NON CONTACT GENERATION AND DETECTION OF ULTRASOUND WITH LASERS

J.-P. Monchalin
Industrial Materials Institute - NRC, Boucherville, Quebec, Canada

Abstract: A broad overview of laser-ultrasonics, which is a technique for non-contact generation and detection of ultrasound is presented. The principles of generation and detection are outlined, stressing a few key characteristics of laser-ultrasonics: the material is actually the emitting transducer and transduction is made by light, thus allowing generation and detection at a distance. These features carry both advantages and limitations that are explained. Another feature, which has been an impediment, is actually the complexity of the "laser-ultrasonic transducer", but in spite of this complexity, it can be made very reliable for use in severe industrial environments. It also can be very cost effective for a number of applications. Applications that have been transitioned to the industry are presented as well as many other potential industrial applications.

Introduction: A main constrain of piezoelectric-based ultrasonics is the need of contact or fluid medium for ultrasound coupling to the tested part. Others are the limited bandwidth of piezoelectric transducers and the sensitivity to the phase of the ultrasonic wavefront across the transducer element, which makes the inspection of parts with acute curvature difficult. As recognized by researchers for many years, these limitations could be eliminated by using lasers and light for generating and detecting ultrasound, so called laser-ultrasound, laser-based ultrasound or laser-ultrasonics. Progress to take this concept out of the laboratory into industry has been quite slow, but during the last few years, we have seen the start of real industrial use, while observing at the same time increasing research activities.

In laser-ultrasonics transduction is made by light, thus eliminating any contact and the material is actually the emitting transducer, which has both advantages and limitations. Another feature, which has been actually an impediment, is the complexity of the "laser-ultrasonic transducer", which is sketched in Fig. 1. As shown in Fig. 1, such a transducer has typically three basic elements, a generation laser, a detection laser and an interferometer, followed by data acquisition and processing electronic hardware. In spite of this complexity, such a transducer can be made very reliable for use in severe industrial environments and it also can be made very cost effective for a number of applications. Two applications that have been transitioned from the laboratory to the plant floor are presented below. An extensive collection of references for the topics presented in this paper can be found in [1]. Basics of generation and detection developed before 1990 can also be found in [2].

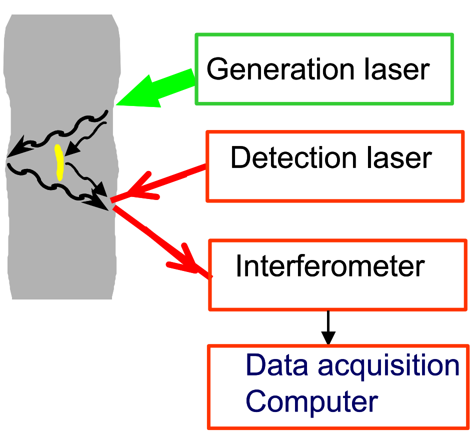

Figure 1. Sketch of the principle of laser-ultrasonics or of a "laser-ultrasonic transducer".

Laser generation of ultrasound: There are essentially two kinds of mechanisms for generating ultrasound, the first one is perfectly nondestructive and is based on a thermoelastic mechanism while the second one is invasive and is based on the ablation of the sample or on the vaporization of some surface layer. The principle of thermoelastic generation is the following: laser light is absorbed to some depth inside the material releasing heat locally; the heated region then expands producing a strain and a corresponding stress that is the source of waves propagating in the material or at its surface. When light penetration is small and the excitation spot much less than an acoustic wavelength, a complex emission pattern is observed in the far field with inclined lobes (from 30 to 60°) for the longitudinal and shear waves. There is in particular no longitudinal emission along the normal to the surface. In order to reproduce the conditions of conventional longitudinal piezoelectric transducers, the source should have a larger extent and there should be some light penetration below the surface. Light penetration is very important in practice since its gives a piston source at the surface of the material emitting normally propagating longitudinal waves, independently of the surface curvature and of the orientation of the laser beam. This is at the basis of the inspection of polymer-matrix composites, which is one of the industrial applications of laser-ultrasonics.

