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Laser-ultrasonics and Laser- tapping for the Inspection of Aerospace Composite Structures

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Abstract

Laser-ultrasonics is a well known and mature nondestructive technique for inspecting polymer matrix composites used in aerospace. This technique uses a pulse echo interrogation mode, in which ultrasound is first generated by a pulsed laser and then detected by a second laser coupled to an optical interferometer. While very successful to find delaminations in laminates, difficulties are found for reliably detecting disbonds in honeycomb and foam core structures, particularly when the detachment occurs at the back skin. For this purpose, a novel technique called Laser-Tapping is proposed. Laser-Tapping is based on the thermoelastic excitation by a pulsed laser of the top skin which bulges and is driven into vibration if it is detached from the material underneath. Laser-Tapping uses essentially the same hardware as laser-ultrasonics but probes in a lower ultrasonic frequency range. Laser-ultrasonics and Laser Tapping can then be advantageously used concurrently. This paper presents examples of applications of a combined Laser-Ultrasonic Laser-Tapping system to honeycombs structures with defects, including delaminations in the skin and skin detachments at the front side and the back side.

Keywords: Laser-ultrasonics, laser-ultrasound, detachment, disbond, unbound, honeycomb, foam core.

1. Introduction

Laser-ultrasonics is by now a well known and mature nondestructive technique for inspecting polymer matrix composites used in aerospace^[1]. This technique uses a pulse echo interrogation mode, in which ultrasound is first generated by a pulsed laser and then detected by a second laser coupled to an optical interferometer. The technique is particularly powerful for inspecting parts of complex shape. As shown in Figure 1, two laser beams essentially collinear are used to scan the part to be inspected. The generation laser beam produces non-destructively, by thermoelastic effect, a stress at the surface of the part, which in turn produces an ultrasonic wave launched normally to the surface, independently of its shape and of the laser beam direction. Ultrasonic waves reflected or scattered by the back wall or flaws are detected by a detection laser beam and an optical interferometer, which senses the phase shift of the scattered light produced by the ultrasonic surface motion. Received signals are essentially processed as in conventional immersion ultrasonics to display C-scans and B-scans.

While very successful to find delaminations in laminates, difficulties are found for reliably detecting disbonds in honeycomb and foam core structures, particularly when the detachment occurs at the back skin. For this purpose, and other inspection tasks for which laser-ultrasonics usually fails (such as probing highly porous and attenuating materials like metallic foams), a novel technique called Laser-tapping is proposed.

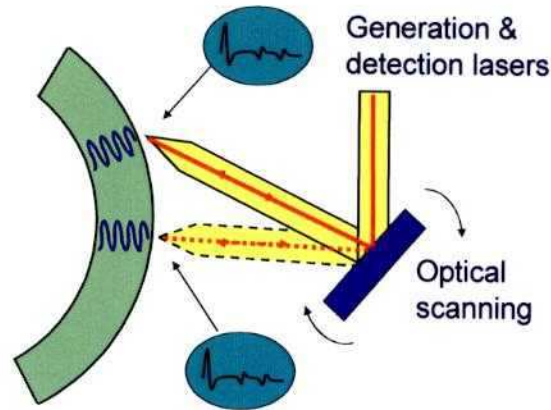


Figure 1. Principle of laser-ultrasonics applied to composite NDT. The light scattered by the surface, which carries the ultrasonic information, is received by an interferometer not represented in this figure.

Laser-tapping is based on the thermoelastic excitation by a pulsed laser of the top layer which bulges and is driven into vibration if it is detached from the material underneath^[2]. This bulging and vibration is then detected by a second laser and an interferometer. The method is made practical by using a two-wave mixing photorefractive interferometer^[3] or a similar interferometric detection device^[4, 5] that are insensitive to optical speckle but are sensitive to acoustic frequencies in the range from 1 kHz to 1 MHz. Laser-tapping uses essentially the same hardware as laser-ultrasonics but probes in a lower ultrasonic frequency range. Laser-ultrasonics and laser-tapping can then be advantageously used concurrently. The combined inspection system provides all the features of laser-ultrasonics, i.e. non contact, no surface preparation and ease of probing complex parts. The inspection system can also be made very flexible by using optical fiber coupling.

