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INSPECTION OF COMPOSITE MATERIALS BY LASER GENERATION AND DETECTION OF ULTRASOUND

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ABSTRACT

Laser-ultrasonics, a technique that uses lasers for the generation and detection of ultrasound circumvents a number of limitations associated with conventional ultrasonics and offers an attractive and even unique method for inspecting polymer-matrix composite materials. The technique operates without contact and at a distance of several feet or meters from the inspected part. The normalcy requirement of classical ultrasonics is eliminated, since generation occurs at the surface of the material and detection is performed directly off its surface, so parts with complex geometries can be more easily inspected.

In this paper, we describe the system that has been developed, which comprises a high power short pulse laser for ultrasound generation by thermoelastic effect, a long pulse receiving laser for detecting ultrasound off the surface, a demodulating interferometer, an optical scanner and a data analysis system for data acquisition and processing. Following many tests performed on various composite parts in the laboratory, we present demonstration tests performed with this system on a CF-18 aircraft in a maintenance hangar. These tests show that the technology is now sufficiently advanced to be readily applicable to the inspection of detached components following manufacturing and for the in-service inspection of aircrafts.

1 - INTRODUCTION

Polymer-matrix composite materials are finding increasing use in aeronautic and aerospace structures. These materials are found more and more in load bearing components, which in turn requires their integrity to be fully evaluated by nondestructive inspection. This applies to newly manufactured parts that can be flawed from improper manufacturing procedures and to parts that have been in service on an aircraft as well, since additional flaws could have occurred and old existing flaws could have grown and become more severe. Flaws that are found in these materials include porosity and foreign inclusions, which originate during fabrication and delaminations between plies, which can be produced during fabrication or can be

caused by the impact of foreign objects on the structure. In the case of adhesively bonded structures, including honeycomb structures, disbonds could also occur, either produced during fabrication or following an impact.

Ultrasonics has been recognized as a superior technique for detecting delaminations and can also be used to detect foreign inclusions and assess porosity ¹. The ultrasonic waves are usually generated and detected by piezoelectric transducers and coupled to the inspected part by direct contact or water. Piezoelectric transduction of ultrasound requires proper orientation of the transducer with respect to the surface when the transducer is used in the pulse-echo mode, which is of most interest since it requires single-sided access and provides flaw depth information. This valuable information cannot be obtained from a transmission mode with emitting and receiving transducers located on opposite sides of the inspected part. Precise orientation requirements follow from the fact that the transducer is a phase sensitive device that emits or receives from its whole surface. Angular tolerance is a few degrees or much less if the amplitude of the ultrasonic echoes has to be precisely monitored. Consequently the inspection of curved or contoured parts requires a surface contour following device, which will be very complex and difficult to implement, especially in the case of acute discontinuities of the surface. Such a device necessarily based on robotics and mechanics is also likely to have limitations in scanning speed, wear and maintenance.

These limitations are eliminated by laser-ultrasonics that uses lasers for the generation and detection of ultrasound at a distance ². In laser-ultrasonics, the source of ultrasound is located at the surface of the material and detection of ultrasonic motion is performed off the same surface, which eliminates the normal incidence requirement of conventional ultrasonics. To explain further this unique capability of laser-ultrasonics, we consider a simple curved part, sketched in cross section in Figure 1. As shown in Figure 1, when the two lasers, one for generation and the other one for detection, impinge at the same location on the surface of the curved part a train of ultrasonic echoes is generated and then detected. As shown in Figure 1, generation produces essentially an ultrasonic wave propagating normal to the surface. When the two laser beams are scanned across the surface by using the rotating mirror, the ultrasonic echoes are still observed, even when the optical beams are far off the normal to the surface. Since there is no need to determine the shape of the inspected part to follow a complex contour, laser-ultrasonics has the capability to be much faster than any advanced robotic system, which can eventually be developed. In the case of flat or gently contoured parts, since the only moving part is the scanning mirror, laser-ultrasonics has also the potential to be much faster than any conventional system.

We will first describe below the system that has been developed, then present the results obtained on various composite parts and the demonstration tests performed on an actual aircraft in a maintenance hangar.

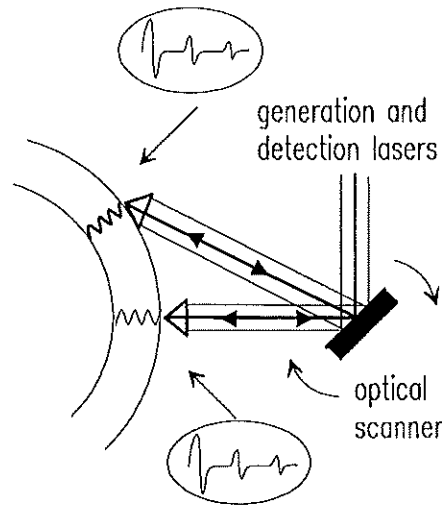


Figure 1 : Laser-ultrasonic inspection of a curved part. The two arrows indicate the generation and detection laser beams, which are shown at two locations, determined by the optical scanner. The inserts indicate schematically the ultrasonic echoes, which can, for example, be observed on an oscilloscope.