Surface waves and plate waves can also be generated efficiently and in a very versatile manner. When the laser beam is focused to a small circular spot, a surface wave with a cylindrical symmetry is emitted from this spot. Good directivity is obtained by focusing the beam with a cylindrical lens to get a line source. More complicated patterns can even be used, such as an array of lines, giving narrower band emission but having the advantage to distribute the laser energy over a broader area so surface damage can be avoided. A converging circular Rayleigh surface wave giving very strong displacement at the center of convergence can be readily obtained by using, in addition to the conventional spherical lens, an axicon (conical lens). Enhancement techniques have been developed by sweeping the line or line array source with a proper velocity.

If one increases the energy density, particularly for small light penetration (metals), one reaches the threshold where the surface starts to melt and then to get vaporized. At this point, matter is ejected from the surface and through various physical processes this vapor and the surrounding air is ionized, thus producing a plasma plume that expands away from the laser spot on the surface. Generation of ultrasound originates from the initial recoil produced by the material ablation and from the plasma pressure. A similar vaporization effect occurs also when the material is covered by a thin absorbing layer, which is blown off, leaving the substrate underneath substantially unaffected if the energy density is below some threshold. In the strong plasma regime on the other hand, a crater mark is left on the surface.

Independently of the mechanism used, it should be recognized that the material is actually the emitting transducer of ultrasound. This distinguishes laser-ultrasonics from piezoelectric-based conventional ultrasonics in which the source of ultrasound is a piezoelectric element separated from the tested material.

Laser detection of ultrasound: To detect ultrasound, the surface is illuminated by a laser beam, continuous or of pulse duration sufficiently long to capture all the ultrasonic signal of interest. Scattered or reflected light is then collected by an optical receiver, which is in the case of most industrial applications an interferometer (see Fig. 2).

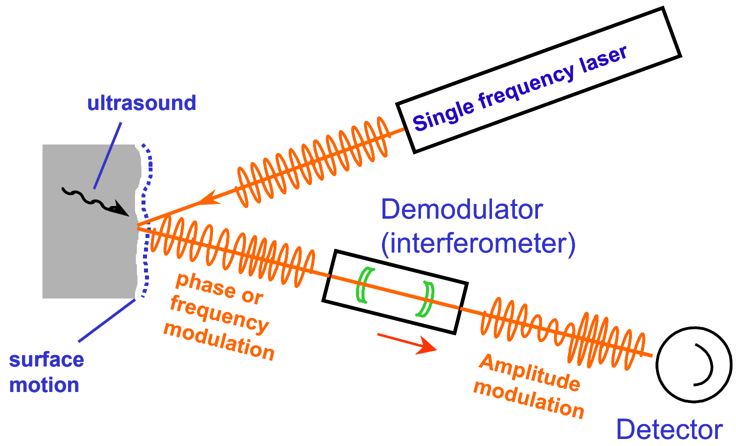

Figure 2. Principle of optical detection of ultrasound with an interferometer (here sketched as a confocal Fabry-Perot): the interfrometer converts the phase or frequency modulation produced by the surface motion in an intensity modulation.

A practical interferometer, which is by now widely used, is the confocal Fabry-Perot. This is a simple system made of two concave identical mirrors separated by a distance equal to their radius of curvature. In excellent approximation each ray retraces its path after multiple reflections in the resonator, which gives to the system a high collection efficiency (etendue or throughput). It can be used in transmission or in reflection. In transmission the responsivity peaks at a frequency equal to about a resonance width. The reflection scheme has on the other hand nearly flat frequency response above this frequency, except for periodic drops at integer of the free spectral range. It should be noted that the responsivity is practically zero at very low frequencies, which means that this system is intrinsically insensitive to vibrations, a key advantage for use in industrial environments. The main weakness of Fabry-Perot demodulators is their lack of sensitivity at low ultrasonic frequencies (below 2 MHz), which is circumvented by devices based on two-wave mixing in photorefractive materials.

