LASER-ULTRASONICS PROBING OF MATERIALS WITH LARGE ULTRASONIC ATTENUATION

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Abstract: Laser-ultrasonics is now a mature technology for non-destructive inspection of materials at a distance. In laser-ultrasonics, a high-peak power pulsed laser generates an ultrasonic wave that propagates in the material. The material ultrasonic surface motion is probed by a continuous or long pulse detection laser. When combined with a two-wave mixing-based photorefractive interferometer that offers low-frequency cut-off phase demodulation, it is possible to perform tests on materials with large ultrasonic attenuation. To illustrate the possibilities of this method, we present results obtained with highly porous metallic foams. We have performed tests to evaluate the elastic properties of such materials, an important property in numerous industrial applications. This new method applied for material mechanical characterization is very promising and presents advantages compared to compressive techniques that are time-consuming and destructive.

Introduction: Laser-ultrasonics has been in development for more than 20 years and offers now an alternative solution for non-contact measurement at a distance in numerous industrial applications [1-4]. Laser-ultrasonics combines a high-peak power pulsed laser for generation, a detection laser, an optical interferometer and a module control to synchronize laser shots and measurements acquisition. The pulsed generation laser interacts with the material to create an ultrasonic wave that propagates in the medium. A continuous or long pulse detection laser probes the material ultrasonic surface motion. This surface motion, created by the ultrasonic waves, produces a phase modulation of the scattered light. The light collected back from the surface is then directed into an optical interferometer (Michelson, confocal Fabry-Perot or photorefractive crystal-based interferometers) that converts phase modulation into an intensity modulation. Laser-ultrasonics is flexible and versatile since lasers and/or interferometer can be modified and designed for each specific industrial application. Several conditions must be fulfilled to obtain good signal-to-noise ratio. First, interaction of the generation laser with the material surface must produce ultrasonic waves efficiently with no or, at least, minimum marks on the surface. Then the detection laser must be powerful enough and the optical collection must be optimized to limit the losses caused by surface material scattering and absorption. The confocal Fabry-Perot interferometer [5] is reputed to be sensitive, robust and simple to implement in industrial environment. However, in practice, the sensitivity to phase modulation of the confocal Fabry-Perot drops at low frequencies with a cut-off frequency of about 1 MHz. Sensitivity below 1 MHz can be obtained with a photorefractive two-wave mixing interferometer (PTWM) [6].

The PTWM interferometer is based on real-time holography in which a reference beam is mixed with a phase-shifted and speckled wavefront signal beam in a photorefractive crystal to produce a speckle adapted reference wave that propagates along the transmitted signal beam and interferes with it. Like the confocal Fabry-Perot, the PTWM interferometer is a large etendue interferometer that can operate with many optical speckles, which is of particular interest when working on highly scattering surfaces.

The optical and ultrasonic properties of the inspected material influence the signal-to-noise ratio. Optical properties such as absorption or reflection coefficients must be known to choose the best wavelength to optimize the ultrasonic wave amplitude generated by the high-peak power pulsed generation laser. Surface properties such as roughness or presence of oxide can greatly modify the amplitude and emission pattern of the laser generated ultrasonic waves. Laser generation mechanisms may occur in thermoelastic, ablation or plasma regimes. Once generated, the ultrasonic waves must propagate in the inspected material without a too large attenuation. This acoustic attenuation may come from ultrasonic wave scattering or absorption. A variety of new materials such as cermet coatings or metallic foams cannot be tested because of their high ultrasonic attenuation due to their porous structure. To illustrate the ability of laser-ultrasonic technology to analyse porous materials, we present in this paper experimental results obtained on metallic foam samples.

Metallic foams offer a combination of attractive properties such as a high surface area, low density, high permeability, thermal and environment resistance and good electric conductivity. New materials have been recently developed and are used in a wide range of applications such as for the fabrication of filters, lightweight structures, implants, heat exchangers, electrodes for fuel cells, batteries, fluid treatment units, and so on. The required structure and properties of these materials depend on the application. The properties of the materials greatly rely on the alloy selected, its microstructure as well as the foam structure. The structure of the foam may exhibit a texture that can lead to anisotropic properties. Thus, in order to characterize these materials, the structure and the properties should be evaluated in different directions. In addition, the properties should be evaluated at different locations to confirm the material homogeneity.