2 - DESCRIPTION OF THE SYSTEM DEVELOPED FOR COMPOSITE MATERIAL INSPECTION

The laser-ultrasonic system is made of two units, a detection unit and a generation unit, linked by optical fibers and is sketched in Figure 2. The generation unit comprises a TEA CO₂ laser for ultrasound generation, optics for coupling colinearly the generation and detection laser beams and large size optics for collecting the scattered light from the surface of the inspected part. In addition, a two-axis mirror scanner, the same size as the collection optics, is used for scanning across the part. The generation spot is about 5 mm (~0.2"). Light from the CO₂ laser penetrates below the surface of the material, resulting in distributed absorption³. This causes a constrained ultrasonic source and consequently the emission of a longitudinal wave normal to the surface.

The generation unit is linked by optical fibers to the detection unit comprising the detection laser and the demodulating interferometer, which is a confocal Fabry-Pérot⁴. One fiber is used to transmit light from the detection laser, while the other one is used to bring scattered light to the interferometer. Both fibers are approximately 15 meters long (~ 45') and shielded. The detection laser is based on Nd-YAG technology, provides long pulses (~ 50 μs long) at the repetition rate of 100 Hz, is highly stable in frequency and has high peak power (~ 2 KW). The confocal Fabry-Pérot is one meter long and has an optical bandwidth of ~ 8 MHz. A PC computer controls the optical scanner and houses a sampling card for digital acquisition of the A-scans. Specially developed imaging software is then used to display C-scans and B-scans.

The system we have developed operates at a distance of ~ 1.5 m ($\sim 5'$) between the surface and the optical scanner and can scan from a fixed system position an area of ~ 1.8 m x 1.8 m ($\sim 6'$ x $6'$) or even larger depending upon the scattering properties of the surface⁵.

Such a system is now commercially available. In more recent developments, a system which allows the scanning of much larger surfaces was assembled by UltraOptec for the US Air Force. By mounting the generation unit at the end of the arm of a gantry displacement system, parts of the size of a wing can be inspected. This system includes also a distance measuring device to determine at the same time, during the scan, the shape of the part. This system is associated to a 3-D imaging software which allows to visualize part shape and ultrasonic results at the same time.

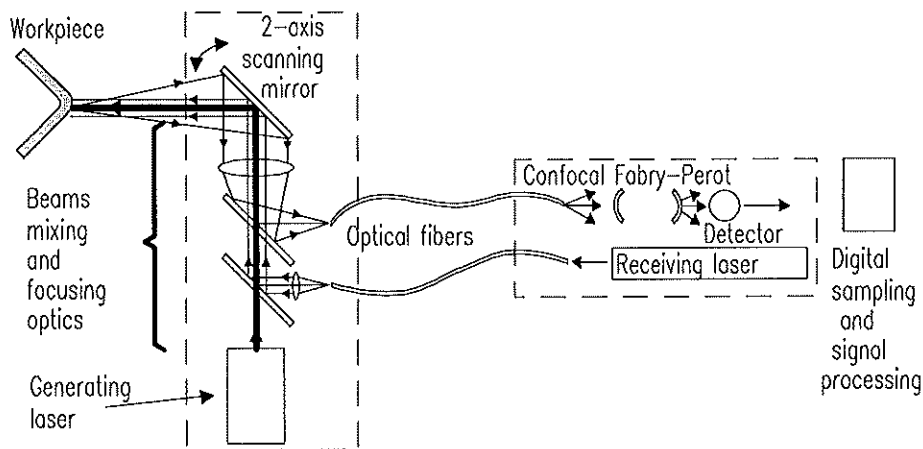


Figure 2 : Schematic of the system developed for composite materials inspection

3 - APPLICATION TO THE INSPECTION OF COMPOSITE PARTS

The use of the system described above (Fig. 2) has been demonstrated on parts of more than one meter across and on a large variety of smaller parts with acute curvature⁵⁻⁷. These parts included laminates of various thicknesses (from a few plies to a thickness of more than one inch), made of various materials (graphite epoxy, kevlar epoxy, glass epoxy), with a bare surface or a painted surface. Specimens with slopes and corners and parts with U-shape, T-shape and sine wave cross sections were also tested. The technique was also demonstrated on various honeycomb structures. Defects such as porosity, disbonds, delaminations and impact damage can be detected. Figure 3 shows the detection of the delaminations caused by an impact.