In the two-wave mixing interferometers, wavefront adaptation is performed actively, by opposition to the confocal Fabry-Perot in which adaptation is performed by passive or linear optical components. The technique is also known as real-time holography. This active wavefront adaptation eliminates the need of an external stabilization device against thermal drift or ambient vibrations, as required for the confocal Fabry-Perot. The basic setup of the two-wave mixing interferometer is sketched in Fig. 3. A signal beam which acquires phase shift and speckle after reflection on a surface in ultrasonic motion, is mixed in a photorefractive crystal with a pump plane wave to produce a speckle adapted reference wave that propagates in the same direction as the transmitted signal wave and interferes with it. These systems have also a large etendue. The response of such devices is flat from a low cut-off frequency, which depends on crystal properties and pump intensity, up to the detector cut-off frequency. There are no periodic sensitivity drops like in the confocal Fabry-Perot. With an InP crystal with proper iron doping, operating at 1.06 μm and with the application of an electric field, the sensitivity is about the same as the maximum sensitivity of the confocal Fabry-Perot used in transmission.

One important advantage of the photorefractive demodulator with respect to the confocal Fabry-Perot is its better sensitivity at low ultrasonic frequencies (below 1 MHz), thus allowing probing more easily materials with strong ultrasonic attenuation. The system has also the advantage to be easily combined with a differential or balanced scheme (two detectors giving responses to phase modulation of opposite sign), so the noise coming from the laser intensity fluctuations can be eliminated to a large extent. Further, by making the pathlengths from the laser to the crystal along the signal and the pump beams to be sensibly equal, the effect of laser phase noise is eliminated. Its weakness, in spite of the use of semiconductor photorefractive crystals with high photoconductivity (GaAs, InP, CdTe), is its rather slow response time, i.e. the time needed for the photorefractive grating to be built up or to be erased. This affects the ability of the system to adapt to motions of the probed object that cause a change of the speckle pattern of the scattered light or a change of its frequency by the Doppler effect. To compensate for the Doppler shift, the frequency of one of the interfering beams can be changed (for example by sending the beam through an acoustooptic shifter) and this has been demonstrated.

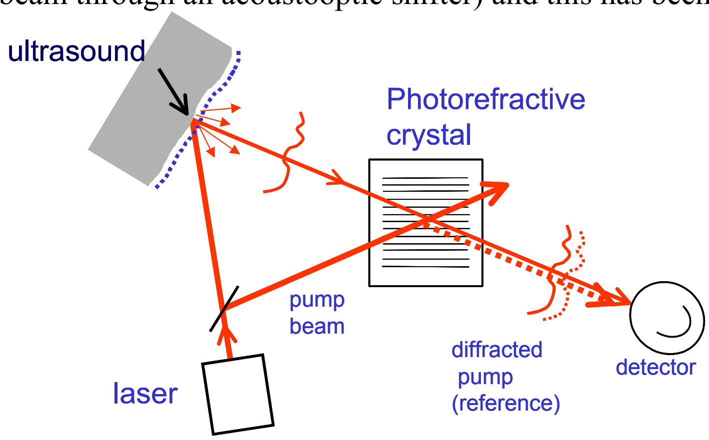

Figure 3. Demodulation with a two-wave mixing photorefractive interferometer.

Detection laser: One key element of the detection scheme is the detection laser. It should be high power, since sensitivity increases with power, and should not contribute to any noise in addition to the fundamental photon or shot noise. High power is particularly needed when the surface is absorbing and detection is at a large distance giving a small collection solid angle. The pulse duration should be sufficiently long to capture all the signal of interest, which means for many applications a duration between 10 and 100µs. Nd-YAG technology at 1.06 µm, which is known to provide high amplification gain, is particularly suited for realizing such a laser by amplifying a small and very stable Nd-YAG laser oscillator. A suitable oscillator is commercially available with power from 100 mW to about 2 W and is based on a small monolithic cavity pumped by a laser diode. Depending upon the repetition rate, the amplifier could be flashlamp pumped (up to 100 Hz) or diode pumped (above 100 Hz). Peak powers of 1 kW and more are typically obtained with pulse duration of the order of 50 µs. More recently, since such a master oscillator-pulsed amplifier system is complex and costly, IMI/NRC has been working on the development of a pulsed oscillator without seeding giving directly about 100 W [3].

