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DETECTION OF SKIN DISBOND IN HONEYCOMBS AND COATING DETACHMENT BY A LASER ACOUSTIC TECHNIQUE

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Abstract. Many engineering structures are composite and include for example a protective coating or a bonded layer. A novel technique, close to laser-ultrasonics but significantly different, has been developed for the detection of disbonds between the coating or the bonded layer and the substrate. It is also applicable to the detection of core unbonds in honeycomb structures. The technique is based on the thermoelastic excitation by a pulsed laser of the top layer or top skin which is driven into vibration if it is detached from the substrate underneath. This vibration is then detected by a second laser coupled to a photorefractive interferometer. The technique can be made very flexible by using optical fiber coupling. One foresees its application to the in-service inspection of aerospace structures for the detection of core unbonds in honeycombs or near surface delaminations. Examples of application to honeycombs and to various coatings are presented.

Keywords: Laser-ultrasonics, laser-ultrasound, laser-based ultrasound, disbonds, coatings, honeycomb structures.
PACS: 42.62 Eh; 43.58.+z; 46.40.-f; 42.62 Cf; 43.40.+s

INTRODUCTION

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. Coatings are another example of structured or layered materials for which bond assessment is critical. Coatings are widely used on industrial material surfaces for protection against wear, oxidation and corrosion, or as thermal barriers. Voids or detachments at the coating-substrate interface result into a fragile coating that could peel off, leaving the substrate unprotected and subjected to severe heat load, erosion, oxidation or corrosion. Coatings are made by different methods such as electroplating, thermal spray, painting, or by vacuum deposition for thin and ultra thin multilayer coatings used in the microelectronic industry.

This paper reports the improvement of an approach based on the transient and local heating of the material surface by a pulsed laser followed by an interferometric interrogation of the surface deformation by another laser [1]. The method is made practical by using a photorefractive interferometer [2] or a similar interferometric detection device [3, 4] that is insensitive to optical speckle but is sensitive to acoustic frequencies in the range from 1 kHz to 1 MHz. On honeycombs, if a sufficiently short pulse is used, the proposed technique could also exploit the ultrasonic waves that are generated to get a more thorough and reliable inspection by allowing one to distinguish disbonds within the skin from the detachment of the skin itself. The principle of the technique, that could be called laser-acoustics or laser tapping is described next, followed by examples of application to honeycomb structures and coatings.

PRINCIPLE OF LASER-ACOUSTICS OR LASER TAPPING

The principle of laser-acoustics is shown in Figure 1. A pulse 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 disbonded layer or skin can then be set into vibration like a membrane [1]. The modes of the vibration 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. 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 1). The fundamental vibration frequency, f_1, of this clamped membrane is given by:

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

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. A more general expression has been obtained from a finite element analysis to remove the assumption of a clamped plate support, considering a bulk of the layer material at the edges [5].

The surface is then illuminated by a detection laser which impinges on the tested part at a location superimposed or near the excitation laser spot. The detection laser light scattered or reflected off the surface is phase modulated by the small surface motion of the part. This light is then collected and sent to an interferometer. The time window required for the measurement is a few cycles of the membrane oscillation which means typically one ms or less. A pulsed detection laser is preferable than a continuous one since a higher peak power can be achieved. Also, the surface has only to be interrogated for a limited time following excitation and not continuously. In addition, since the laser energy is partly absorbed by the tested part, a pulsed laser limits the heat load deposited on the tested part. The pulse duration τ_L of the detection laser should be longer than the vibration period of the membrane T (2T and beyond). τ_L could be for example 200 μs and is in this case well adapted to detachments characterized by a period T of 50 μs and shorter. The detection spot size should be about the same as generation and in any case much less than 2a, otherwise there will be some integration over the vibrating membrane surface resulting into a lower signal, since the membrane is nearly clamped at its edges. The excitation and the detection lasers are scanned over the surface of the tested part to produce an image. Alternatively the part can be moved in front of both laser beams. 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.

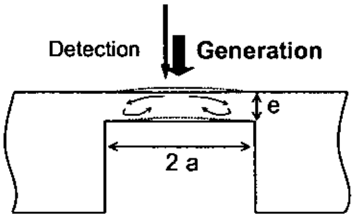

FIGURE 1. Thermal excitation and flexural vibration of a nearly clamped membrane with optical detection.

