Noncontact Debonding Identification in Adhesive Joint using Guided Waves

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Abstract

This study proposes a debonding identification method in adhesive joints by utilizing a complete noncontact laser ultrasonic measurement system. This measurement system consists of a Q-switched Nd:YAG laser for ultrasonic wave generation and a laser Doppler vibrometer (LDV) for ultrasonic wave detection. The distance between the two laser beams, shot for wave generation and detection, is kept as a constant and they are synchronously scanned over the target adhesive joint. Energy features is then extracted from the acquired ultrasonic waves to present the difference induced by debonding problem. This proposed method has following advantages over the existing techniques: (1) it owns higher and more stable signal to noise ratio; and (2) debonding identification can be realized by spatial comparison and without relying on any baseline data got from pristine condition. It is successfully demonstrated by detecting debonding problem in several adhesive joint specimens.

Keywords: Noncontact laser ultrasonics, Debonding identification, Synchronized scanning

Introduction

For many years, adhesive bonding has been used in the production of furniture coating during the Egyptian and Roman time [1]. And in the recent time, it still takes an important role of the world industry. For example, adhesive bonding was used for the aerospace industry since it has great advantages in the construction of aerospace components [1,2]. The automobile industry also uses adhesives extensively [3,4]. The adhesive bonding become so popular in those industries because it has numerous advantages such as lightweight [3], reduction of noise and vibration [1], great flexibility [5], high strength [1], and corrosion resistances [1]. However, the uses of adhesive bonding might results a debonding damage in the structure which is critical to the structure itself,

because the debonding damage makes the force experienced by the material much larger by the designated force [1]. Although this defect can cause a prone problem on the structure, the detection of adhesive debonding is challenging because it often occurs between laminates and invisible from external surfaces. To overcome this problem, several non-destructive testing (NDT) has been developed. The common available NDT techniques for debonding damage include optical fiber [6-8], piezoelectric [9-12], and laser ultrasonic [13-16]. Among these techniques, the laser ultrasonic technique uses ultrasonic waves of short wavelength and high frequency on detecting debonding damage. It also popular since laser ultrasonic is couplant free, non-contact, and allow long range sensing from the target structure. The visualization of debonding damage also possible to be done without using any baseline data from pristine condition [16]. One issue of a full non-contact laser ultrasonic technique is that the power level, laser duration and laser beam size need to be carefully tailored because high laser power density above a certain threshold will cause damage to the target structure, such as surface melting, vaporization, ablation and plasma phenomena [17]. Due to the restricted laser power, the ultrasonic response can remain detectable only within a limited distance for most of the target structures. In laser ultrasonic scanning techniques, limited laser power level also limits the size of the scanning area as well.

This study develops a new synchronized laser scanning technique and uses this technique for detecting hidden debonding damage. In the scanning area, this new technique synchronously moves the two laser beams used for ultrasonic wave generation and detection, and the distance between the excitation and sensing points can be adjusted for different target structures. The proposed technique offers the following advantages: (1) since the distance between the excitation and sensing points is kept to be short and constant, the proposed technique is less affected by the limitation of the laser power level and can cover a much larger scanning area; (2) because of the improved signal to noise ratio achieved by the short and constant distance between the excitation, damage can be reduced by less time averaging; (3) through spatial comparison, damage can be detected and visualized without relying on baseline data obtained from the pristine condition of the target structure; (4) the proposed technique is validated for hidden debonding damage detection in bonded aluminum sheets.

Synchronized Laser Ultrasonic Scanning System

This section develops a full noncontact laser ultrasonic scanning system to identify the debonding problem on the specimen. The main system of the laser ultrasonic devices can be split into two systems: an ultrasonic wave generation system and a sensing system. A pulse laser and laser Doppler vibrometer are used to generate and sense the ultrasonic wave. A complete noncontact laser ultrasonic scanning system is developed and adopted in this study [18]. The system is mainly composed of a Qswitched Nd:YAG pulse laser, an LDV and a control unit. The ultrasonic waves are created through the thermal expansion of an infinitesimal area heated by the pulse laser. Then, LDV measures the generated ultrasonic responses based on the Doppler

effect of light. This system set-up has been widely used with two scanning strategies: (1) fixed laser excitation and scanning laser sensing and (2) fixed laser sensing and scanning laser excitation as illustrated on the Figure 1.



