Development of a full fiber-coupled laser ultrasound robotic system using two-wave mixing 1064 nm detection and 532 nm YAG generation

Jean-François Vandenrijt [a], Dimitrios Kokkinos, Cédric Thizy, Fabian Languy,
Juan Felipe Simar and Marc P. Georges [b]

Centre Spatial de Liège, Université de Liège, Liege Science Park, B-4031 Angleur (Liège), Belgium

[a]Corresponding author: jfvandenrijt@ulg.ac.be
[b]mgeorges@ulg.ac.be

Abstract. An all-fibered laser ultrasonic system for complex shape composite parts is presented. It is based on two-wave mixing detection and a long pulse laser working at 1064 nm and generation by a fibered YAG Q-switch laser working at 532 nm. A compact optical head combining both beams is interfaced to a robot system for scanning. Some practical issues of this system are studied.

INTRODUCTION

Laser ultrasonics (LU) [1,2] is an interesting technique for the inspection of composite structures with complex shapes. The wider use of composite materials in the aerospace industries induces intensive research on adapted nondestructive inspection techniques. Ultrasonics is widely used in industry but requires either direct contact with the part inspected or to work at distance in water tank. LU offers the advantage that no contact or couplant is needed with the inspected part, and difficult to access points can be accessed by laser beams at distance. LU usually combines two principles. The first one is the generation of an ultrasound wave at distance by a laser [2]. The latter insulates briefly the material on its surface which generates the ultrasound through thermoelastic nondestructive effect or through the destructive ablative effect. For industrial application on composites, the second one has to be avoided and the laser and its parameters must be correctly chosen to work in thermoelastic regime. The second principle is the detection of ultrasound at distance by an interferometric system with a large optical etendue allowing working with potentially scattering surfaces [2]. Various principles have been presented in literature. In any cases, a laser beam is sent on the surface to be probed and the ultrasound wave travelling to the surface will perturb the phase of the laser probe beam. These variations can be measured through a passive interferometer, like the confocal Fabry Perot (FP) [2], or through adaptive interferometers based on the two-wave mixing (TWM) in photorefractive crystals [2].

Our works aim at developing a robotic system addressing medium composite parts provided by aerospace industries. These parts have generally a square meter size and complex shapes [3]. Industrial companies which are part of this project produce curved or assembled parts fully made of carbon fiber reinforced polymers (CFRP). Economic interest of LU has been demonstrated for high end military aircraft composite parts and the question obviously arises in the civilian industries, moreover distinguishing medium and large parts, respectively smaller or larger than the square meter (to fix ideas) [5]. Large parts could be scanned at high speed with high repetition rate laser (a few kHz), but this requires huge efforts in laser for both the generation and detection systems. It is now known that LU is not the cost-effective solution kept by major industries for inspection of large composite parts. Despite the efforts and technological breakthrough of LU equipment manufacturers in the last decade, other techniques made noteworthy advances. For example SAUL [6] can address complex shaped composites and simply consists of post-processing classical ultrasonic data. However, some place remains for demonstrating the cost efficiency of LU for medium-sized parts as considered in the project.

In this project our aim is to develop a medium cost industrial LU system which can address medium size complex shaped CFRP parts. The idea is to have a flexible lightweight optical head which couples both the generation and detection laser beams. This optical head is interfaced on the flange of a 6-axis robot system that can be programmed to follow paths on complex structures. An obvious way to have flexibility is to work with fibered laser beams, with all laser and detection equipment located at a remote location, a few meters away from the inspection working area. However one must be careful in developing fibered system in term of mechanical environment and interfaces of the fibers because this can impact the quality of beams at the output of the fiber.

In this paper, we make use of a commercial detection system by Tecnar, including TWM detection and a long pulse laser at 1.06 µm) and which is already fiber-coupled. We will combine it to a YAG Q-switch 532 nm fiber-coupled system. We will first explain the choice of these systems. Then after we present the development of the combined optical head which is further interfaced to the robot. Some practical issues are analyzed like the distance of working and incidence angle to the surface.

CHOICE OF GENERATION AND DETECTION LASER WAVELENGTHS

Since we want to combine the generation and detection laser beams, a common way is to use two separate wavelengths and to incorporate a dichroic beamsplitter which transmits one wavelength and reflects the other one. The detection systems available on the market work either in the near infrared (1.06 µm or 1.55 µm) or in the green (532 nm). Since we want a system with sufficient peak power to address black composite surfaces, while cost effective, we considered the PDL laser proposed by Tecnar Company with the TWM detection probe (based on GaAs photorefractive crystal). This laser works at 1.06 µm and is based on an MOPA configuration. This system is already full fiber-coupled and is delivered with a 10 meter robust flexible conduit which guides the different beams from remote sources and detectors on one side to a small lightweight optical probe on the other side.