The evaluation of the elastic properties of foams represents important technical challenges, such as the material sampling, the specimen preparation and interpretation of the results. The elastic properties are generally evaluated by uniaxial compression tests on cylinders. To adequately evaluate the properties of the foams, the dimensions of the specimens must be at least 10 times larger than the largest pores. The thickness of the specimens must be large enough to get precision in the displacement reading, especially for the measurement of the elastic modulus (i.e. in the small deformation range of the compressibility tests). To get statistically representative results, multiple tests must be done (at least five). Thus, time-consuming and destructive tests must be performed in order to fully characterize the properties of such materials. Furthermore, in many cases, materials are not produced in shapes adequate to perform these tests.

We present a method based on laser-ultrasonics that allows measuring some elastic properties of metallic foams in a simpler and faster way. This method consists in exciting locally a sample and by detecting the vibration modes of the whole metallic foam structure. By reducing adequately the PTWM interferometer low frequency cut-off, vibrations below 100 kHz are easily detectable. A similar approach of the method was introduced in [7], where the inspected material was a thin and high reflecting disc, and the phase demodulator was a Michelson interferometer. Vibration frequencies of a thick circular plate sample are directly related to its mechanical properties and geometrical features by the equation (1) [8]:

$$f_{ij} = \frac{K_{ij}\left(\frac{h}{r},\sigma\right)}{2\pi r}\sqrt{\frac{Y}{\rho}}, \qquad (1)$$

where Y is Young's modulus, ρ is the mass density, r is the radius, h is the thickness, σ is the Poisson's ratio. K_{ij} depends of the ratio h/r and σ. Indices i and j correspond to the vibration modes of the thick disc. Flexion and torsion fundamental modes are respectively f_{20} and f_{01}.

This non-contact method is relatively simple to implement. Furthermore, the PTWM interferometer advantageously replaces the Michelson-based vibrometer since it can operate with many optical speckles.

Results: The studied samples are titanium foams (Ti-6Al-4V). They were produced using the process described in [9]. Small discs (10 mm diameter and 5 mm thick) were machined from a larger disc (200 mm diameter and 20 mm thick). Twelve specimens are used in the experiment. A typical micrograph of the microstructure of the foams taken using a scanning electron microscope is presented in Figure 1. The average density of the foams is 1.01 ± 0.07 g/cm^3. The foams have open cells and are permeable.

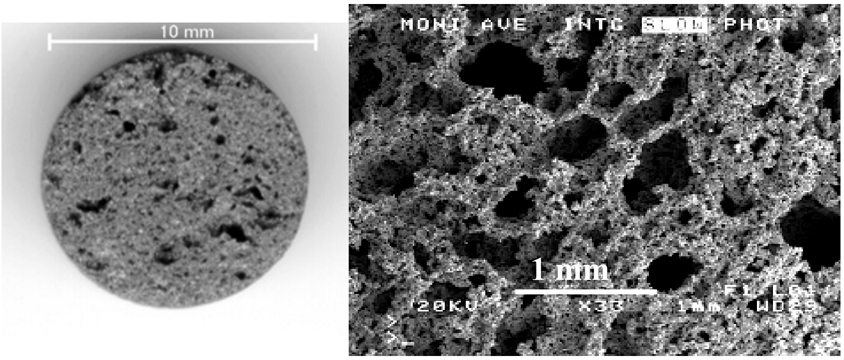

Figure 1. Photograph and micrograph of a titanium foam specimen.

To induce the vibration, a CO_2 laser is focused on the sample. The 10.6μm wavelength CO_2 laser has a pulse duration of 200 ns, and a typical energy per pulse of about 80 mJ. A 65μs pulse duration, 1.064μm wavelength Nd:YAG laser probes the opposite surface of the sample for detection. Although we chose to work in transmission mode (generation and detection laser spots on opposite sides of the sample) for commodity, working in pulse-echo mode (generation and detection laser spots on the same side of the sample) is also possible. Diameters of laser spots are closed to 1 mm, which is much less than the 10 mm diameter of the metallic foam specimens.