Digital signal processing: Laser-ultrasonics, like any other ultrasonic technique could benefit advantageously of digital signal processing to increase sensitivity. Operations such as averaging, adaptive filtering could be used as well as more advanced methods such as split-spectrum processing or wavelet denoising.
Regarding imaging, a numerical imaging approach such as the one based on the Synthetic Aperture Focusing Technique (SAFT) can be combined with laser-ultrasonics to obtain high quality images. Processing can be done in the time domain but since this is can be very computation intensive and fairly long, methods that operate in Fourier space and make use of Fast Fourier Transform algorithms have been developed [4]. These methods, significantly different from the conventional time SAFT, although sometimes called F-SAFT, are based on a plane wave decomposition of the acoustic field for each

frequency combined with a back-propagation algorithm. This processing technique has been applied in particular to the imaging of stress corrosion cracks in steel. One example of the results obtained is shown in Fig. 4 where the crack opening image of stress corrosion cracks in a stainless steel test sample is compared with the image obtained conventionally by liquid penetrants. The laser-ultrasonic image was obtained by scanning the opposite surface and applying an F-SAFT reconstruction algorithm using the laser generated shear waves.

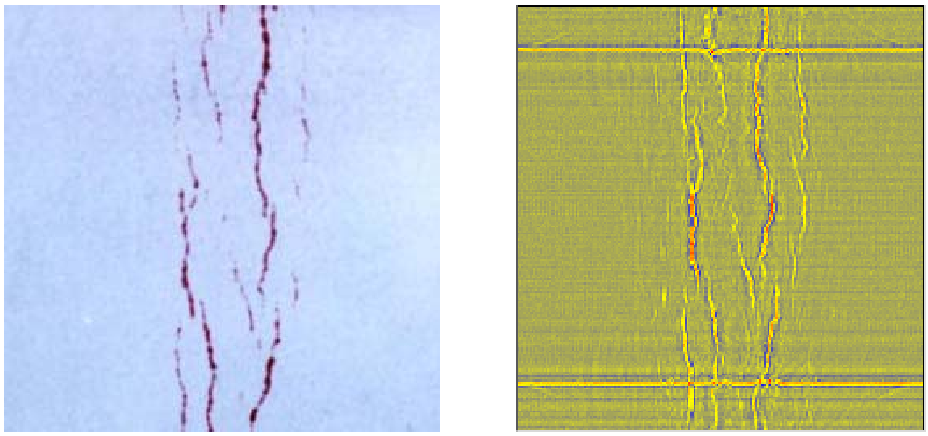

Figure 4. Comparison of crack opening images obtained by liquid penetrants (left) and laser-ultrasonic F-SAFT processing using shear waves and an annular aperture (right). The horizontal lines observed at right are artifacts originating from the small size of the test sample.

Industrial applications: Laser-ultrasonics has been the object of continuous efforts by the scientific and research community to better understand the phenomena taken place during generation and detection of ultrasound and to devise ways to make it usable in an industrial environment. These ways have aimed to push sensitivity, increase bandwidth, insure robustness and reliable operation in spite of ambient disturbances (such as vibrations). However, implementation of the technique is complex, particularly in comparison with conventional piezoelectric-based ultrasonics and also costly and these factors have slowed its industrial use. Nevertheless we have seen it transitioned during the recent years to the industrial floor. It has been applied to the thickness determination of microelectronic thin layers, the inspection of aircraft structures made of polymer-matrix composites and the on-line wall thickness gauging of seamless tubes.