Figure 1. Conventional laser ultrasonic scanning strategies, fixed laser excitation and scanning laser sensing (left), scanning laser excitation and fixed laser sensing (right).

As an example, An et al adopted the second strategy to visualize a crack. The overall working principle are like [18]: First, virtual grid points for excitation on the target structure are created, and the sequences of excitation points are predetermined. Then, the control unit transmits a trigger signal to the Nd:YAG pulse laser to shoot the excitation laser beam to the first determined excitation point. Simultaneously, the same trigger signal also transmitted to the LDV to activate the data acquisition. Then, the control unit sends a signal to the galvanometer so then the laser excitation point moves to the next predetermined point. By repeating the ultrasonic excitation and sensing to all the determined scanning points, an ultrasonic wavefield image can be reconstructed over the target surface and processed for damage detection.

As the goal of the system is to visualize a clear ultrasonic wave propagation, a good signal to noise ratio is needed. Hence, higher power lasers for both ultrasonic wave generation and detection are usually being used to improve the signal to noise ratio. But, if the laser power exceeds a certain threshold determined by the material characteristics of the target structure, it will form a damage on the specimen surface [17]. The distance between laser excitation point and laser sensing point also need to be controlled to obtain a good signal to noise ratio. This distance limitation between those points lead to a limited size of the scanning area. Another way to improve the signal to noise ratio is by utilizing a great number of time averaging of the response signals. But, as the number of time averaging get greater and greater, the data acquisition process will take much more time.



Figure 2. Proposed synchronized laser ultrasonic scanning strategy.

This study proposes a new synchronized scanning strategy using the complete noncontact laser ultrasonic scanning system as illustrated in Figure 2. Two laser beams for ultrasonic wave generation and detection are shot on the target structure with a short and constant distance. Then, these two laser beams synchronously scan the target structure along the scanning sequence. Each pair of the excitation and sensing points corresponds to a spatial point located in the middle of the two laser points. The distance between each spatial points is defined as scan gap and it indicates the scanning density in the scanning area. based on the structure and its damage type, the wave propagation distance and scan gap can be adjusted to optimize the scanning procedure. The advantages of this synchronized scanning strategy over the conventional scanning strategies mentioned in Figure 2 are: (1) the signal to noise ratio of the acquired ultrasonic signals is improved because the wave propagation distance is kept to be short and constant. The improvement of the signal to noise ratio lead to faster scanning because less time averaging is needed; and (2) Larger scanning area can be inspected with the energy level of the laser beam being kept within a practicable range.

For detecting damage using the synchronized scanning strategy, a unique feature need to be extracted from the acquired signals. For different target damage type, different features can be developed. Giurgiutiu et al measures the variation of the signal amplitude, phase, velocity and mode conversion of ultrasonic waves [19]. These features are based on the linear behavior of ultrasonic wave propagation and often used to evaluate gross damage (e.g., open-crack, corrosion, debonding) with dimensions comparable to the ultrasonic wavelength. For detecting micro damage such as fatigue crack, fiber debonding and delamination, nonlinear features of ultrasonic are shown to be more sensitive [20].







The extracted features then can be processed to show the damage index (DI). In this synchronized scanning strategy, the DI values for each spatial point in the scanning area can be calculated as

$$DI_i = \sum_j W_{i\pm j} \times Feature_{i\pm j}, j = 0, 1, 2, 3, \dots$$
 (equation. 1)

Where $Feature_{i\pm j}$ is the extracted feature value corresponding to the *i*th spatial point or its spatially adjacent i±*j*th points, as shown in Figure 3. $W_{i\pm j}$ is the weight value for its feature and it is define based on the overlapping degree between the wave propagation distances related to the adjacent points.

$$W_{i\pm j} = \begin{cases} \left(1 - \frac{j \times d_s}{0.5 \times d_w}\right)^2 & if \ (j \times d_s) < (0.5 \times d_w) \\ 0 & if \ (j \times d_s) \ge (0.5 \times d_w) \end{cases}$$
(equation. 2)

where d_w and d_s are the distance of the wave propagation and the scan gap respectively. The calculation of DI values using Equation 1 can inspect the structural condition of the target scanning area. when a damage exists in the scanning area, the DIs on the damage region will be different from the DIs in the intact region. To visualize the damage, this damage detection method does not rely on any baseline data obtained from the pristine condition of the target structure, which make it insensitive to environmental and operational variations such as temperature and loading changes.