This paper presents the principle of the Laser tapping technique followed by results on honeycombs structures with defects, including delaminations in the skin and detachment of the skin from the honeycomb ribs, at the front side and back side. Honeycomb-structured materials allow reducing weight while keeping a very high stiffness, and are then widely use in the aeronautic industry. Detachments between the skin and the ribs of the honeycomb result in a weaken structure. Therefore, probing honeycomb-structured components to find any detachment is highly critical to assess the quality of newly produced parts and the damage that could be produced during service. In particular, since laser-tapping detects both skin delaminations and skin disbonds and cannot distinguish between them, the distinction can be provided by the time-of-flight between the laser ultrasonic echoes.

2. Principle of Laser Tapping

The principle of laser tapping is shown in Figure 2. A pulsed laser is absorbed at the material surface and produces a transient and local surface heating. When the laser heating is not uniform and concentrated over an area smaller than the size of the detached zone, localized thermal stresses are produced that cause a strong lifting and bending effect. The detached layer or skin can then be set into vibration like a membrane. The modes of the vibration induced by laser heating are determined by the material elastic properties, the geometrical shape and the thickness

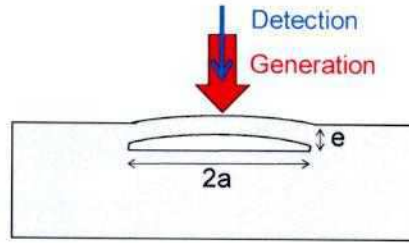


Figure 2. Laser excitation of flexural vibration of a detached area in a material.

of the detached area. In particular, for honeycombs, the thickness considered is the skin thickness. Also for honeycombs, it should be noted that each cell is actually a vibrating membrane that can be set into vibration if the heating zone, i.e. the laser spot, is smaller than the cell size. For a circular membrane, the vibration frequencies can be calculated by assuming a clamped circular plate (see Figure 2). The fundamental vibration frequency, f_1 , of this clamped membrane is given by:

$$f_1 = 0.47 \frac{e}{a^2} \sqrt{\frac{Y}{\rho(1-\nu^2)}} \quad (1)$$

where e is the thickness of the membrane, a is its radius, ρ is the mass density, Y is the Young's modulus and ν is the Poisson's ratio of the material. When using typical parameters of carbon-epoxy, this formula indicated that vibration frequencies are likely to be in the 20 kHz to 1 MHz range, obviously depending on depth and dimensions of the detachment.

The surface is simultaneously illuminated by a detection laser which impinges on the tested part at a location superimposed to the excitation laser spot. The detection laser light scattered or reflected off the surface is accordingly phase modulated by the small surface motion of the part. This scattered light is then collected and sent to an interferometer. The excitation and the detection lasers are scanned over the surface of the tested part to produce an image. The technique can be seen as an equivalent to the tap test used in industry and can then be called laser tap test or laser tapping. While proposed many years ago, the technique has not found practical use in industry^[2]. The technique was at that time tested using Michelson-type interferometers for detection. These interferometers have a maximum sensitivity to surface displacement when only one speckle of the light scattered by the surface is collected and collecting many speckles results in a reduction of the sensitivity. Also, the intensity of the collected speckle strongly varies from one location of the surface to another, and scanning a part to get an image of the adhesion integrity of the structured material is not very practical.