Regarding the inspection of aircraft structures made of polymer-matrix composites, this application has been actively pursued for many years by IMI/NRC, UltraOptec Inc. a licensee of IMI/NRC and General Dynamics of Forth Worth, Texas (now Lockheed Martin Aeronautics Company). Lockheed-Martin has at one point continued independently its own development, which has led to systems that are now routinely used for testing composite parts of the F-22 fighter fabricated by the company. Laser-ultrasonics is particularly interesting for inspecting complex parts and for such parts has advantages regarding ease of operation (no additional tooling, no previous detailed knowledge of the shape or precise orientation of the part) and inspection throughput.

This application is first based on the generation of a longitudinal wave normal to the surface independently of the laser beam incident direction, as shown in Fig. 5. As explained above this characteristic is based on the penetration of laser light below the surface, which is in practice obtained by using a TEA CO_2 laser operating at 10.6 μm. Since the system should inspect large areas, a standoff distance of more than one meter is required. This requirement coupled with a scattering surface, which could be also highly absorbing, makes the use of a high power detection laser mandatory. In all the systems developed and presently used, this detection laser is based on Nd-YAG technology and has been described above. A confocal Fabry-Perot is also used as demodulator. In addition to the use at Lockheed Martin, such a technology has been also used at validation and production stages by aerospace companies in Europe using a system assembled by UltraOptec.

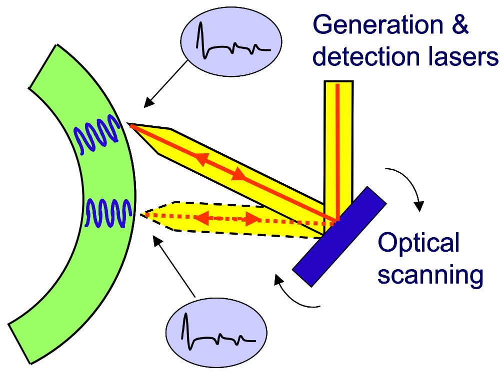

Figure 5. Effect of penetrating laser light: generation occurs perpendicularly as if a conventional piezoelectric transducer was moved over the surface.

IMI/NRC has also demonstrated that this technology could be used not only for inspecting fabricated parts but also for inspecting an aircraft during a maintenance operation. Fig. 6 shows the laser-ultrasonic C-scan image of the horizontal stabilizer of a CF-18 airplane. Inspection was performed with no surface preparation in a maintenance hangar on a plane in flying conditions.

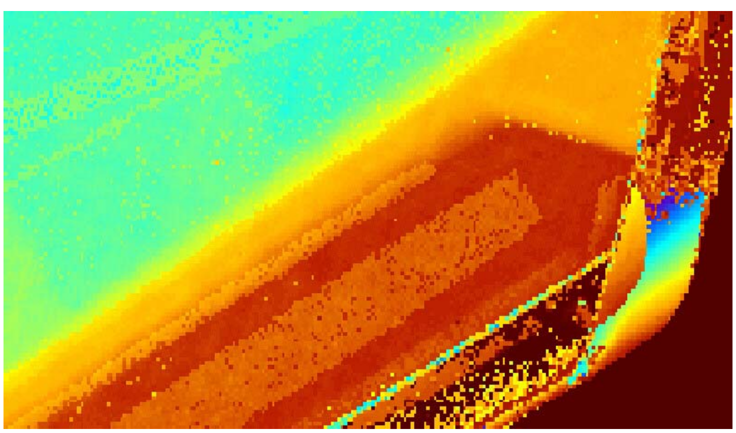

Figure 6. Laser-ultrasonic C-scan image of part of the horizontal stabilizer of a CF-18 airplane in undismantled and ready for take-off conditions. One will notice that, unlike conventional water jet ultrasonics, laser-ultrasonic allows scanning to the very edge of the part.

If much larger areas have to be inspected or for complete flexibility of access all around a given stationary part, the generation unit that houses essentially the generation laser could be mounted at the end of the arm of a gantry robot (with 3 translation axis and one rotation axis in addition of the optical scanning mirror). Such a system has been implemented by UltraOptec for the US Air Force McClellan base. The systems presently in use at Lockheed Martin while having several distinguishing features with respect to the system assembled for the US Air Force make however use of the same concept of a generation unit mounted on a gantry robot.

