Fully Non-Contact Laser Excitation and Reception Ultrasonic Propagation Imaging System with Repeat Scanning Technique

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ABSTRACT

A reliable nondestructive evaluation technique is essential to detect any possible damage at the initiation phase to allow preventive measures to be taken for failure prevention. Composites are used in aerospace structures e.g., aircraft wing-box, which are highly susceptible to impact damages. Ultrasound has been widely used, but conventional contact ultrasonic inspection techniques are often difficult or not accessible in hard to reach locations and generally require disassembly of the structure for inspection, which limits in-field applicability. A novel fully non-contact hybrid ultrasonic propagation imaging (UPI) system that uses Q-switched laser (QL) ultrasonic scanning excitation and laser Doppler vibrometer (LDV) sensing has been devised and implemented. The problem of the lower sensitivity of LDV than those of contact sensors was solved by time domain averaging through repetitive scanning technique. Since not LDV but QL is used for scanning, LDV can be fixed into its own maximum sensitive status. Multiple 3D imaging processing such as ultrasonic wave propagation imaging (UWPI) and wavelet-transformed ultrasonic propagation imaging (WUPI) algorithms were used to extract reliable damage features without overlook. The pure laser hybrid system enables remote and fully non-contact automatic one-sided inspection for temporal reference-free damage evaluation, and is also applicable to in-field structures. Experimental analyses were conducted for impact damage on carbon fiber reinforced polymer composite wing-box specimen. The proposed laser excitation and sensing UPI system provided enhanced results for damage visibility, and accuracy in determining damage location and size. The results demonstrated the possibility of quantitative, fast and automatic damage evaluation for in-field application as well.

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INTRODUCTION

Aerospace and other engineering structures are often subjected to fatigue stress, cyclic loading, environmental factors, aging, impacts and other miscellaneous causes, leading to various flaws and damages. Early detection allows preventive measures to be taken to prevent damage and possible failure. Conventional ultrasonic techniques include pulse-echo or pitch-catch methods using contact, typically with piezoelectric transducers for ultrasound generation and signal detection [1, 2]. The main problem with this method is its contact nature and the need for a gelatinous couplant between the transducer and test structure. Various PZT (lead zirconate titanate) transducers [3 - 5], fiber acoustic wave grating sensors [6], and microelectromechanical systems-based contact transducers [7] have been successfully integrated and used for the ultrasonic inspection and detection of damages. However, these methods are not practical on couplant-sensitive specimens, are difficult to use on structures with complex geometries or at high temperatures, and are very time-consuming for large area inspections [8].

A hybrid combination of a laser for ultrasonic generation and LDVs for detection could be an attractive alternative for a rapid and more efficient non-contact ultrasonic system. LDV is a velocity and displacement measurement technique based on Doppler effect, and the proposed sensors being non-contact is also suitable for water and couplant sensitive materials. Hence, this technique is applicable to wide range of materials like metals, polymers and composites (metal or polymer matrix) as well. In this research study, the advantages of a hybrid laser ultrasonic system has been combined with UWPI and WUPI algorithms to effectively extract the defect-sensitive features. The proposed hybrid UPI system provides fully non-contact automatic and single-sided inspection and a temporal reference-free damage evaluation capability. This approach could also be implemented in the field for various damage types.

FULLY NON-CONTACT LASER EXCITATION AND LDV RECEPTION ULTRASONIC PROPAGATION IMAGING SYSTEM

Laser is one of the non-contact techniques for ultrasonic generation. It is directly incident on the structure, and in turn generates thermoelastic stresses and strains that act as an ultrasonic source. Piezoelectric transducers (PZT) are also used for ultrasonic generation but they are contact techniques and the produced displacement is very small (0.1% strain only, typically) and there are chances of sensitivity fluctuations caused by minute variations in couplant thickness. The piezoelectric ultrasonic generation poses certain other shortcomings as the need to maintain good coupling tends to restrict scanning speed as well. The diameter of the probe defines the extent of the near field, so that in contact mode of operation, the material immediately below the surface of the specimen may fall into a form of 'dead zone'. Hence, laser as the non-contact source for ultrasonic generation was considered for use in this research study.