Debonding Detection on Bonded Aluminum Sheets

Figure 4. Specimen geometrical information: (a). Top view of the specimen, (b). Side view of the specimen, (c). Debonding information of specimen 1, (d). Debonding information of specimen 2.

To validate the proposed technique, two set of bonded aluminum sheets are used in this study, debonding damage is introduced between the bond of two aluminum sheets. The detailed geometrical information about these specimens are explained in Figure 4. The complete noncontact laser ultrasonic measurement system mentioned above is used in this study. The actual hardware composition is shown in figure 5. The system consists of sensing system and ultrasonic wave generation system. For the ultrasonic wave generation system, a Q switched Nd:YAG laser, a galvanometer, and a focal lens are used. The Nd:YAG laser has a wavelength of 1064 nm and a maximum peak power of 3.7 MW, and generates a pulse input with 8 ns pulse duration at a repetition rate of 20 Hz. The galvanometer then locates the pulse laser to the desired point on the target specimen. For ultrasonic wave detection, a commercial LDV with a built-in galvanometer and an auto-focus This device has a helium-neon laser as its laser source, with its wavelength equal to 633nm. It can measure the target's surface velocity in the out of plane direction within the range of 0.01 μ m/s to 10 m/s. A personal

computer (PC) is employed to control the scanning system. It sends out a trigger signal to launch the excitation laser beam and to simultaneously start the data collection. Also, the PC generates control signals to aim the excitation and sensing laser beams to the desired target positions.



Figure 5.(a). Experimental setup for debonding detection on specimen and (b) scanning area covered on the specimen 1 (top) and specimen 2 (bottom), red-dashed line shows the scanning area equal to 75 mm × 20 mm square area on the surface of the specimen.

In this experiment, a peak power of around 0.2 MW is used for the pulse laser excitation and a sampling frequency of 2.56 MHz is used to measure the ultrasonic response with a samping time equal to 1.6 ms with 0.16 ms as pre-trigger time. In this experiment, the scanning area is set to be 75 mm \times 20 mm square area on the surface of the target specimen. A total of 64 (16×4) spatial inspection points are assigned within the scanning area, making the scan gap equal to 5 mm. The wave propagation distance between the excitation and sensing points is fixed to 15 mm. The distances from both Nd:YAG laser head and LDV laser head to the target specimen are set as 1 m. To improve the signal to noise ratio, the responses from a single wave propagation path are measured 50 times and averaged in the time domain by utilizing the embedded program from the LDV device.

Two representative signals obtained from the intact and debonding region of one specimen are displayed in Figure 6. it is shown that the signal obtained from debonding region is having greater amplitude in compare with the obtained intact signal.

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Figure 6. Time-domain signals from intact area and debonding area





The damage index (DI) is extracted by calculating the energy of the total signal. As the signal is obtained as a velocity-time signal, the energy defined as the total square of the signal.

$$DI = \sum v(t)^2$$
 (equation. 3)

All the DI values can be visualized for the scanning area, and spatial points with unusual high DI values indicate the existence of debonding damage and can be used to

locate the damage as well. Figure 7 shows the visualization results obtained from two bonded aluminum sheets specimens. Here, all the DI values are normalized with respect to the highest DI values of all in both specimens. The damage visualization results demonstrate that the proposed technique can successfully localize the hidden corrosion in both specimens.

Conclusion

In this study, a damage detection technique using a fully noncontact laser ultrasonic scanning system and synchronized scanning strategy is developed to detect debonding damage on the specimen. In the proposed synchronized scanning strategy, the distance between the excitation and sensing laser beams is kept relatively short (15 mm in this paper), with these two laser beams are synchronously moved over the scanning area. By keeping the wave propagation distance with much shorter distance than the other conventional scanning strategies, (1) the signal-to-noise ratio can be significantly improved which imply to a faster scanning time, and (2) a larger inspection area can be scanned without high power laser beams. The energy of the propagated wave is defined as a damage-sensitive feature for hidden debonding detection. By examining the spatial distribution of the damage feature over the scanning area, the debonding in both specimens are successfully detected and located using the proposed technique. However, additional improvements are in need for this technique. For example, a better damage sensitive feature could be used to have a better accuracy of damage visualization.