This limitation is circumvented by measuring the surface displacement with a two-wave mixing (TWM) photorefractive interferometer, since this interferometer is speckle insensitive (it has a large etendue). For practical applications, the response time of the interferometer, i.e. the photorefractive grating build up time, should be made fast enough for the interferometer to adapt itself to changes in the speckle pattern, to vibrations and to the Doppler effect (this occurs when scanning over a surface that is not normal to the laser beams)^[6]. The response time must also be longer than the vibration period of the membrane for the interferometer to work effectively. There is then a tradeoff between, on one side, the sensitivity of the interferometer to low frequency ultrasonic frequencies and, on the other side, its ability to adapt to ambient vibrations, part motions and use of a pulsed laser. The response time is controlled by the photorefractive optical pump beam power, extracted from the detection laser.

3. Results on Honeycomb with Carbon Epoxy Skins Samples

Laser tapping can be successfully applied to the detection of the typical flaws found on honeycomb structures with laminate skins. Tests were made on a test sample with artificially produced delaminations in the skin and detachments between the skin and the honeycomb ribs, as sketched in Figure 3.

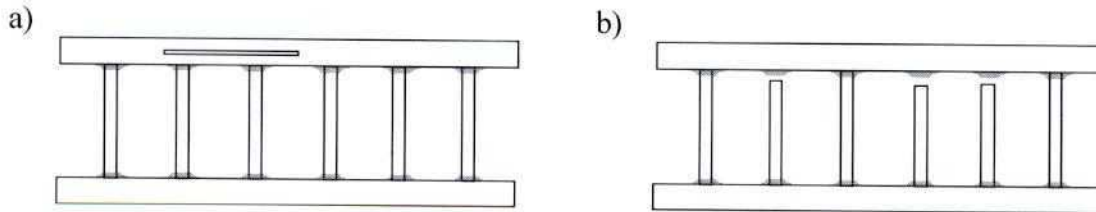


Figure 3. Side views sketches of a) a delamination within the skin and b) detachments between the skin and the honeycomb ribs.

The excitation laser is a CO₂ TEA laser, which delivers pulses of 120 ns duration at 10.6 μm wavelength. This laser makes the detached area to lift up and vibrate nearly like a membrane clamped at its edges and generates also ultrasonic waves. The excitation mechanism is in this case purely thermoelastic and non-damaging. The detection of the vibration and ultrasound is performed by a pulsed single frequency Nd:YAG laser which delivers pulses of 65 μs duration at full width half maximum with a 1.064 μm wavelength. The detection laser light scattered off the surface of the inspected part is sent to a TWM photorefractive interferometer using an InP:Fe photorefractive crystal under an applied voltage^[7]. Both lasers were scanned on the part to be inspected using a 1-mm step size along the X and Y axes. The beams were collinear and overlapped so that generation and detection were performed at the same location. Vibration frequencies are more likely to be in the 20 kHz to 1 MHz range depending on the material properties and detachment dimensions. The low frequency cutoff of the TWM phase interferometer was adjusted to 15 kHz, which means a grating build up time of about 10 μs , by properly setting the optical pump power of the interferometer.

Figure 4 shows the results obtained on an aluminum honeycomb part containing three square skin delaminations (top) and two areas with detachments between the skin and the ribs (bottom) of different sizes. The horizontal dimension of each scan is about 14 cm. Figure 4a show a C-scan of the inspected area obtained by filtering the signal with a 500 kHz cutoff high pass filter and by plotting the maximum amplitude of the ultrasonic echoes in the first 10 μs of the signal. As seen in this image, the delaminations within the skin are well detected but not the detachments between the skin and the honeycomb. From the time of arrival of the first echo or the reverberation time between echoes, the depth of the delamination can be readily determined. Figure 4b shows a C-scan of the frequency of the peak amplitude in the Fourier domain from signals in a much longer time gate (140 μs). In this case, the low frequency membrane vibration is dominant and the frequency, which varies from 30 to 120 kHz, is related to the size of the detachments. The higher is the frequency, the smaller is the size of the detached area. As seen in this image, both delaminations within the skin and detachments between the skin and the honeycomb are detected. The additional indications present on the left appear to be natural and real anomalies. These anomalies, as well as all the artificial defects, have been also detected by a commercial bond tester. Also, the apparent noise in the image originates from the honeycomb structure, the skin being itself a detached membrane over each honeycomb cell. In practice, it is