While proposed many years ago [1], the technique has not found practical use in industry. A first shortcoming is that the technique was tested using a Michelson-type interferometer (homodyne or heterodyne) for detection. These interferometers are sensitive to the optical speckle produced by a rough surface, which means that these interferometers have a maximum sensitivity to surface displacement when only one speckle of the light scattered by the surface is collected. 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 thus the sensitivity of the device can also strongly varies. Then, scanning a part to get an image of the adhesion integrity of the structured material with such an interferometer is not very practical. Actually, the technique was demonstrated on a honeycomb structure with specially polished aluminum skins for which the light reflected off the surface is nearly speckle-free. A second shortcoming occurs with honeycombs. As indicated by Eq. (1), the vibration frequency of a detached membrane is a function of both its thickness and its diameter, which means that for a honeycomb structure, a delamination within the skin or to a detachment of the skin from the honeycombs cannot be readily discriminated from the vibration signal.

The first shortcoming is circumvented by measuring the surface displacement with a two-wave mixing photorefractive interferometer that collects the scattered light. As mentioned above, such a system is speckle insensitive (it has a large etendue) and this is a key element to the practical use of the approach. The response time, τ, of the interferometer, i.e. the photorefractive grating build up time, is the characteristic time 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). The grating build up time also gives the time required by the interferometer to write the photorefractive hologram or to build up its sensitivity from the beginning of each optical detection pulse. Then, a too slow grating build up time results in an interferometer highly sensitive to ambient vibrations and part motion, inadequate for inspection in industrial conditions. This grating build up time is controlled by the photorefractive optical pump beam power, extracted from the detection laser. For the approach considered here, τ has also to be longer than the vibration period T for the interferometer to work effectively (the photorefractive grating should be quasi-stationary during the vibration period). For example, if $T = 10$ μs (vibration frequency of 100 kHz), τ has to be more than 10 μs, let us say 20 μs (corresponding to a cutoff frequency $1/(2\pi\tau) \leq 10$ kHz). 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.

To solve this difficulty, two practical methods of scanning are considered. In a first method, the scanning is stopped during interrogation. This method however puts severe requirements on the mechanics of the scanner and its control since mechanical parts have to be repetitively set into motion and stopped, but it leaves a long time for the interferometer to adapt to speckle. There is also in this case no Doppler effect associated to scanning. The response time should also be short enough to allow the photorefractive crystal to adapt to ambient vibrations. For example, considering a laser repetition rate of 500 Hz, more than 1 ms is available for interrogation, so it could be very long (corresponding to a relatively weak pump power sent onto the crystal). In this case, the longer vibration period T that could be detected (corresponding to large or thin membrane) is given in practice by the laser pulse duration τ_L. Also in this case, a large part of the laser power can be sent onto the surface since the pump requires less laser power.

In a second method, the scanning is continuous. In this case, τ is much shorter in order to provide adaptation to the speckle variation and Doppler shift. A shorter τ results in a higher interferometer cutoff frequency and then puts a lower limit on the vibration frequency and an upper limit on the size of detachment or disbond that can be detected (or a lower limit on the membrane thickness). In principle, large detachment or disbond can be missed using this approach, thus making the technique very unattractive since large and severe flaws have to be detected above all. For example, if one assumes scanning over a slope at 45° with a tangential velocity of 1 m/s (i.e. if the laser repetition rate is 400 Hz, the projected laser spot or pixel size is 2.5 mm) the Doppler shift is about 2 MHz. To compensate for such a shift, the response time has to be made very short (100 ns), which is in practice hardly feasible on one hand and would restrict the method to the detection of very small disbonds on the other hand. In such a case, one could use a frequency compensation scheme, which makes the interferometer to operate as if the beam is at normal incidence [6]. In this case, there is no Doppler effect and a response time τ typically hundred times as large can be used, let's say $\tau = 20$ μs, which means for the example above that disbonds as large as about 15 mm can be detected. To detect reliably larger disbonds, one solution is to reduce the scanning speed. Another approach is the detection higher order vibration modes of the membrane. As sketched in Figure 2, when both the excitation and the detection spots are sufficiently small, much less than 2a, the diameter of the membrane, let us say 2a/5 or 2a/10, higher order modes are produced and are essentially excited at the edge of the disbond. When the excitation is at the middle of the membrane, the fundamental mode is preferentially excited and the disbond may not be detected due to a too fast response time of the photorefractive interferometer as mentioned above. Therefore in this case, the disbond will give an indication only along its edge whereas its central part will show nothing. This higher order modes detection approach is applicable to the stop scanning method as well as to the continuous scanning method.