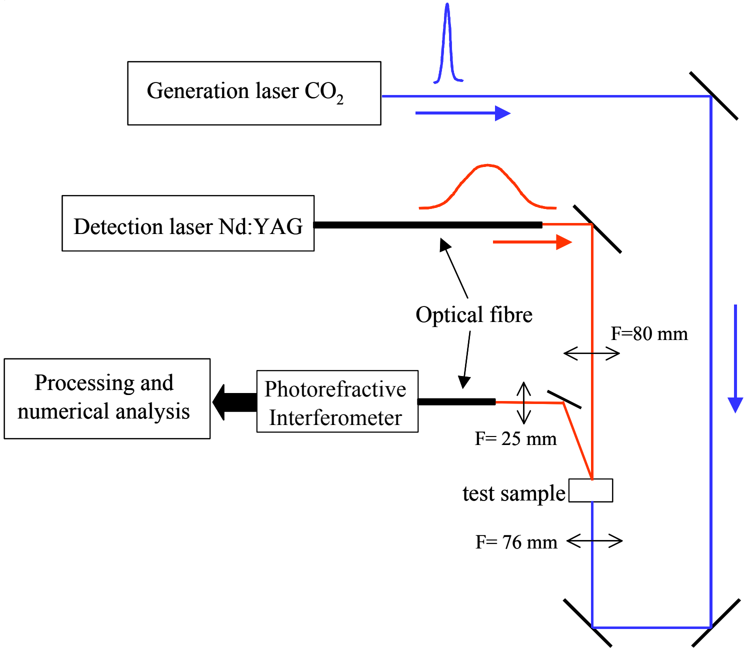

Figure 2. Experimental setup.

The PTWM interferometer is operated with a InP:Fe photorefractive crystal under high voltage. The frequency response of the interferometer is typically a high-pass filter, whose low frequency cut-off is fixed by the reference pump power illuminating the crystal. In this experiment, the power is adjusted so that frequency cut-off is expected to be 25kHz. The PTWM interferometer is equipped with a balanced detection scheme to eliminate the intensity fluctuations.

The samples are held without stress by a three-point support that is made of a polymer foam, so the sample is acoustically isolated and can vibrate freely. The support itself is mounted on a rotational stepping motor, which allows performing some statistical data analysis, checking measurement reproducibility and evaluating anisotropy.

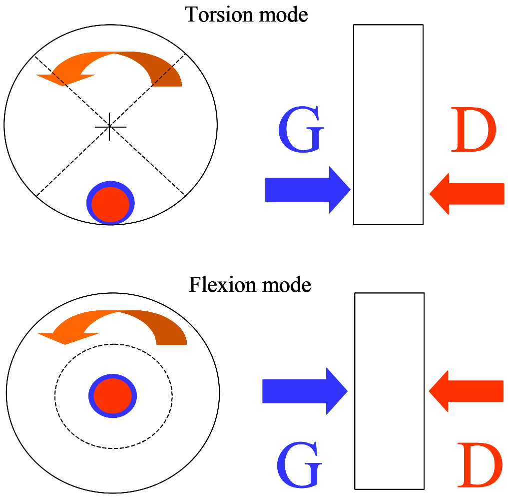

Figure 3. Schemes for generation and detection of the first two natural frequencies of flexural vibration

Assuming first that the material is isotropic, the Young’s modulus and the Poisson’s ratio of the material can be found by measuring the values of the first two natural frequencies of vibration. In practice, it is necessary to perform two series of measurement. As shown in figure 3, the first natural vibration f_{01}, a torsion mode, is obtained when the sample is excited on the edge. Since this vibration has two mutually perpendicular nodal diameters, detection is also preferable on the edge. The second natural vibration shape f_{20}, a flexion mode, has a nodal circle. So best results are obtained when exciting and detecting at the centre of the sample. Figure 4 presents some typical time-domain signals and their FFT obtained with one sample in each configuration.