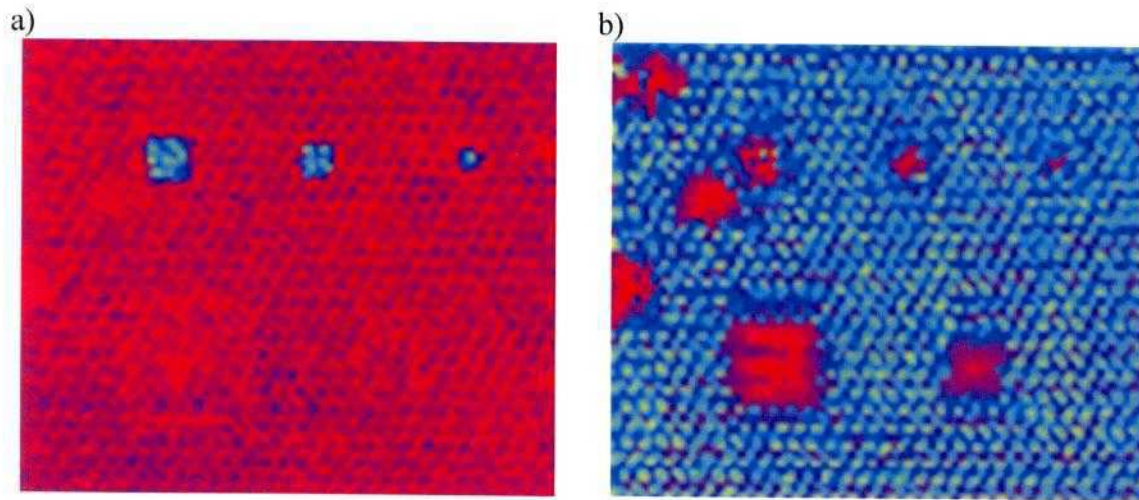


Figure 4. Results on a part containing three square skin delaminations (top) and skin-core detached areas (bottom) of different sizes. a) Ultrasonic echo C-scan (plot of the maximum amplitude after high pass filtering) and b) vibration frequency C-scan (plot of the frequency of the maximum of the signal in the Fourier domain).

not straightforward to determine the depth of a delamination from the vibration data alone. Figure 4 illustrates how this can be obtained by choosing a sufficiently short excitation pulse that produces both ultrasonic echoes and membrane vibrations. Also, Figure 5 shows a profile of the vibration frequency along a horizontal line crossing the two detached areas in Figure 4b. The detachment on the right side has a larger vibration frequency, which is expected since its size is smaller. The figure also shows the generation of higher frequency modes when the laser beams are either outside or close to the edges of a detached area. The higher frequencies are due to the excitation of higher order vibration modes of the membrane. As sketched in Figure 6, when both the excitation and the detection spots are sufficiently small, much less than the diameter of the membrane, higher order modes are produced and are essentially excited at the edge of the detached area. This feature can be very useful for detecting large detachment of very low fundamental resonance frequency outside the detection bandwidth of the interferometric detection system.

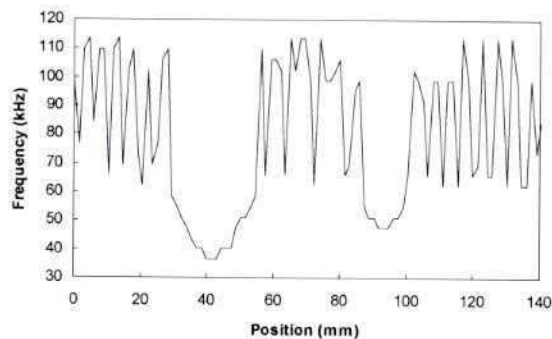


Figure 5. Profile of vibration frequencies along a horizontal line crossing the two disbonded areas in Figure 4b.