Concerning the generation, we needed to choose a cost-effective laser that is fiber-coupled and has a different wavelength than the detection. Literature shows that the efficiency of generating longitudinal waves in graphite/epoxy depends on the optical penetration depth, itself function of the wavelength [7]. Furthermore, short pulses (in the ns or tens of ns range) are required. TEA CO_2 lasers (10.6 µm) are generally used in most LU commercial systems because they industrialized and reliable. However there is no optical fiber technology for such pulsed CO_2 lasers and light is brought to the inspected part via mirrors in an articulated arm, which does not offer the flexibility of optical fibers. The best wavelengths for graphite/epoxy are small bands between 3.3 and 4 µm, which can be found in OPO lasers [8]. In principle they can be coupled to fibers but not commercial and cost-effective solution is offered at the moment and must constitute a development in itself. Therefore despite the great hopes of this solution, we discarded it. The other remaining wavelengths are those provided by YAG Q-switched lasers, either at 1.06 µm or 532 nm. We discarded 1.06 µm because it corresponds to the detection laser wavelength and we decided to work at 532 nm. The advantage of this wavelength is that some companies offer fiber-coupled YAG Q-switched laser with sufficient energy to be used for generation (a few tens of mJ). The laser we considered is the Ultra 50 from Quantel which is initially coupled to a 3 meter optical fiber interfaced through an SMA connector to the laser head. The laser works at 30 Hz repetition and allows 30 mJ at the output of the fiber. Because of this repetition rate, the repetition rate of the detection system was also set to 30 Hz.

DEVELOPMENT OF THE OPTICAL HEAD

Figure 1 shows an overview of the whole setup. The PDL unit incorporates the long pulse laser which is split in two beams by a beamsplitter (BS). One beam is sent into the pump beam fiber (PBF) and constitutes the pump beam for the photorefractive crystal (PRC) of the TWM detection unit. The second beam is directly sent to the optical head. Figure 2 gives a detail sketch of the optical head which incorporates the detection optical probe provided by Tecnar. The latter contains the detection laser fiber (DLF) and the output beam is further collimated and passes through a frontal lens (FL) which refocuses the illumination beam at a distance of 20 cm. The light reflected by the object enters the optical probe through FL and is launched into the signal beam fiber (SBF) which transports the signal beam directly to the TWM detection unit (figure 1). In the TWM unit, the signal beam is mixed in the PRC with the pump beam. A differential photodetector (PD) module is placed in the signal beam after the PRC. The PDL laser allows long pulses of 80 µs duration with a repetition rate of 30 Hz and peak power of 300 W.

The generation laser is a Ultra 50 from Quantel which delivers 30 mJ at the output of a 3 m fiber specially developed by Quantel. We used this fiber (GLF) to develop the optical head which is shown in Figure 2 and which combines the detection and generation beams. Later the 3 m fiber has been replaced by a new 10 m long fiber no longer developed by Quantel but by Ceramoptec, with the same numerical aperture and core diameter as the former. This allows having the same length than the Tecnar flexible conduit and to attach the new GLF fiber to it and place the generation laser unit at the same remote location than the PDL unit. A computer controls the different units of the setup. The analog differential signal of the TWM unit is digitized by a high speed digitizer onboard the computer.