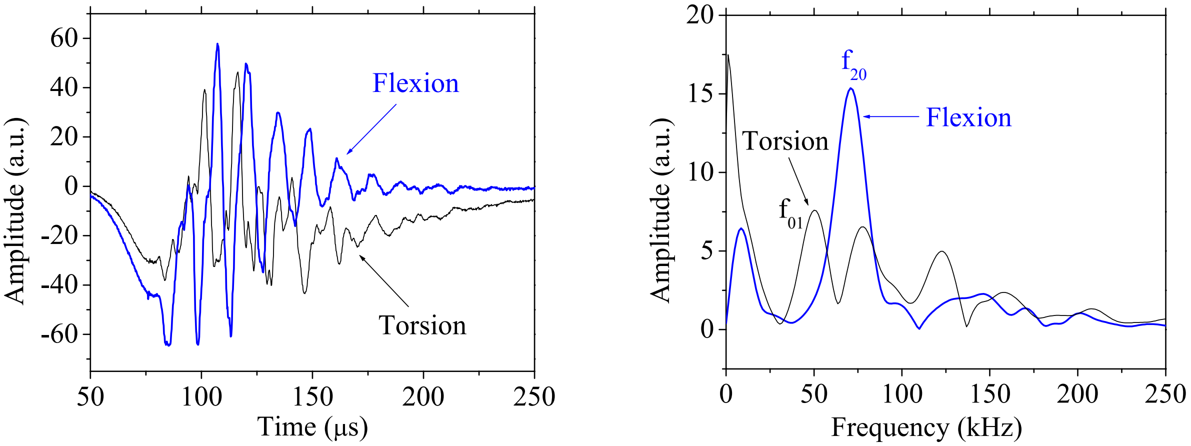

Figure 4. Time-domain and FFT signals corresponding to flexion f_{20} and torsion f_{01} modes.

Discussion: From the FFT signals, we measure the value of peak frequency corresponding to the fundamental vibrations. The sample is rotated by steps of 0.5 degree between each laser shot. Acquisitions are performed during two revolutions of the sample. The values of peak frequency are then reported on a polar representation graph. Some typical results obtained with two specimens are presented in figures 5 and 6.

A circular symmetry is observed for the second natural vibration f_{20}. In the first sample, f_{20} = 63.8 kHz. The cross shape observed for the first natural vibration f_{01} reveals the presence of anisotropy. F_{01} is between 46-48 kHz. The missing points or the values very different from the mean are due to a poor laser ultrasonic generation or a small detection light level collected back from the surface. In the second sample, the value of f_{20} is slightly different and is about 57 kHz. F_{01} is between 40-42 kHz and the anisotropy is not clearly visible.

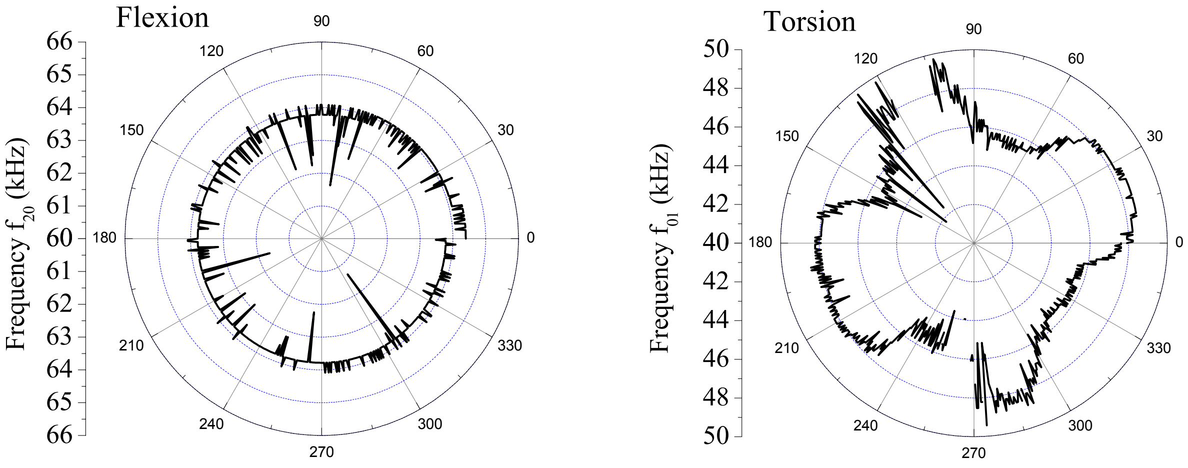

Figure 5. Polar presentation of the first two natural frequencies of flexural vibration in sample #1.