The proposed hybrid UPI system is based on the combination of laser for ultrasonic generation and piezoelectric LDV for detection. This allows full non-contact and remote operation benefits for non-destructive inspections. Lasers are very strong and effective sources of broadband ultrasonic generation, and provide high spatial resolution with an ability to operate on curved and rough surfaces in hard-to-access locations. Since there is no requirement for a coupling medium to transmit the ultrasound, the laser ultrasound allows remote scanning over relatively large distances and minimal surface contamination [9, 10] at a higher test speed than conventional setups. The non-contact sensing capability of LDV with a comparatively large stand-off distance from the target specimen is one of its advantages. Thus, the proposed hybrid UPI system is a rapid and efficient non-contact ultrasonic system that can perform improved single-sided inspections. The remote capability of this laser-air hybrid ultrasonic technique also increases the range of inspections to areas beyond the reach of current contact inspection methods. Such a hybrid system greatly reduces cost relative to the other alternative, and also provides an adequate signal-to-noise ratio (SNR) for defect detection and discrimination. Being completely non-contact, it also provides advantages for mass- and couplant-sensitive structural components in various fields.

System Components

The laser for non-contact ultrasonic generation, laser mirror scanner for laser beam control and scanning, LDV as non-contact ultrasonic sensors are three of the main system components. An air-cooling Q-switched diode-pumped solid state laser was used. It has a nanosecond pulsed TEM00 ($M^2 < 1.2$) mode, a maximum pulse repetition frequency of 10 kHz, wavelength of 532 nm with a laser beam diameter at the exit port and beam divergence of 0.4 mm and 1.6 mrad, respectively. The high resolution galvanometric LMS had dimensions of 69 mm × 78.5 mm × 77.9 mm, and weighed only 650 g. PC interface boards provided synchronous interference-resistant control of the scan systems and lasers in real time, and enabled high speed scanning. A vibrometer single point sensor head LDV (OFV-505) was used as the non-contact sensor. The light source of the LDV is a helium neon laser. It has a wavelength of 633 nm, laser power < 1 mW and cavity length of 204 mm ± 1 mm.

Hybrid Q-switched Laser Ultrasonic Generation and LDV Sensing System

The system configuration consists of a QL, a galvanometric LMS, a LDV, a programmable filter, a digitizer, and a computer for hardware control and image processing. The LDV is fixed and focused at a particular sensing point while the LMS deflects the laser beam into the target specimen for scanning. This non-contact configuration also provide with the ability for one-side inspection with much larger standoff distance (in meters) between the specimen and the LDV.

CHARACTERIZATION AND SENSITIVITY OPTIMIZATION OF THE HYBRID SYSTEM

Non-contact ultrasound is a method of non-destructive testing where ultrasound is generated and used to test materials without the generating sensor making direct or indirect contact with the test material. This has been very difficult, as ambient air is the only acoustic coupling medium, and a typical transducer is very inefficient in air. Its performance is influenced by several factors. Thus characterization and optimization of the system has been performed in this research study.

The experiment was conducted on an aluminum plate specimen with a thickness of 0.5 mm. LDV being a non-contact sensing technique, requires performance optimization so as to characterize its sensitivity and to obtain the high efficiency for UPI system configuration. LDV was located on the same side of the specimen. The target area of 50 mm × 50 mm was located 10 mm below the LDV sensing point. The standoff distance between the aluminum test specimen and LDV was 0.5 m. LDV was operated at the setting of 5 mm/s/V which is considered to be of maximum sensitivity and a bandpass of 90 Hz – 100 kHz was used. A SNR of 33.91 dB was obtained, and visible wave propagation was generated as shown in Figure 1. Thus, it is suitable to be used as an ultrasonic receiver in hybrid combination in the UPI system.

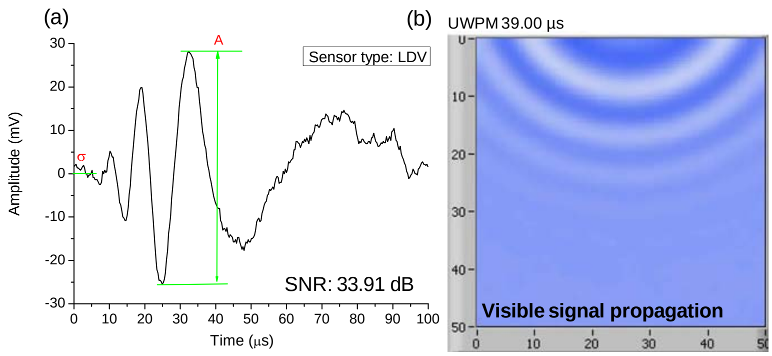

Figure 1. (a) Time domain ultrasonic signal with respect to one impinging point, and (b) visible ultrasonic wave propagation movie (UWPM).