EXAMPLES OF APPLICATIONS

Honeycomb Carbon Epoxy Test Sample

A first example is the application to a carbon epoxy honeycomb structure with artificially produced delaminations in the skin as well as skin or core unbonds, as shown in Figure 3.

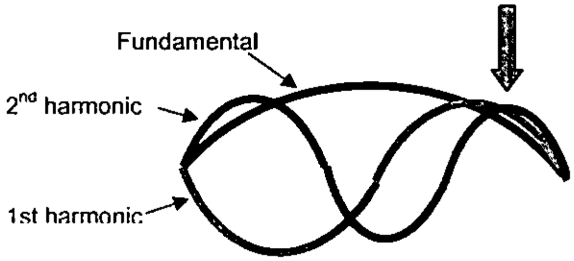

FIGURE 2. Detection of higher vibration modes of the disbond area.

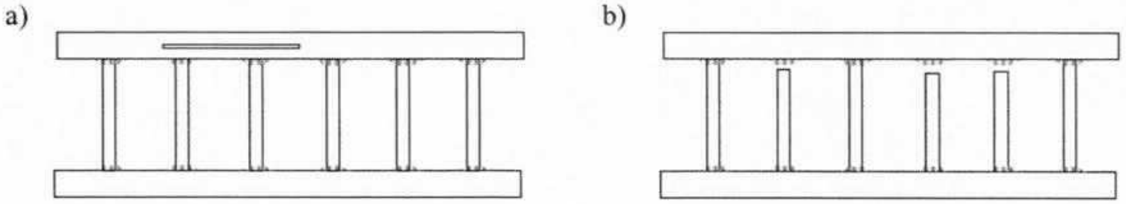

FIGURE 3. Sketch of side view a) of a delamination within the skin and b) of skin unbonds for an honeycomb structure.

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 phase interferometer based on 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 scanning system was of the stop type. 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 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 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

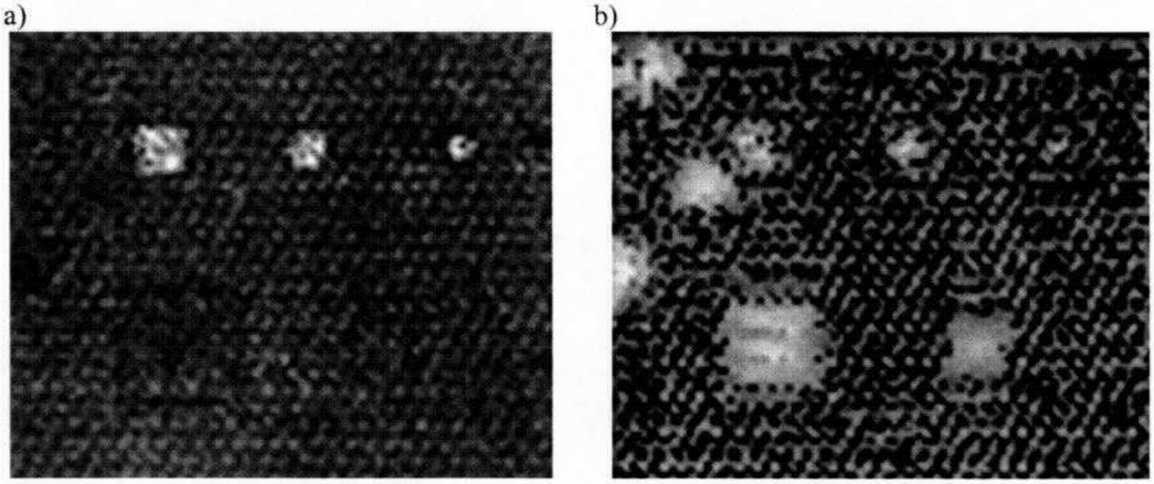

FIGURE 4. Results on a part containing three square skin delaminations (top) and two core unbond areas (bottom) of different sizes. a) Ultrasonic echo C-scan (plot of the maximum amplitude after high pass filtering) and b) vibration frequency C-scan (plot of the frequency of the maximum of the signal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