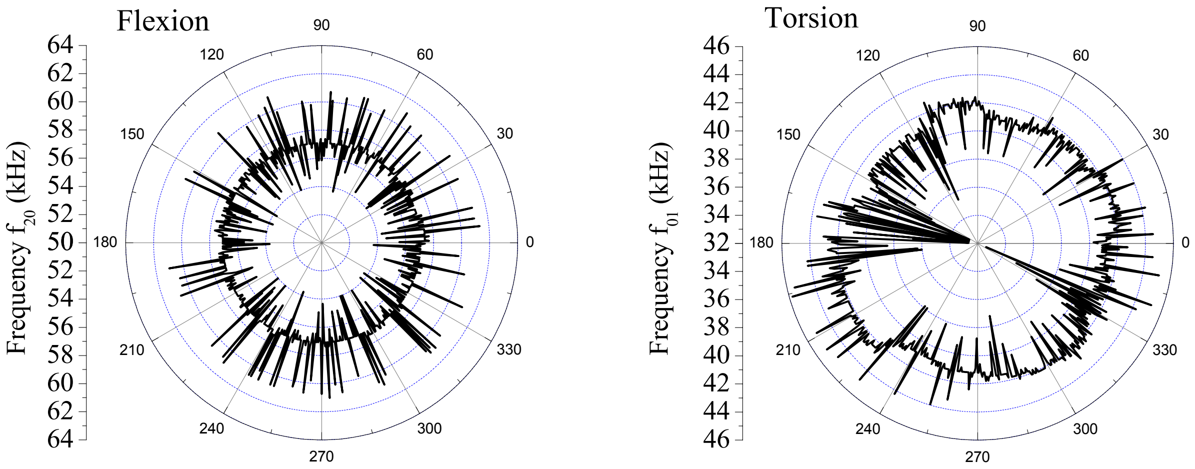

Figure 6. Polar presentation of the first two natural frequencies of flexural vibration in sample #2.

To evaluate the Young's modulus of the metallic foams, the method that is presented assumes that the material is macroscopically homogeneous and that the anisotropy is negligible. These assumptions simplify the resolution of the problem by affirming that the Poisson's ratio is constant and isotropic.

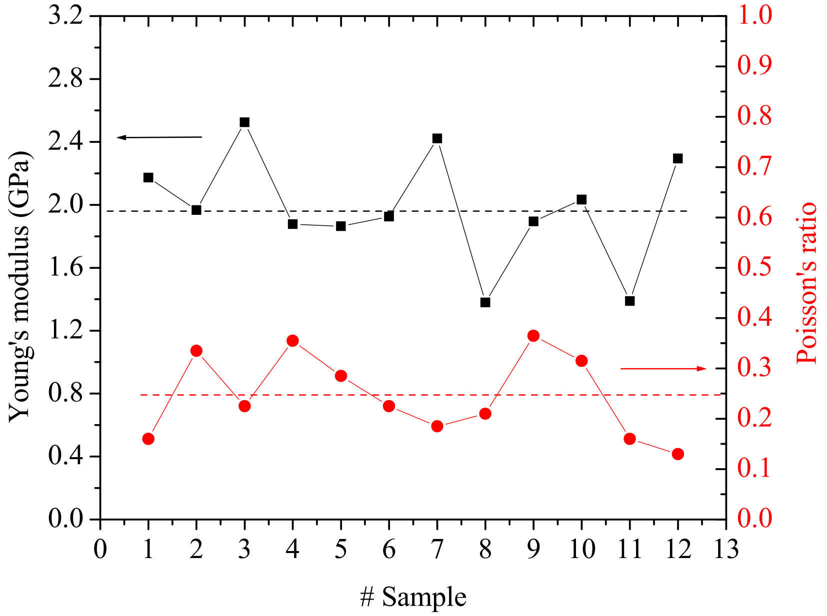

Figure 7. Poisson's ratio and Young's modulus for each specimen.