Repeat Scanning Technique

Repeat scanning technique was developed based on the laser UPI system where LMS directs laser beam with high precision control to the target surface. It adopts raster scanning pattern over the scanning area, and the scanning is repeated for the desired number of iterations, which produces final results with repeat averaged values, resulting in improved SNR, as determined from the experimental results. One of the experimental verification results conducted on a carbon fiber reinforced plastic composite wingbox specimen has been presented here. A QL (532 nm) was used for ultrasonic generation while LDV was employed as the ultrasonic receiver. LMS and LDV were positioned 1 m away from the target surface. The laser was operated at 1.3 mJ energy with a pulse repetition frequency (PRF) of 50 Hz. A 100 mm x 100 mm scanning was iterated over the target area for 15 repetitions. A bandpass of 20 kHz -100 kHz was implemented, the data was smoothed by repeating 3 pixel × 3 pixel spatial averaging two times and 5 fold (5X) gain was applied to obtain the final results in the form of UWPM generation. The UWPM freeze frames for single scan and 15X repetition averaging, at a certain time frame (76.8 μs) and at the same color scale for UWPM generation has been shown for comparison in Figures 2 (a) and (b). It shows comparatively higher signal intensity in 15X repetition scan result. One of the most important factors for the non-contact sensing is the improvement is SNR and the results were further analyzed so as to identify the quantitative variation or improvement in resulting SNR. The trigger point at 10 µs was considered for the noise estimation. The repeat scanning iterations were done for 1, 5, 10 and 15 times. The improvement in SNR due to repeat scanning has been presented in Figure 2 (c). The SNR with single scan was 17.76 dB, which increased by 6.4 dB, 10.1 dB and 12.8 dB after 5, 10 and 15 repeat scans respectively.

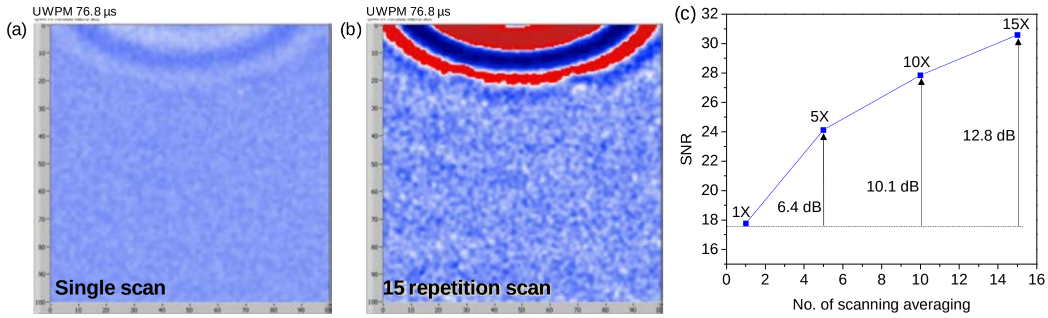

Figure 2. UWPM freeze frames comparison at same time frame and color scale showing improvement in signal intensity due to repeat scanning technique. (a) Single scan (b) 15 repeat scanning. (c) Improvement in SNR for different number of repeat scans.

ULTRASONIC PROPAGATION IMAGING TECHNOLOGY

The proposed technique involves interaction of laser ultrasonic generation/propagation with the structural inhomogeneity and the variation thereafter in the nature of detected ultrasound, as the basis for defect analysis. These algorithms provide temporal reference-free damage evaluation such that the result is generated in a simple image or movie form. In addition, damage localization and size evaluation can be quantified immediately through visualization of the result. An incident ultrasonic wave is scattered by the presence of flaws in the specimen. UWPI method [4, 5] generates results in the form of an ultrasonic wave propagation movie. The movie shows the propagation of the ultrasonic wave field with many crests and troughs. These crests and troughs represent the actual wave field of the generated ultrasound in the target structure. WUPI [11] using the wavelet transform decomposes a signal into a family of wavelets. Wavelets are localized in both time and frequency and this WUPI algorithm utilizes continuous wavelet transform (CWT). It computes the continuous wavelet transform (CWT) of the 1D input signal with real-valued wavelets. The WUPI method has a frequency selectivity capability; hence, it is useful for the isolation of ultrasonic modes of interest in generating WUPI movies. It generates results showing an exclusive concentration of ultrasonic energy at the location of material property and geometry discontinuities of the scanned structure. These could be used to quantitatively evaluate defect size and location.