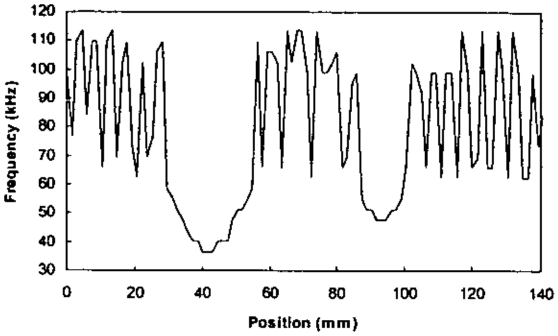

FIGURE 5. Profile of vibration frequencies along an horizontal line crossing the two unbond areas in Figure 4b.

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 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. 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. As mentioned before, it is not straightforward to determine the depth of a disbond from the vibration data alone. This example 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 unbond 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 disbond. This has been noted previously and it is very useful for detecting large disbonds in the continuous scanning mode.

Anti-wear Tungsten Carbide-Cobalt coating on steel

The second example shows the detection of detachment of a Tungsten Carbide-Cobalt (WC-Co) coating on steel. These coatings are currently developed for replacing hard chromium coatings, which are at the source of environmental problems. They are used on parts such as aircraft landing gears which are subjected to fatigue cracking. Fatigue cracks may lead to detachment between the coating and the substrate, which are likely to be followed by a complete coating peel-off, leaving the substrate unprotected from corrosion. Therefore the detection of such disbonds is very important. Figure 6a shows the signals obtained over a location where the coating is well-bonded and another location where it is detached from the substrate. The large oscillations at about 200 kHz are a clear signature of a detached area. Figure 6b shows a plot of the vibration amplitude over a line scan taken in a region where the coating is partially detached from the substrate.

Silicon Carbide Protecting Layer on a Carbon-Carbon Substrate

The third example shows 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 with time produced by oxidation. If these voids grow bigger, the coating could get detached leaving the C-C substrate unprotected and subjected to severe oxidation. Therefore the detection of disbonds between the coating and the C-C substrate is important.

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 obtained on this C-C sample with SiC coating protection are shown in Figure 7. Figure 7a 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. Microscopic observation of the edges actually confirms that the coating is disbonded in these areas. These disbonds are more clearly observed in Figure 7b, which shows the amplitude profile along the dotted line in Figure 7a. For comparison, Figure 7b also shows the amplitude along a well bonded line.

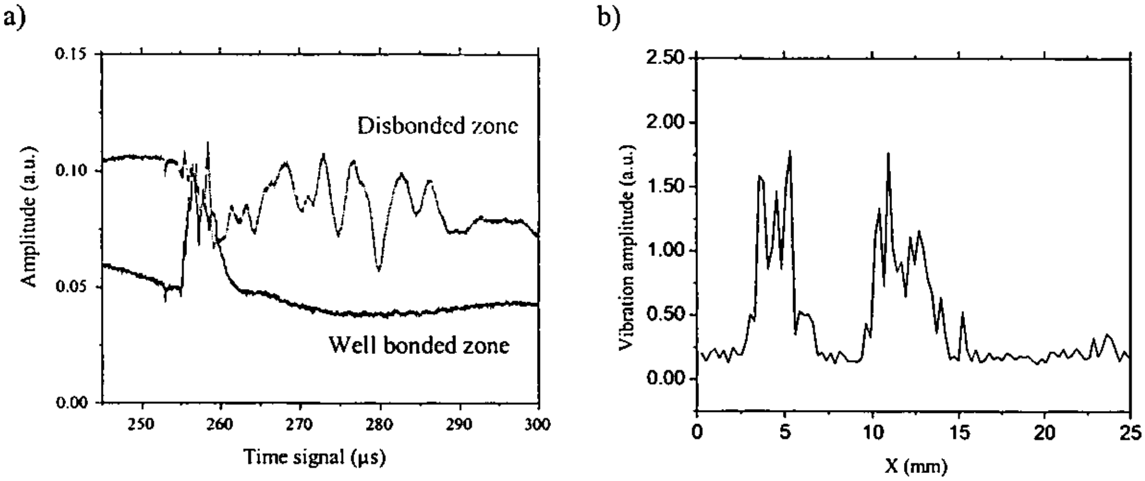

FIGURE 6. a) Signals obtained by laser-acoustics over a location where the coating is well-bonded and another location where it is detached from the substrate. b) Profile of the vibration amplitude in a region where the coating is partially detached from the substrate.