From the tables giving circular frequencies of the natural vibrations for various conditions of h/r and various values of Poisson's ratio ν [8], we determine the experimental Poisson's ratio and the value of K_{ij}. Then the Young's modulus is calculated from equation (1), using the measured values of h=5 mm, r=5 mm and ρ=1.01 g/cm^3. The mean Poisson's ratio value is about 0.25 ± 0.08, and then the mean Young's modulus is equal to 1.98 ± 0.35 GPa. The value of elastic modulus, which is a first approximation, is in good agreement with values measured on similar metallic foams by compression and destructive techniques [9]. Figure 7 presents the results obtained for each tested specimen. The dashed lines represent the mean value.

Then, non-destructive evaluation of the elastic modulus of the metallic foams using low frequency acoustic excitation is an attractive method to determine the elastic properties of this kind of material. This technique can be used on small specimens of simple geometry and allows obtaining results simultaneously along different directions. The technique is non destructive and allows measuring the modulus without imposing a plastic deformation of the material. Thus, laser-ultrasonics is a powerful tool to characterize the structure as well as the properties of these kinds of materials.

Conclusion: Laser-ultrasonics combined with photorefractive TWM interferometer offers a good solution for mechanical characterization of metallic foams. We have demonstrated the feasibility to evaluate in first approximation the Young' modulus of simple metallic foam specimens. Although it has been neglected in the analysis, the technique was sensitive enough to evidence a slight anisotropy in some specimens. This method can also be applied to the characterization of any material that exhibits porosity and/or high ultrasonic attenuation.

References: [1] Choquet, M., Héon R., Padioleau C., Bouchard P., Néron C. and Monchalin, J.-P., «Laser ultrasonic inspection of the composite structure of an aircraft in a maintenance hangar», Review of Progress in Quantitative Nondestructive Evaluation, vol. 14, eds. D. O. Thompson and D. E. Chimenti, Plenum, New-York, 1995, p. 545.

[2] Pétillon, O., Dupuis, J.-P, Voillaume, H., Trétout, H., «Applications of Laser Based Ultrasonics to Aerospace Industry», Proceedings of the 7th European Conference on Non-Destructive Testing, Copenhagen, 26-29 May 1998, pp.27-33.

[3] Monchalin, J.-P., Choquet, M., Padioleau, C., Néron, C., Lévesque, D., Blouin, A., Corbeil, C., Talbot, R., Bendada, A., Lamontagne, M., Kolarik II, R. V., Jeskey, G. V., Dominik, E. D., Duly, L. J., Samblanet, K. J., Agger, S. E., Roush, K. J., Mester, M. L., «Laser ultrasonic system for on-line steel tube gauging», in Review of Progress in Quantitative Nondestructive Evaluation, vol. 22A, eds. D. O. Thompson and D. E. Chimenti, AIP Conference Proceedings, New-York, 2003, p. 264.

[4] Monchalin, J.-P., «Laser ultrasonics: From the laboratory to the industry», Review of Progress in Quantitative Nondestructive Evaluation, vol. 23, eds. D. O. Thompson and D. E. Chimenti, AIP Conference Proceedings, New-York, 2004, p. 3.

[5] Monchalin, J.-P. and Héon, R., «Laser ultrasonic generation and optical detection with a confocal Fabry-Perot interferometer», Materials Evaluation, 44, 1231 (1986).

[6] Delaye, P., Blouin, A., Drolet, D., de Montmorillon, L.-A., Roosen, G., Monchalin, J.-P., «Detection of an ultrasonic motion of a scattering surface by photorefractive InP:Fe under an applied DC field», J. Opt. Soc. Am., 14, 1723 (1997).

[7] Franca, D. R. and Blouin, A., «All-optical measurement of in-plane and out-of-plane Young's modulus and Poisson's ratio in silicon wafers by means of vibration modes», Meas. Sci. Technol. 15 (2004) 859–868.

[8] Gustav Martincek, «Determination of Poisson's ratio and the dynamic modulus of elasticity from the frequencies of natural vibration in thick circular plates», J. Sound Vib. (1965) 2 (2), 116-127.

[9] Gauthier, M., Menini, R., Bureau, M.N., So, S.K.V., Dion, M.-J., Lefebvre, L.P., «Properties of Novel Titanium Foams Intended for Biomedical Applications», ASM Materials and Processes for Medical Devices Conference, Anaheim, Californie, 8-10 sept. 2003, p.382-387.