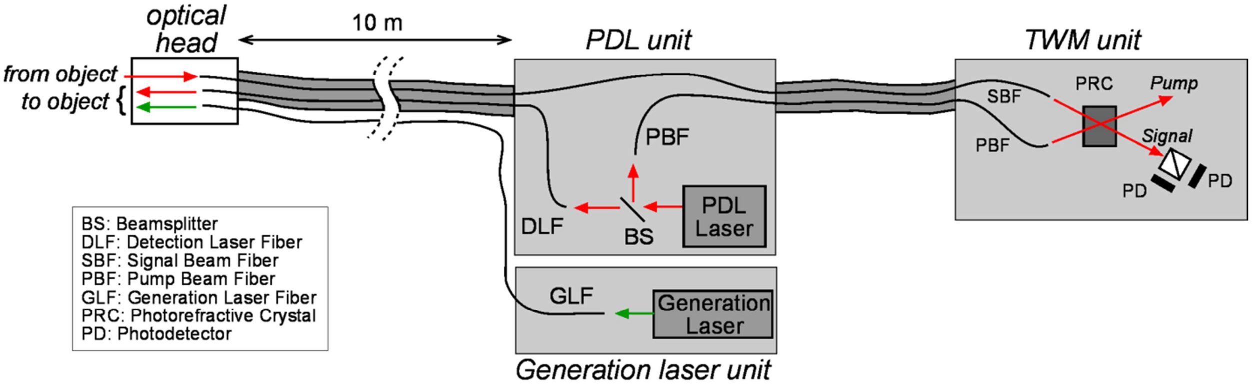

FIGURE 1. Overall scheme of the equipment

Figure 2 shows a detail of the optical head which combines the green generation laser beam (GLB) and the detection probe. A dichroic beamsplitter (DBS) transmits the illumination and signal beam (SB) to and from the probe to the object. The GLB is made incident to the same object point via a folding mirror M and the DBS which reflects the 532 nm wavelengths. The lens L position allows selecting the generation beam diameter. Although it is shown focused on the object, the best configuration we found for the GLB is a collimated beam. Indeed a focused beam induced damage in surface of the samples. All results shown in this paper are then obtained with a collimated GLB with a diameter of typically 10 mm.

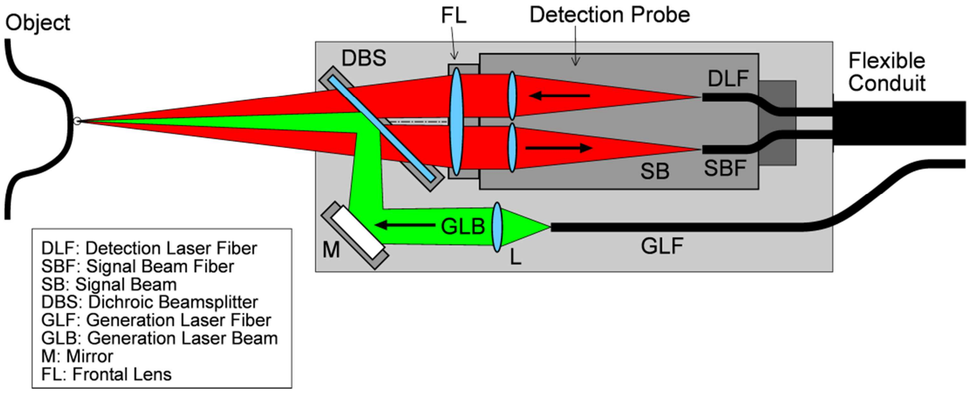

FIGURE 2. Sketch of the laser ultrasound optical head

ANALYSIS OF SOME PRACTICAL ISSUES

Based on the concept shown in Figure 2, a prototype of the optical head has been built and interfaced on the 6-axis robot (ABB IRB-2600), as is shown in Figure 3(a) and (b). A problem that could arise with fiber is a change in modes that are transmitted through the fiber, especially when the fiber curvature changes during the robot movement. With the 3 m fiber, the pattern at the output of the fiber was quite homogeneous and not too sensitive to movements of the fiber. However, a 10 m fiber was considered for the final implementation of the system, as already said earlier. Although the fiber has similar properties than the previous one, it is more sensitive to curvature changes and a mode looking like TEM01 appears, except that one lobe is brighter and the other one is darker. Although the generation beam does not damage the CFRP samples, the apparition of a locally brighter spot could exceed the ablation threshold and damage the inspected part. Also the generation performance could be affected. In order to see these potential effects, we have performed the experiment shown in Figure 3(b). A CFRP coupon was firmly attached to the optical head at the best position of focus of the detection probe. Then the robot has moved the optical head all along the optical table used for the inspection (1.8 m x1.2 m) and in position vertical, as in Figure 3(a). The travel path is shown in blue in Figure 4(a), where the orange spot represents the location of the robot arm basis. During the movement the generation and detection system were continuously working. A-scans (Figure 4(b) are captured during the whole movement and compiled as B-Scan in Figure 4(c). It can be observed that the first peak amplitude is higher in some parts of the trajectory which corresponds to positions where the GLF undergoes an important change of orientation. Figure 4(d) shows the amplitude of the BW echo taken on the line shown in Figure 4(b). It can be observed a slight increase of the BW echo too and which corresponds to increase in the first peak. At the end of the travel we have not seen any degradation on the focus point of the CFRP coupon.