The on-line wall thickness gauging of seamless tubes follows from collaboration between IMI/NRC and the Timken Company with support of the US Department of Energy. The gauge has now measured reliably since its deployment nearly a million tubes. The use of laser-ultrasonics in this case follows from the need of a sensor for measuring at elevated temperature right on the production line the wall thickness and eccentricity. Since the system has to operate in a severe industrial environment, it was made of essentially two units, an environment controlled cabin and a measuring head on top of the line linked by an umbilical cord containing optical fibers for transmission of the generation and detection laser beams and for bringing the scattered light to the interferometer. The cabin houses the lasers, the confocal Fabry-Perot interferometer, control electronics, processing and display data computers. This system also includes a fiber-coupled pyrometer to measure tube temperature and a fiber-coupled coordinate measuring system to determine the measuring locations on the passing tube in rotation and to provide full thickness mapping. A picture of the measuring head on top of the line and above a passing tube is shown in Fig. 7. It was also found that the system could provide more than thickness information such as a measurement of the austenitic grain size by proper analysis of ultrasonic attenuation [6].

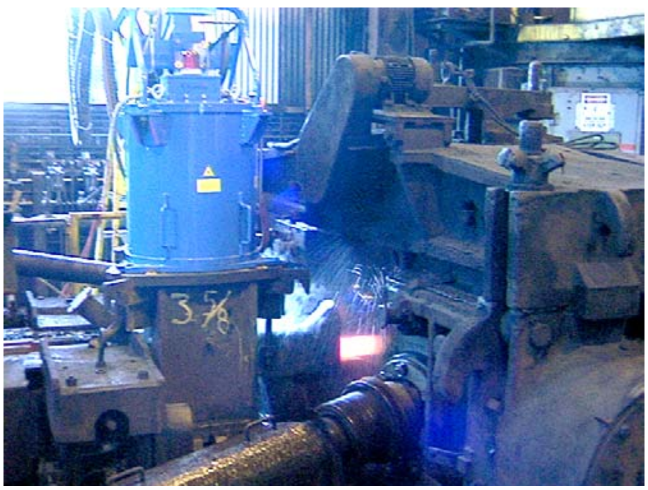

Figure 7. View of the inspection head located on-line measuring a tube being processed.

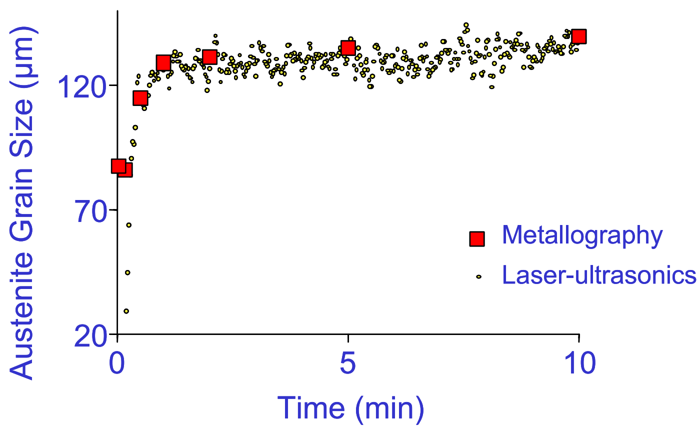

Figure 8. Laser-ultrasonic “metallography”.