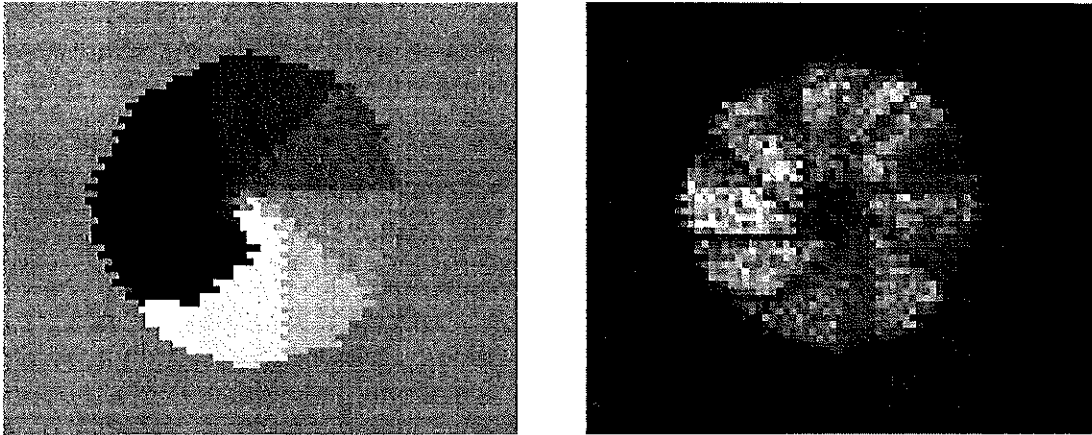


Figure 3 : Laser-ultrasonic C-scan image of the damage produced by an impact on a graphite-epoxy laminate. Left : time-of-flight C-scan, right : amplitude C-scan.

4 - INSPECTION OF A CF-18 PLANE IN A MAINTENANCE HANGAR

These tests were conducted at the maintenance facility for CF-18 fighters of Bombardier Inc./Canadair Defense System Division, located at Mirabel, Québec, within the airport area ⁸. The test plane had already been serviced and inspected according to the prescribed maintenance procedure (using in particular manual ultrasonic inspection). It was in a flying condition and fully loaded with fuel. It had not been the object of any particular preparation for laser ultrasonic inspection.

The installation of the system in the hangar next to the plane is shown in Figure 4. The prototype system used for these tests, because of the configuration of its scanner, which directs the beams essentially in the forward direction, allows only direct scanning of vertical or near vertical surfaces. This limitation has been eliminated in the now commercially available system by a different scanner design, which allows direct scanning of surfaces lying either in the front of the unit or in its back, as well as scanning from above or from below the surface. During the tests, near horizontal surfaces, such as those of the wing or of the horizontal stabilizer, were scanned from underneath by adding a large folding mirror set at an angle of $\sim 45^\circ$ to redirect the beams upwards towards the inspected part.

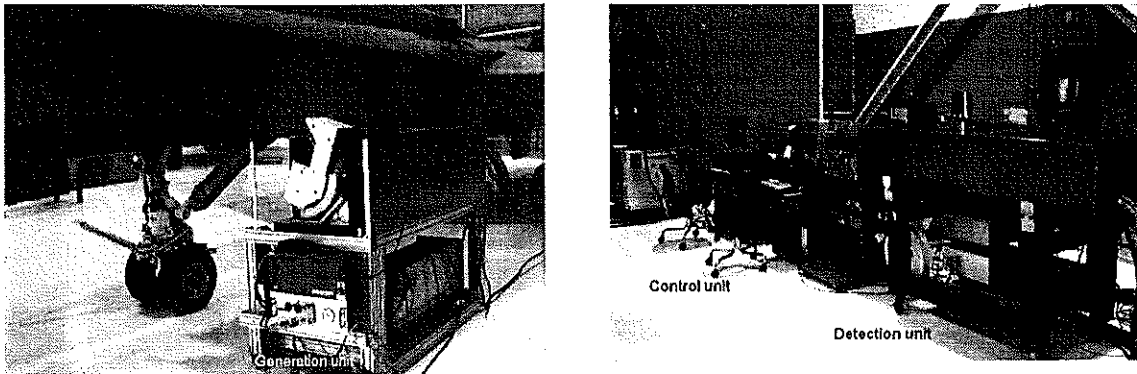


Figure 4: Installation of laser-ultrasonic system next to the CF-18 plane.