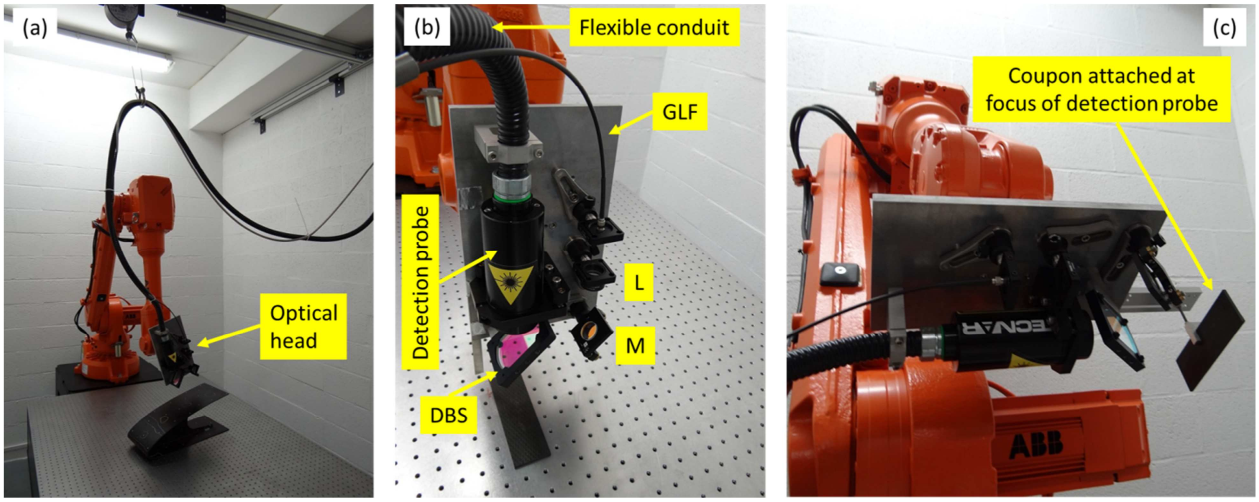

FIGURE 3. (a) global view of optical head attached to robot, (b) detailed view of the optical head, (c) CFRP coupon attached to the optical head for testing behavior of signals during scan.

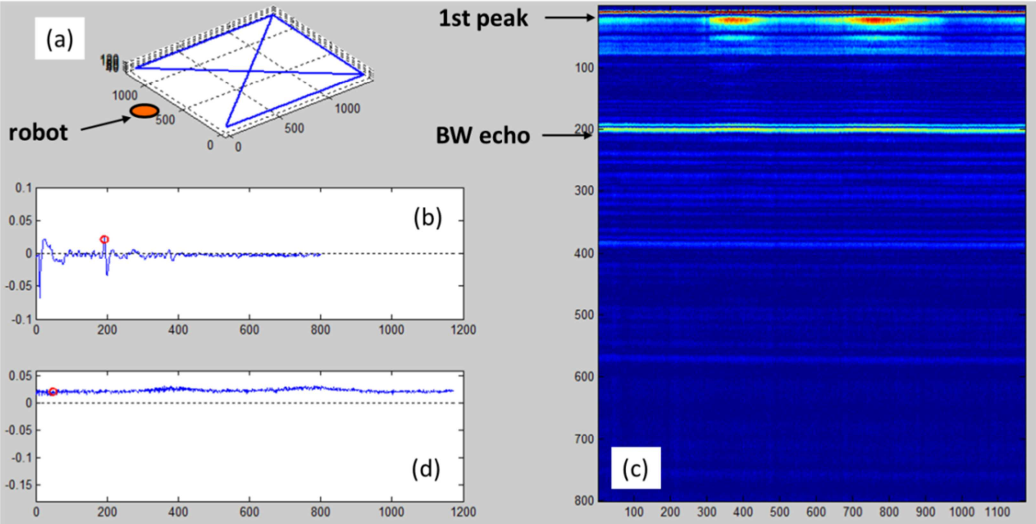

FIGURE 4. Investigating effect of generation fiber curvature change on LU signal during scan: (a) travel of the robot, (b) typical A-scan, (c) B-scan along the travel, (d) backwall echo along the travel.

Other important practical issues are the working distance and the angular tolerance. Most of the curved industrial samples we intend to inspect in the project are CFRP made by the RTM technique. Therefore the coupons used for investigations shown here have the same characteristics: 0-90° geometry with 12 plies of dry tissue 5H satin (ref G026), further impregnated in mold with epoxy resin RTM-6. The first layer is made of epoxy.