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References

- 1. Pocius, A.V. (2012), Adhesion and Adhesives Technology, Hanser Publishes, Munich.
- 2. Bhowmik S., Bonin H. W., Bui V. T., Weir R. D., (2006), "Durability of adhesive bonding of titanium in radiation and aerospace environments", International Journal of Adhesion and Adhesives, Vol. 26(6), 400-405.
- 3. Cole G.S., Sherman A. M., (1995), "Light weight materials for automotive applications", Material Characterization, Vol. 35 (1), 3-9
- 4. Silva L. F. M., Öchsner A., Adams R. D., (2011), Handbook of Adhesion Technology, Springer, Berlin.

- 5. Morent R., De Geyter N., Axisa F., De Smet N., De Leersynder E., Leys C., Vanflateren J., Machal M. R., Schacht E., and Payen E., (2007), "Adhesion enhancement by a dielectric barrier discharge of PDMS used for flexible and stretchable electronics", Applied Physics, Vol. 40, 7392-7401.
- Sulejmani S., Sonnenfeld C., Geernaert T., Luyckx G., Mergo P., Urbanczk W., Chah K., Thienpont H., and Berghmans F., (2014), "Disbond monitoring in adhesive joints using shear stress optical fiber sensors", Smart Materials and Structures, Vol. 23 (7).
- 7. Yuan F. G., (2016), "Structural Health Monitoring (SHM) in Aerospace Structures", Elsevier, Cambridge.
- 8. Kim S., Cha M., Lee I., Kim E., Kwon I., Hwang T., (2014), "Damage evaluation and strain monitoring of composite plates using metal-coated FBG sensors under quasi-static indentation", Composites Part B: Engineering, Vol. 66, 36-45.
- Sevillano E., Sun R., Perera R., Arteaga A., de Diego A., Cisneros D., (2016), "Comparison of PZT and FBG sensing technologies for debonding detection on reinforced concrete beams strengthened with external CFRP strips subjected to bending loads", Materiales de Construcción, Vol. 66 (322).
- 10.Xu B., Zhang T., Song G., Gu H., (2013), "Active interface debonding detection of a concrete-filled steel tube with piezoelectric technologies using wavelet packet analysis", Mechanical System and Signal Processing, Vol. 36 (1), 7-17.
- Tzoura E. A., Triantafillou T. C., Providakis C., Tsantilis A., Papanicolaou C. G., Karabalis D. L., (2015), "Damage detection of reinforced concrete columns retrofitted with FRP jackets by using PZT sensors", Structural Monitoring and Maintenance, Vol. 2 (2).
- 12. Sohn H., Kim S. D., In C. W., Cronin K. E., Harries K. (2008), "Debonding monitoring of CFRP strengthened RC beams using active sensing and infrared imaging," Smart Structures and Systems, Vol. 4, No. 4, 391-406.
- 13. Liu P., Sohn H., and Park B., (2015), "Baseline-free damage visualization using noncontact laser nonlinear ultrasonics and state space geometrical changes", Smart Materials and Structures, Vol. 24 (6).
- 14. Kessler S. S., Spearing S. M., Soutis C., (2002), "Damage detection in composite materials using Lamb wave methods", Smart Materials and Structures, Vol. 11 (2), 269-278.
- 15. Chia C. C., Lee J. R., Park C., Jeong H., (2012), "Laser ultrasonic anomalous wave propagation imaging method with adjacent wave subtraction: Application to actual damages in composite wing", Optics & Laser Technology, Vol. 44 (2), 428-440
- 16. Park B., An Y K., Sohn H. (2014), "Visualization of hidden delamination and debonding in composites through noncontact laser ultrasonic scanning", Composites Science and Technology, published online. (1990).
- 17. Scruby, C. B. and Drain, L. E., (1990), "Laser Ultrasonics: Techniques and Applications", Taylor and Francis, London,
- An Y. K., Park B. and Sohn H. (2013), "Complete noncontact laser ultrasonic imaging for automated crack visualization in a plate." *Smart Mater. Struc.*, Vol. 22 (2) 025022

- 19. Giurgiutiu, V. and Cuc, A. (2005), "Embedded non-destructive evaluation for structural health monitoring, damage detection, and failure prediction," Shock Vib. Digest, Vol 37(2), 83–105.
- 20. Jhang, K. Y. (2009), "Nonlinear ultrasonic techniques for nondestructive assessment of micro damage in material: A review," Int. J. Precis. Eng. Man. Vol 10, 123-135.