All components scanned with the laser ultrasonic prototype were first carefully inspected visually to identify any surface damage prior to the laser-ultrasonic scan. No damage or surface modification due to either the generation or the detection lasers was observed during these tests. Power levels of both lasers were set well below any damage threshold to the paint of the aircraft.

Once the generation unit was properly located, the inspection area was visually determined by using the Helium-Neon tracer beam which is superimposed with the generation and detection beams and by manipulating the optical scanner via the control computer. This allows the definition of a rectangular inspection area on the component. Note that this rectangular area can exceed the dimension of the inspected part (see Fig. 5 below). The collected data was then used to generate ultrasonic images (B-scan and C-scan) of the components by using a software developed by UltraOptec. Various parts of the aircraft fuselage, wing and stabilizer were inspected. We are presenting here, as example, only the results obtained on the horizontal stabilizer, which is a complex composite structure with an aluminum honeycomb core (see Figures 5 and 6 below). As should have been expected, since the plane had gone through complete inspection before our tests, we did not find any important flaw, which would have required a repair. Only a small defect was found, of a size well below the critical size requiring corrective action.

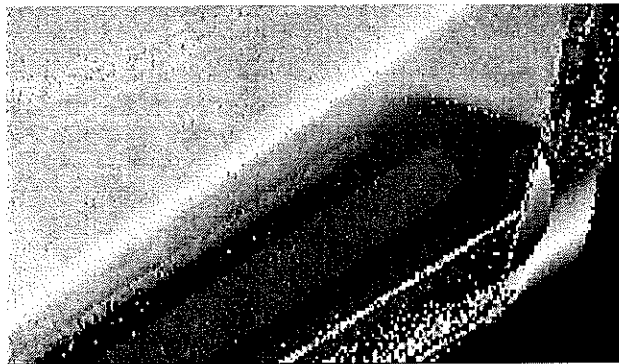


Figure 5: Laser-ultrasonic C-scan image of a section of the horizontal stabilizer near its edge (576 mm x 298 mm).

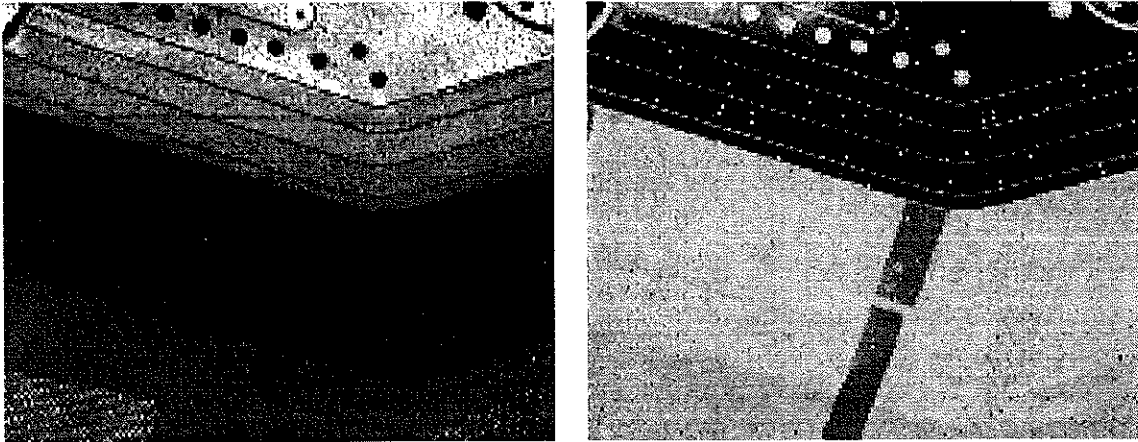


Figure 6: Laser-ultrasonic C-scan images of a section of the horizontal stabilizer (450 mm x 360 mm) near the attachment point to the fuselage. The left image is obtained by gating the signal to conserve only the positive polarity echoes, whereas the right image uses echoes with negative polarity. In these images, one can observe a titanium-composite joint of varying thickness in the upper half. In the left image, one can see the honeycomb structure at the lower left, while on the right image, one can observe a structure that is barely visible in the left image.

5 - CONCLUSION

We have described a pulse-echo laser ultrasonic system that allows us to effectively inspect polymer-matrix composite materials. The use of this system was demonstrated on numerous parts of various shapes, thicknesses and compositions. Its use for service inspection of aircrafts was also demonstrated by inspecting a CF-18 in a maintenance hangar. Such a system is now commercially available and efforts are currently pursued to introduce it to industry. In conclusion, we have developed the laser ultrasonic technology to a point it now appears sufficiently matured to be used for routine inspection of composite parts on the production floor and for the in-service inspection of aeronautic and aerospace structures.

ACKNOWLEDGMENTS

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