Other potential industrial applications: We have presented two applications of laser-ultrasonics that have made the transition from laboratory to industry. Many other applications are potential for industrial use and are at various stages of development. Among those, the application to the characterization of hot metals during processing comes first. As noted above with respect to the laser-ultrasonic tube thickness gauge, laser-ultrasonics could be used to measure the grain size of steel in the austenitic phase. Fig. 8 shows an example of this “laser-ultrasonics metallography”, in which grain size determined by analysis of ultrasonic attenuation and grain size measured by conventional metallography after quenching are compared. This data was obtained by heating the steel sample in a Gleeble thermal simulator [5]. Laboratory use of laser-ultrasonics with such a simulator as well as on-line application appears presently near commercialization. It should also be noted that laser-ultrasonics could provide on a metal processing line, at the hot stage (hot rolling) or at lower temperature near finishing (cold rolling, annealing) further information such as texture (or anisotropy), distribution between various phases, degree of recrystallisation and information on the mechanical properties. Laser-ultrasonics has been in particular tested on a finishing line by IMI/NRC under support of the American Iron and Steel Institute with the purpose of measuring these properties.

Other potential industrial applications of laser-ultrasonics include the detection of degradation of metallic structures, such as fatigue cracking, stress corrosion cracking and corrosion thinning in airframes. There is also definite potential for measuring on-line the mechanical properties of a paper web and its tension. The detection of defects at a smaller scale (e.g. on chips or electronic boards) has also been explored and is an application well adapted to laser-ultrasonics by the capability of the technique to provide high frequency ultrasonic testing without water coupling.

Conclusion: We have presented an overview of the basics and of the various technological aspects of laser-ultrasonics. We have outlined the various principles and discussed the phenomena involved in laser generation and detection. We have also presented the advantages and drawbacks of this technique, particularly in comparison with conventional piezoelectric-based ultrasonics. Several of those are linked to the basic characteristic of laser-ultrasonics, which is the use of light as a means for ultrasound emission and detection. Light allows ultrasonic testing without contact and at a distance, thus making possible a wide range of high temperature applications, but sensitivity is on the other hand dependant upon the number of detected photons, which in turn could require a special high power laser for detection. Many advantages and drawbacks of laser-ultrasonics are also linked to the fact that the material is actually the emitting transducer. This distinguishing feature allows probing more easily parts with complex shapes but may lead to several limitations depending upon the material, such as very weak emission or material damage. Detection interferometers well adapted to industrial applications have also been described, including the confocal Fabry-Perot and the two-wave mixing photorefractive interferometer, which is expected to find a broader use, displacing the confocal Fabry-Perot.

A third feature of laser-ultrasonics that has been noted is the complexity of the technique that includes usually two lasers and a detection interferometer. This makes it generally a high cost solution, but in spite of that, it turns out to be cost effective for several applications and we have described the application to the inspection of polymer-matrix composites and to the wall thickness measurement of hot steel tubes during processing. Other potential applications that are at various stages of advancement have also been outlined. In spite of the successes, which show that this technology has really a practical impact and is not simply a laboratory curiosity, efforts should continue to improve its performances and to find ways to diminish its implementation costs.

References:

1. J.-P. Monchalin, “Laser-ultrasonics: from the laboratory to industry”, in *Review of Progress in Quantitative Nondestructive Evaluation*, vol. 23A, eds. D. O. Thompson and D. E. Chimenti, AIP Conference Proceedings, New-York, 2004, pp. 3-31.
2. C. B. Scruby and L. E. Drain, *Laser-Ultrasonics :Techniques and Applications* , Adam Hilger, Bristol, UK,1990.
3. A. Blouin, L. Carrion, C. Padioleau, P.Bouchard, J.-P. Monchalin, “Single-frequency pulsed laser oscillator and system for laser-ultrasonics”, WCNDT 2004, these proceedings.
4. D. Lévesque, A. Blouin, C. Néron, and J.-P. Monchalin,“Performance of ultrasonic imaging with frequency domain SAFT (F-SAFT)”, WCNDT 2004, these proceedings.
5. S.E. Kruger, A. Moreau, C. Bescond and J.-P. Monchalin, “Real-time sensing of metallurgical transformations by laser-ultrasound”, WCNDT 2004, these proceedings.
6. G. Jeskey, R. Kolarik II, E. Damm, J.-P. Monchalin, G. Lamouche, S. E. Kruger and M. Choquet, **“**Laser ultrasonic sensor for on-line seamless steel tubing process control**”,** WCNDT 2004, these proceedings.