.

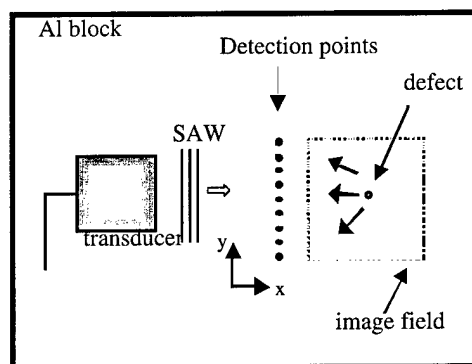


FIGURE 10: Imaging of surface flaws using a linear phased-array optical receiver.

In a preliminary experiment to demonstrate the laser ultrasonic phased array receiver system, a 5MHz piezoelectric transducer and wedge were used to generate surface waves on a

semi-polished aluminum block as shown in Fig. 10. (This will eventually be replaced with a laser generation source.) The receiver array was used to detect the surface acoustic waves scattered by a 1.2mm hole. A nine element linear receiver array was used with a 1mm spacing between elements. A *single* balanced photodetector pair was used to sample the signals from each element for preliminary array analysis. The total optical power was 600 mW and the beam ratio was approximately 10. The resulting signals (averaged 100 times) are shown in Fig. 11. The first arrivals are the direct surface waves generated by the transducer. The signals are normalized according to the calibration reference, and the variation in amplitude and shape of the first arrival is due to the directivity of the generating transducer. The scattered signal from the defect is also picked up by all nine array elements. The defect is positioned close to the midpoint of the array and thus the scattered signal arrives first to the center elements and later to the outer elements. These results demonstrate that multiplexed optical detection is indeed feasible.

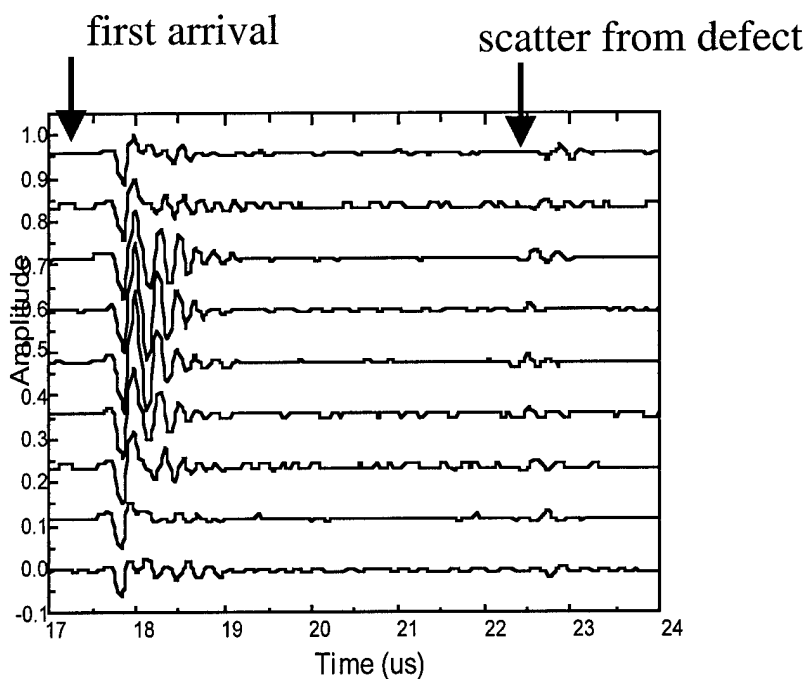


FIGURE 11: Signals detected by the 9-element linear phased array optical receiver.

3.2.1 Image Analysis - Synthetic Aperture Focussing: The data received from the array can be processed using conventional synthetic aperture focusing techniques and presented as an image in order to demonstrate defect localization. Using the coordinate system defined in Fig. 10, the time that it takes for a scattered signal to reach the n^{th} array element (assuming plane wave illumination) from a field point (x,y) is given by:

$$t_n(x,y) = \frac{x + \sqrt{x^2 + (y - y_n)^2}}{c} + t_0 \quad (3)$$

where $(0, y_n)$ is the array element location, t_0 is the time the ultrasound takes to travel from the transducer to the array, and c is the surface wave velocity. The total signal $S(x,y)$ from any field point is then taken as the sum of signals from all of the elements in the array:

$$S(x,y) = \sum_{n=1}^N W_n(t_n(x,y)) \quad (4)$$

where $W_n(t)$ is the time signal received by array element n . The resulting image is given in Fig.12 for the data in Fig. 11. The image shows an 8x8mm section of the sample surface positioned 2.5mm from the array (x direction) and centered on the array (y direction). The interferometer shows good focusing capability as is indicated by the localization of the defect seen in the center of the image. Further resolution enhancement is possible by increasing the number of array elements and increasing the frequency.

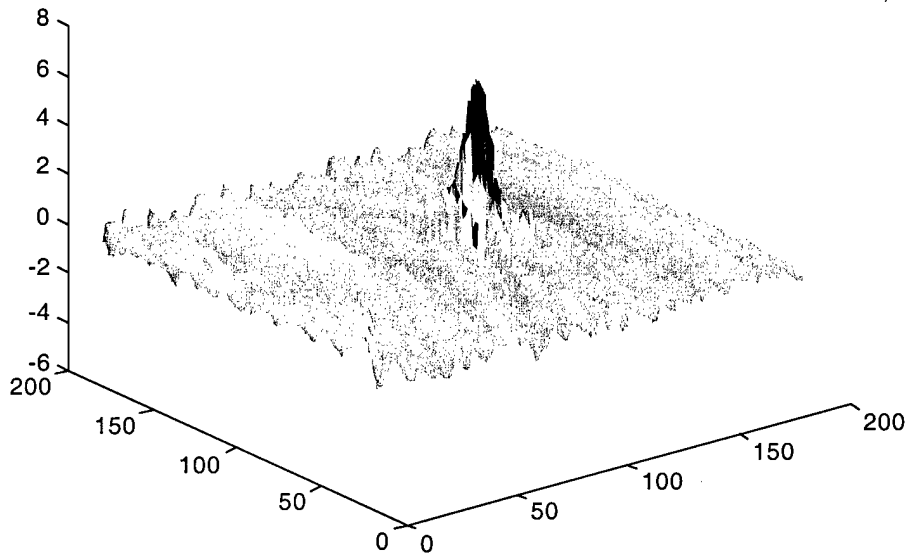


FIGURE 12: Reconstructed image using synthetic aperture focussing. Vertical axis is proportional to the acoustic impedance. Note that the flaw region is easily visible even with just an 8-element array. Better resolution can be obtained with larger arrays.

IV. CONCLUSION:

In summary, our current work on distributed optical matched-filter receivers has established that:

- They offer an effective means of avoiding excessive sample heating and damage while retaining high frequency bandwidth and high sensitivity.
- They can be configured as point, line, line array, and chirped receivers depending on the frequency and directivity characteristic necessary for a given application, the damage threshold of the material under inspection, and the available detection laser power. The systems can be broadband or narrowband, omni-directional or highly directional, depending on the application.

Furthermore, we have shown that it is possible to configure laser ultrasonic phased arrays for detection of the flaws in structures. All these systems show great promise for the future of laser ultrasonics in aircraft structural diagnostics.