For these samples we have studied the amplitude of first and echo peaks in function of the distance and found the curve shown in Figure 5 for the first peak. The echo amplitude is proportional to the first peak amplitude, as is shown in Figure 5(b) on data taken from the same set as Figure 5(a).

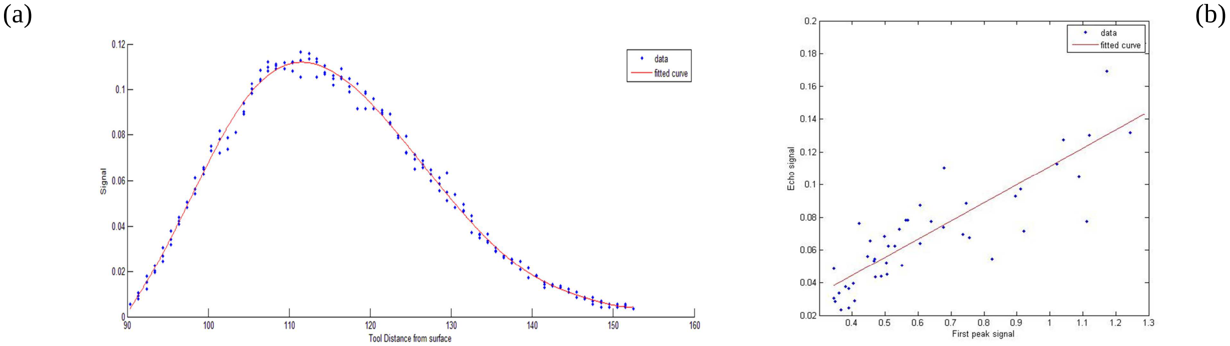

FIGURE 5. Effect of the working distance on the signal: (a) first peak amplitude in function of distance to front end of optical head, (b) amplitude of echo in function of amplitude of first peak

LU is in principle largely tolerant to the incidence angle to the normal of the surface. Most composites we need to inspect exhibit non negligible specular reflectivity. This requires working close to the normal incidence for capturing the highest amount of light in the detection probe. In fact, the problem is not simple since most of our samples exhibit both specular and scattering reflectivity. Therefore, studying these issues is strongly dependent on the samples characteristics. Figure 6(a) shows the normalized amplitude of first peak and back-wall echo in function of the angle. Data are fitted by high-order polynomials. Figure 6(b) shows the ratio between first peak and echo amplitude in function of the angle, which can be considered as constant versus the incidence angle.

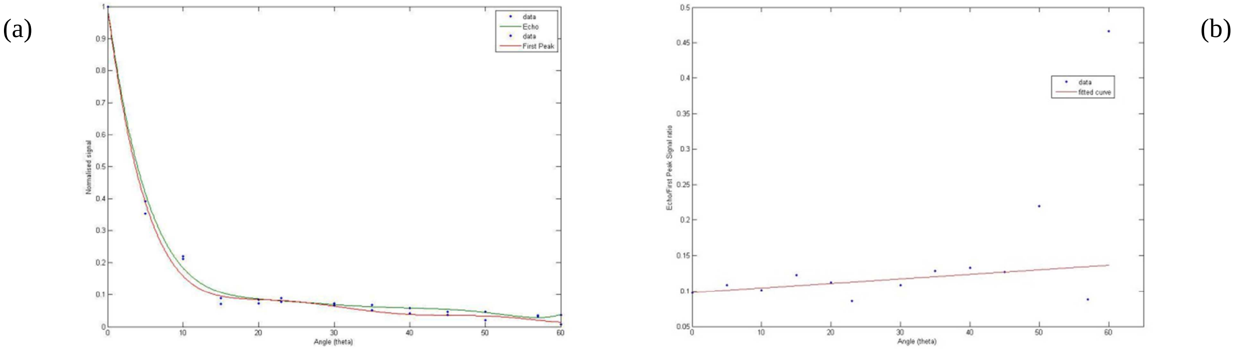

FIGURE 6. Effect of incidence angle on the signals: (a) normalized amplitude of first peak and echo in function of the angle, (b) Ratio between first peak and echo in function of the angle of incidence.