IMPACT DAMAGE DETECTION

Due to the high strength-to-weight and stiffness-to-weight ratio, composite materials are attractive for a wide range of applications. Unfortunately, they are too brittle under dynamic loading, particularly impact loading [12], which can significantly reduce their properties. Unlike metal cases, composites can be fairly easily damaged by impact, which could be sustained during manufacturing, transportation and storage, and damage severe enough to cause a catastrophic failure can result, while still not being detectable to the naked eye [13]. Impact could cause both visible and significant non-visible internal (sub-surface) damages in the form of matrix cracking and broken fibers [14]. It can result in premature catastrophic failure due to decreased strength caused by the impact loading.

The experiment was conducted on a carbon fiber reinforced plastic composite skin-spar-stringers wing-box specimen as shown in Figure 3 (a), which consisted two impact damages on the outer surface of the skin. The standoff distance from LMS and LDV to that of the composite wing-box was setup at 1 m. The LDV sensing point was 50mm away from the nearest point in the target scanning area as shown in Figure 3 (b). LMS scanned 100 mm x 100 mm of the target area, with laser pulses at a pulse repetition frequency (PRF) of 50 Hz and 1.3mJ energy, which was in the ultrasonic regime for the composite skin surface, as high energy pulse in the plasma regime, which could cause surface ablation. The pitch of the laser impingement points were 0.5mm. The signals were filtered using a bandpass of 20-100 kHz and 5fold (5X) gain was applied, while the data was smoothed by repeating 3 pixel × 3 pixel spatial averaging two times during post-image processing for image smoothing.

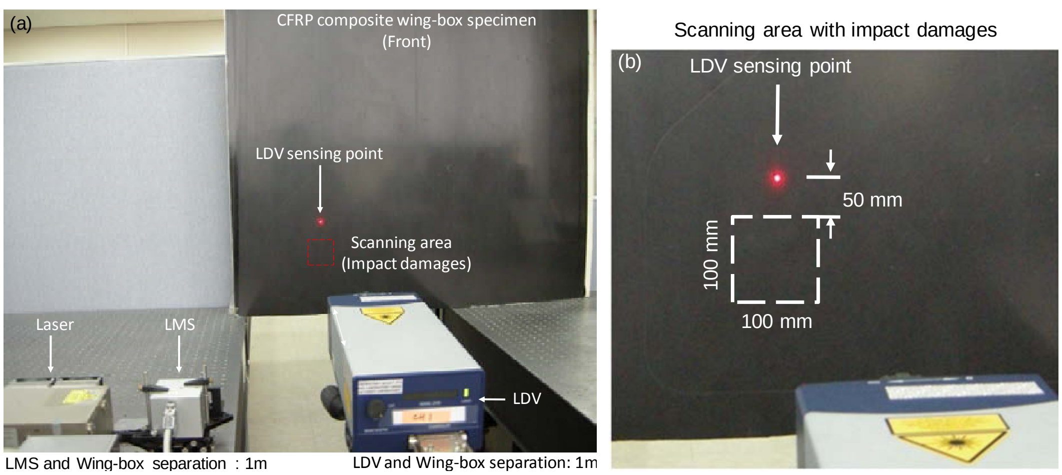

Figure 3. (a) Experimental setup for impact damage evaluation in carbon fiber reinforced plastic composite wing box specimen using hybrid laser ultrasonic generation/LDV sensing and (b) Scanning area in the target specimen with LDV sensing point.

UWPM and WUPM algorithms were considered for the damage evaluation. A 45 kHz WUPM was generated, and a freeze frame at 83.2 μs is presented in Figure 4 (a), which shows clear detection of two distinct impact damages and localization. The result was further analyzed so as to determine the estimated damage size as shown in Figure 4 (c). This estimation could be compared with the C-scan result obtained for the same damage as shown in Figure 4 (b), which shows close proximity and hence determines the effectiveness of the system. The UWPM shows concentric incident ultrasonic wavefield as if emerging from the sensing point. An incident ultrasonic wave is scattered by the presence of flaws, and is generated in the form of an ultrasonic wave propagation movie. Conventional result in the form of UWPM was generated and the freeze frames at 73.6, 80.8 and 96 μs are presented in Figures 5 (a) - (c), which show the change in propagation pattern of the incident wavefield at two different locations as indicated in the figures. This scattered wave indicates the detection of the flaw, which is due to the interaction of the propagating wave with the discontinuity i.e., impact damages in this case.