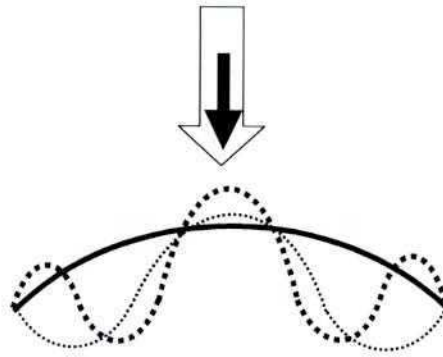


Figure 6. Amplitude distribution of the fundamental and higher vibration modes of a detached circular area.

Aerospace components are usually of structured and complex shape, and very frequently only one side of the part can be accessed for testing. Tests were made on a Nomex honeycomb structure with carbon epoxy skins that has received an impact that crushed the part surface and cause skin detachment. Laser tapping scanning from the impacted side clearly shows the detached area at the impact site, as shown in figure 7a. The opposite side did not show any visible damage but, as shown in figure 7b, inspection from this side by laser tapping actually reveals the impacted zone. The indication appears as expected as a mirror image of that in figure 7a.

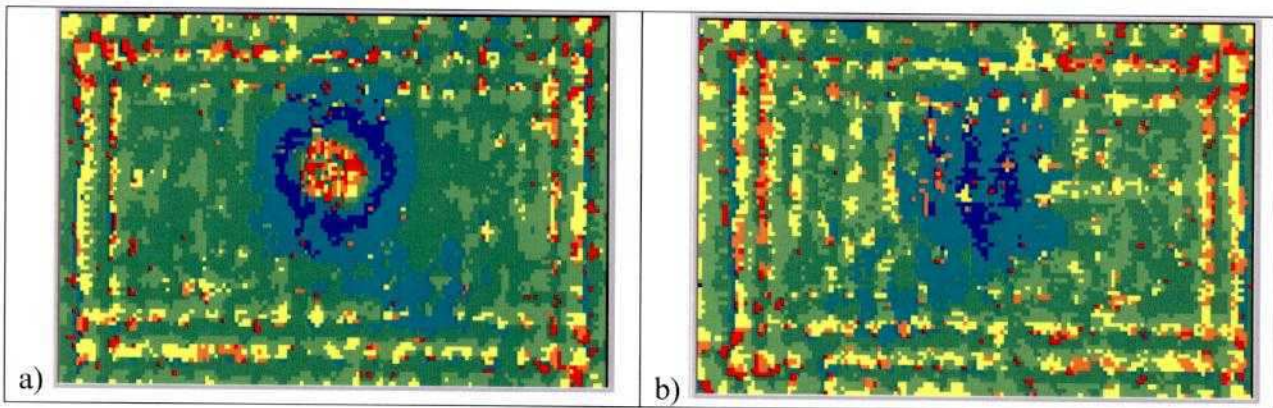


Figure 7. Laser tapping vibration frequency mapping on a honeycomb structure having been impacted: on one side, with the laser scanned a) laser scanning on the impacted and damaged surface and b) laser scanning on the opposite side.

4. Conclusion

We have reported a novel technique for detecting reliably delaminations in the skin and detachments between the skin and the honeycomb core. This technique, which can be called laser tapping, is based on the bulging and vibration of the detached skin or layer following absorption of a laser pulse. Detection of the induced surface motion is then made by a two-wave mixing photorefractive interferometer. This large etendue interferometer provides a means to detect low frequency membrane vibrations while scanning optically rough surface parts. On honeycomb structures, if a sufficiently short pulse is used, the proposed technique could also exploit the ultrasonic waves that are generated at the same time to get more thorough and reliable

inspection, in particular by allowing one to distinguish delaminations within the skin from detachment of the skin from the honeycomb core.

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