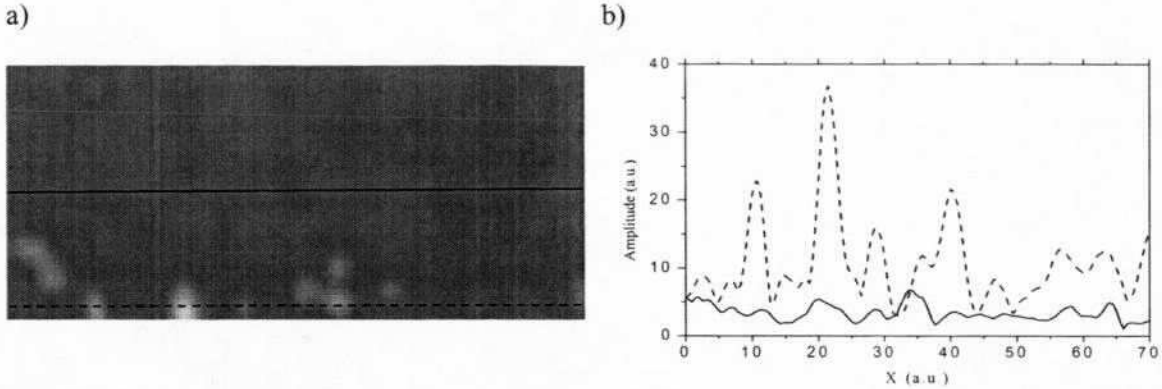

FIGURE 7. a) C-scan of the maximum amplitude of the laser-ultrasonic data in the Fourier domain. b) Amplitude profile along the solid and dotted lines on the C-scan in Figure 7a.

CONCLUSION

We have reported a novel technique for detecting reliably coating detachment and skin unbond in honeycombs. This technique, which can be called laser-acoustics or 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. Detection of a large area at low frequency can be assured either by a stop scanning approach or by the detection of higher harmonics of the fundamental membrane vibration. 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 a more thorough and reliable inspection by allowing one to distinguish disbonds within the skin from detachment of the skin itself. Experimental results on coatings and on a honeycomb structure with core unbonds show the viability of the technique.

REFERENCES

1. P. Cielo, X. Maldague, G. Rousset, C. K. Jen, *Materials Evaluation* **43**, pp. 1111-1116 (1985).
2. A. Blouin and J.-P. Monchalin, *Appl. Phys. Lett.* **65**, pp. 932-934 (1994).
3. M.P. Petrov, I.A. Sokolov, S.I. Stepanov, G.S. Trofimov, *J. Appl. Phys.* 68, pp. 2216-2225 (1990).
4. K. Paivasaari, A.A. Kamshilin, "Adaptive sensors of rough-surface ultrasonic vibrations based on the polarization self-modulation effect", *Fourth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications*, SPIE Proceedings vol. 4072 (2000), pp. 70-80.
5. G. Rousset, D. Lévesque, L. Bertrand, X. Maldague and P. Cielo, *Can. J. Phys.* **64**, pp. 1293-1296 (1986).
6. B. Campagne, A. Blouin, C. Néron, J.-P. Monchalin, "Doppler Frequency-Shift Compensated Photorefractive Interferometer For Ultrasound Detection On Objects In Motion", in *Review of Progress in QNDE*, **22**, edited by D.O. Thompson and D.E. Chimenti, AIP Conference Proceedings, Melville, New York (2003), pp. 273-280.
7. P. Delaye, A. Blouin, D. Drolet, L.A. de Montmorillon, G. Roosen and J.-P. Monchalin, *Journal of the Optical Society of America B* **14**, pp. 1723-1734, (1997).