Thus, this hybrid combination of laser and LDV allowed larger standoff distance (1m) between the test specimen and the LDV sensor. In general, although the non-contact ultrasonic receiver is considered to have a lower SNR, repeat scanning technique was implemented for the LDV sensing experiment. As observed from the experimental results, repeat scanning had provided dramatic improvement in the SNR. Impact damages were clearly detected in both the damage evaluation algorithms with the possibility for damage size estimation as well.

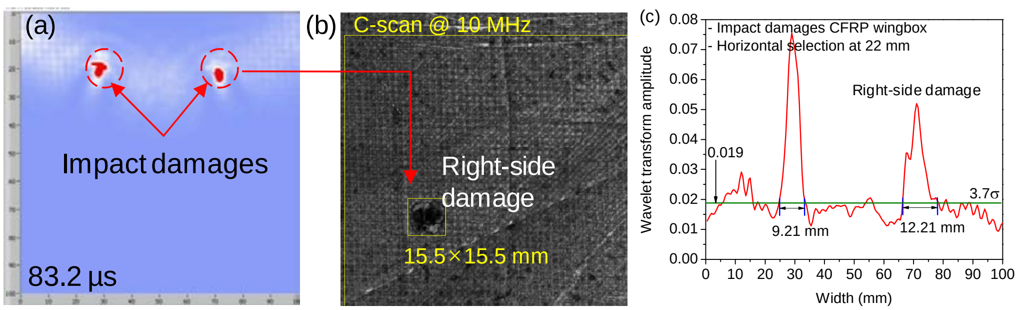

Figure 4. Impact damages in the carbon fiber reinforced plastic composite wing box detected (a) on wavelet transformed ultrasonic propagation movie result and (b) Damage size comparison with the C-scan result (c) Further analysis of the result for damage size estimation.

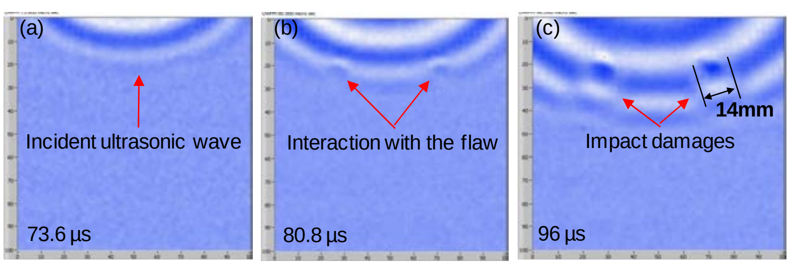

Figure 5. Freeze frames of UWPM showing incident ultrasonic waves and its interaction with the flaw (a) at 73.6 μs (b) at 80.8 μs, incident waves interact with the impact damage (c) at 96 μs, scattered waves indicate impact damage detection.

CONCLUSION

A hybrid ultrasonic propagation imaging system with fully non-contact excitation and reception based on scanning laser excitation and fixed laser Doppler vibrometer sensing has been proposed. Low sensitivity had been one of the major limitations in such fully non-contact applications. However, characterization and optimization studies were conducted to tackle this issue and it was found that the optimization of certain parameters results in improved performance and this approach is suitable for a non-contact hybrid UPI system. Furthermore, repeat scanning technique was devised and implemented which showed an improvement in SNR at an average ratio of 12.8 dB for 15 repeat scanning (i.e. + 0.85 dB per repeat scan) as found out from the experimental results. For the development of a reliable damage evaluation system, both the excitation/sensing technology and the associated damage analysis, and interpretation algorithm for quantitative evaluation and easy detection are equally important. UWPI and WUPI were used as the damage evaluation algorithms which enhanced the damage evaluation capability. Hybrid QL/LDV system was used for impact damage evaluation in composite wing box specimen. Impact damages were readily detected and localized in the damage visualization algorithms. Furthermore, this sensing system allows single side inspection, which eliminates the need for assembly and disassembly of certain inspection specimens and could be easily accessible in hard to reach locations of some structural components as well.

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