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Photorefractive Interferometry Applied To Novel Laser Tapping Nondestructive Technique

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Abstract. Photorefractive interferometers are a key technology to the practical implementation of a novel technique applied to the detection of disbands in coatings or honeycomb or foam core structures. The technique is based on the pulsed laser thermoelastic excitation of the top layer, which is driven into vibration if detached from the material underneath. This vibration is then detected by a second laser coupled to a photorefractive interferometer.

OCIS codes: (120.0120) Instrumentation, measurement, and metrology, (190.5330) Photorefractive nonlinear optics, (120.3180) Interferometry, (120.7280) Vibration analysis.

1. Introduction

One important application of photorefractive materials is their use in adaptive interferometers for the detection of ultrasound. When ultrasound is generated by a laser (laser-ultrasonics), a truly non contact ultrasonic inspection technique is realized with applications ranging from testing at high temperature in a steel mill to the inspection of polymer matrix composites used in aerospace industry. These applications have been actually implemented in industry and have been commercialized. For these applications, photorefractive interferometry is competing with the older confocal Fabry-Perot (CFP) detection scheme, which is essentially based on the demodulation effect of the confocal cavity working as an optical filter. Both schemes are practical for industrial use since they are both optical speckle insensitive. Compared to the CFP, photorefractive interferometers have the advantage of a much broader detection bandwidth, particularly towards low frequencies. As it has been demonstrated, thicker materials or more attenuating materials can then be advantageously probed using a photorefractive interferometer instead of a confocal Fabry-Perot. More recently a novel approach using laser-based excitation and detection has been introduced. This approach is particularly useful when ultrasound interrogation is not effective. One example is the skin or layer detachment in honeycomb or foam core structured materials. Such structured materials are widely used in the aeronautic industry since they allow reducing weight while keeping a very high stiffness. Another example is detachment of coatings, which are either too thin, thus requiring very high ultrasonic frequencies, or are attenuating ultrasound. This novel technique, called laser tap test or laser tapping, is based on setting the detached layer or membrane into vibration like if it was struck by a hammer. Since these vibrations are typically in the range 10 kHz-1 MHz, the confocal Fabry-Perot is not appropriate whereas photorefractive interferometers are perfectly suitable. In this presentation, we will report examples of applications of this novel technique, to honeycomb structures and coatings.

2. Principle of laser tapping

The principle of laser tapping is shown in Figure 1. A laser pulse 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 disbonded layer or skin can then be set into vibration like a membrane [1]. The modes of the vibrations induced by laser heating are determined by the material elastic properties, the geometrical shape and the thickness of the detached area. In particular, for honeycombs, the thickness considered is the skin thickness. For a circular membrane, the vibration frequencies can be calculated by assuming a clamped circular plate. 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.

Figure 1. Laser thermoelastic excitation and flexural vibration of a nearly clamped membrane with optical detection.

The surface is then 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 then phase modulated by the small surface motion of the part. This 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. While proposed many years ago, the technique has not found practical use in industry. The technique was then tested using a Michelson-type interferometer 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) [2]. 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. Inspection of a honeycomb carbon epoxy part

As an example of application, a carbon epoxy honeycomb structure with artificially produced delaminations in the skin as well as skin or core unbonds was scanned by laser tapping. The excitation laser is a CO₂ TEA laser and the detection is performed by a pulsed single frequency Nd:YAG laser. The detection laser light scattered off the surface of the inspected part is sent to a TWM phase interferometer based on an InP:Fe photorefractive crystal under an applied voltage [3]. 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

Figure 2. Results on a part containing three square skin delaminations (top) and two core unbond 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).

performed at the same location. Vibration frequencies are in the 20 kHz to 1 MHz range and the response time of the TWM was fixed at about 10 μ s, which means a frequency cutoff of 15 kHz. Figure 2 shows the results obtained on a part containing three square skin delaminations (top) and two core unbond areas (bottom) of different sizes. The horizontal dimension of each scan is about 14 cm. Figure 2a is obtained by filtering the signal with a 500 kHz cutoff high pass filter and by plotting the maximum amplitude of the ultrasonic echoes. As seen in this image, the delaminations within the skin are well detected but not the disbonds 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 2b is the frequency of the peak amplitude in the Fourier domain. 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. As seen in this image, both delaminations within the skin and disbonds between the skin and the honeycomb are detected. The additional indications present on the left appear to be real disbonds. Also, the apparent noise in the image originates from the honeycomb structure, the skin being itself a detached membrane over each honeycomb cell.

4. Inspection of a Silicon Carbide Protecting Layer on a Carbon-Carbon Substrate

Another example is the detection of detachments occurring between the SiC oxidation protecting layer and a C-C substrate. Carbon-carbon is widely used as thermal shield in rocket engines and on the fuselage of space vehicles, such as the US space shuttle. Since carbon is prone to reaction with oxygen above 450 °C, C-C materials are generally protected by a ceramic coating such as one made of silicon carbide. The coating being porous, voids are produced with time by oxidation. If these voids grow bigger, the coating could get detached leaving the C-C substrate unprotected and subjected to severe oxidation.

These coatings are however porous and strongly attenuate ultrasound, so pulse-echo ultrasonics does not work. Actually, this approach was tried on the C-C sample used and no echo was observed. However, with the laser-acoustic technique described here, vibration signals are clearly observed when the coating is detached from the substrate. The results are shown in Figure 3. Figure 3a presents a C-scan of the maximum amplitude of the data in the Fourier domain. Detachments are observed at the bottom of the figure near the edge of the specimen, as confirmed by visual observation. These disbonds are more clearly observed in Figure 3b, which shows the amplitude profile along the dotted line in Figure 3a. For comparison, Figure 3b also shows the amplitude along a well bonded line.

Figure 3. a) C-scan of the maximum amplitude of the laser-ultrasonic data in the Fourier domain. b) Amplitude profile along the solid and dotted lines on the C-scan in Figure 3a.

5. Conclusion

We have reported a novel technique for detecting reliably coating detachment and skin unbond in honeycombs, which is based on the unique properties of the TWM photorefractive interferometer: insensitivity to speckles and practical detection bandwidth ranging from a few kHz to several tens of MHz.

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From: Campagne, Benjamin [benjamin.campagne@eads.net]
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Je, soussigné Benjamin Campagne, certifie avoir lu l'article « photorefractive interferometry applied to novel laser tapping nondestructive technique » et accepte d'être co-auteur.
Cordialement

I, Benjamin Campagne, declare to have read the article « photorefractive interferometry applied to novel laser tapping nondestructive technique » and accept to be a co-author.
Best regards

Benjamin Campagne

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