DISCUSSION - CONCLUSION

We have shown the development of a fully fiber-coupled laser ultrasound system for inspection of curved shape composite parts. The detection system is a TWM probe coupled to a PDL laser working at 1.064 nm made by Tecnar. It incorporates a flexible conduit with optical fibers between the detection optical probe and the different remote units of the system containing the laser and control electronics. The generation laser is a fiber-coupled YAG Q-switch laser provided by Quantel. The optical detection probe and the generation laser fiber are coupled inside an optical head. The latter is interfaced on a 6-axis robot arm for scanning complex parts. Some practical issues were investigated. First we considered the effect of change in curvature of the generation fiber during the robot movement. We observe some changes in the laser beam pattern exiting the fiber, which has an effect on signals amplitudes. This does not impact the use of the time-of-flight technique. However, if we want to work in amplitude, we need more investigations to analyze if the ratio between the first peak and the echo is well kept constant. Other practical issues are the distance of working and the incidence angles. This is of importance if one wishes to relax the constraint imposed on the robot scanning. However, these aspects are related to the reflectivity of the samples (specular/scattering) which themselves are strongly related to the composition and surface properties. Here we considered coupons that are typical to larger industrial parts we will investigate in the future.

Currently, deeper investigations on the potential damaging of surface or subsurface will take place. A slight yellowing sometimes appears but it is not clear if this is a simple change of epoxy color or true damage. Furthermore, we currently investigate the scanning of complex parts of one square meter maximum dimension.

ACKNOWLEDGMENTS

This work is performed in the SKYWIN Wallonia project "ECOTAC", contract Nr 6490. Industrial and university partners of the project who were involved in production of coupons and samples are acknowledged. The authors would like to thank Dr Marc Choquet from Tecnar Company for fruitful discussions, as well as the staff of the Centre Technologique en Aérospatiale (CTA) from St-Hubert (Quebec, Canada), for fruitful discussions.

REFERENCES

1. C.B. Scruby and L.E. Drain, *Laser Ultrasonics. Techniques and Applications* (Adam Hilger, Bristol, New York, Philadelphia, 1990)
2. J-P. Monchalin, "Laser-ultrasonics: from the laboratory to industry," *Quantitative Nondestructive Evaluation*, ed. by D. O. Thompson and D. E. Chimenti (American Institute of Physics Conference Proceedings, 2004), Vol. 700, pp. 3-31
3. M. Kalms, O. Focke andC.von Kopylow, "Applications of Laser Ultrasound NDT method on Composite structures in Aerospace Industry," *Proceedings of 9th Int'l Symposium on Laser Metrology*, ed. By Chenggen Quan, Anand Asundi (SPIE, 2008), Vol. 7155, 71550E
4. A. Blouin and J-P. Monchalin, "Detection of ultrasonic motion of a scattering surface by two-wave mixing in a photorefractive GaAs crystal," Appl. Phys. Letters **65**, 932–934 (1994).
5. H. Voillaume, D. Simonet, C. Brousset, P. Barbeau, J.-L. Arnaud, M. Dubois, T. Drake, M. Osterkamp, "Analysis of commercial aeronautics applications of laser ultrasonics for composite manufacturing," *Proceedings of 9th European Conference on Nondestructive Testing*, paper We.1.1.1 (2006), available at http://www.ndt.net/article/ecndt2006/doc/We.1.1.1.pdf
6. D.L. Hopkins, M. Brassard, G.A. Neau, J.-N. Noiret, W.V. Johnson and L. Le Ber, "Surface-Adaptive Ultrasound (SAUL) for phased-array inspection of composite specimens with curved edges and complex geometry," *Review of Progress in Quantitative Nondestructive Evaluation: Vol. 32*, ed. by D. O. Thompson and D. E. Chimenti (American Institute of Physics Conference Proceedings, 2013), Vol. 1511, pp. 809-816
7. M. Dubois, P. Lorraine, B. Venchiarutti, A.S. Bauco, R. Filkins, T. Drake and K. Yawn, "Optimization of temporal profile and optical penetration depth for laser-generation of ultrasound in polymer-matrix composites," *Review of Progress in Quantitative Nondestructive Evaluation: Vol. 19*, ed. by D. O. Thompson and D. E. Chimenti (American Institute of Physics Conference Proceedings, 2000), Vol. 509, pp. 287-294
8. M. Dubois, S.-Y. Chuang, P. Lorraine, T. Drake, K. Yawn and R. Filkins, "Progress on the development of an advanced laser ultrasound generation source for inspection polymer-matrix composites," *Review of Progress in Quantitative Nondestructive Evaluation: Vol. 21*, ed. by D. O. Thompson and D. E. Chimenti (American Institute of Physics Conference Proceedings, 2002), Vol. 615, pp. 300-307