PORTABLE AND HYBRID LASER GENERATION / AIR-COUPLED DETECTION SYSTEM FOR NON DESTRUCTIVE INSPECTION

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Abstract: This review presents a portable head instrument, using a hybrid laser generation/air-coupled detection system for ultrasonic non-destructive inspection. The equipment is made of a low-cost Nd:YAG pulsed laser linked to a multimode optic fiber to generate Surface Acoustic Waves (SAW). Instead of a long-pulse detection laser coupled to an interferometer, a small air-coupled ultrasonic transducer is used to perform the detection. A compact probe holder supporting the optical assembly and the air-coupled transducer has been designed, and integrated with an *XY* scanner system to move the probe above the sample. Inspection tests are carried-out on representative samples, and the performances of the portable head are evaluated for surface and subsurface defect detection in aeronautic composite materials.

Introduction: Conventional ultrasonic techniques for Non-Destructive Testing (NDT) of materials manufactured by the aeronautic industry have traditionally relied on systems using contact piezoelectric transducers for both generation and detection. These standard inspection systems, including pulse-echo, through transmission and tandem mode require an immersion medium (usually water), or a coupling agent (gel, mineral oil…) between the sample to be inspected and the piezoelectric transducer. In the aeronautic and aerospace industry, a variety of composite materials (such as water-sensitive, porous or skin-honeycomb structures) do not allow the contact with this coupling medium. To overcome this obstacle and to improve speed inspection, there has been a steady effort to develop alternative NDT methods that are coupling free. These techniques can include thermography [1,2], shearography [3,4] or laser ultrasonics [5,6]. However, each one of these methods present attractive features and drawbacks. For example, laser-based ultrasonic techniques provide a number of advantages such as non contact generation and detection, broad bandwidth, ability to operate on curved and rough surfaces, but remain a complex and very expensive technology. Furthermore, a certain reflectivity of the detection surface is required.

During the last decades, many improvements have been made in the design of air-coupled ultrasonic transducers. These type of transducers has already been investigated in the through transmission mode for NDT of aeronautic composite materials [7,8]. The major drawback is the low signal amplitude, due to the high acoustic impedance mismatch between solid and air (leading to low transmission of ultrasound across the interface). Despite of this, the flexibility of this new technique offers a potential for new compact and low-cost NDT systems.

This paper describes the development of a hybrid portable prototype equipment suitable for surface and subsurface defect detection in metallic and composite materials. This device is based on a low cost pulsed Nd:YAG laser to generate Surface Acoustic Waves (Rayleigh waves) in the thermoelastic regime. Rayleigh wave motion is confined to a layer with thickness equal to about one wavelength [6,9]. This wave mode is always present, and its magnitude is the largest of all the other waves modes: this is because it only propagates over a two-dimensional surface rather than throughout three-dimensional space. To provide flexibility of operation under safety conditions, a high power optical fiber is used to deliver the laser energy onto the testing area. Instead of a long pulse detection laser coupled to an interferometer, a small air-coupled transducer performs the ultrasound detection. Although the bandwidth of air-coupled transducers is narrow compared to the bandwidth of interferometers, the variety of available commercial air-coupled transducers enable to operate in a frequency range between 0.1 MHz and 4-5 MHz. But with high frequencies, the ultrasound attenuation increases significantly in air, so the distance between the transducer and the sample must be reduced, involving difficult alignment.

A probe holder supporting the optical assembly and the air-coupled transducer has been designed, and integrated with an *XY* scanner system to move the probe above the sample. This hybrid system is packaged as a compact NDT equipment, and could be easily transposed for in-service aircraft inspection. The performances of the portable laser generation/air-coupled detection system are evaluated on representative composite samples, and the results are compared with those obtained by other NDT methods.

Equipment: The compact pulsed laser used for the generation of ultrasounds is a Q-swiched *QUANTEL BRILLIANT Ultra* laser. The maximum energy is 45 mJ @ 1064 nm, the repetition rate can be adjusted between 0 and 20 Hz, and the pulsewidth is 8 ns. The Nd:YAG oscillator is coupled to a 1 mm diameter multimode optical fiber (ended with an SMA connector), and a variable optical attenuator is used to adjust the maximum power level that can be delivered onto the sample without damage. In order to concentrate as much as possible the ultrasound energy in the direction of the air coupled transducer, a focusing probe was developed to focus the laser beam into a line. In this way sufficient energy can be deposited without raising the power density so high as to cause ablation, and the wave propagation direction is restricted to be perpendicular to the line. The focusing arrangement is made of a plano-convex lens to collimate the laser beam emerging from the fiber, and a cylindrical lens to focus the beam into the line (about 10 mm x 0.5 mm) at the top surface of the sample. The optical assembly is placed into a stackable lens tube.

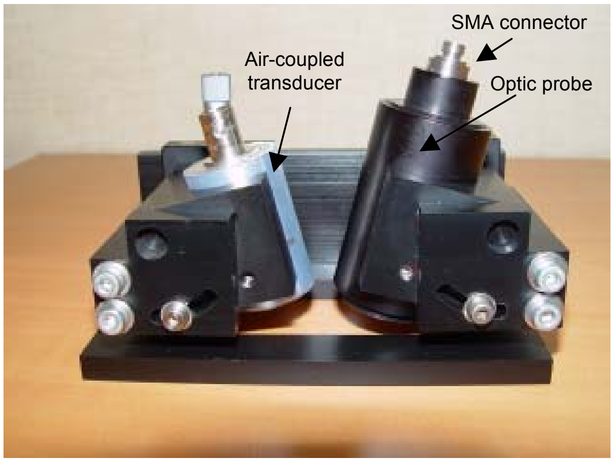

Figure 1: Probe holder

Rayleigh waves propagating in the direction perpendicular to the laser line are detected with the air-coupled transducer placed at few millimeters in front of the optic probe. A panel of 3 *SECOND WAVE* NCU transducers has been evaluated (active diameter: 12 mm, bandwidth centered on 0.5 MHz for NCT55 model, 1 MHz for NCT510 model and 2 MHz for NCT520 model). The probe holder was designed and manufactured for supporting the optic probe, and can be indifferently fitted out with one of the above transducers. Several parameters can be adjusted: distance between laser beam and transducer, rotation angle for optic probe and transducer, and distance between each component and the sample. The probe holder is presented in Figure 1.

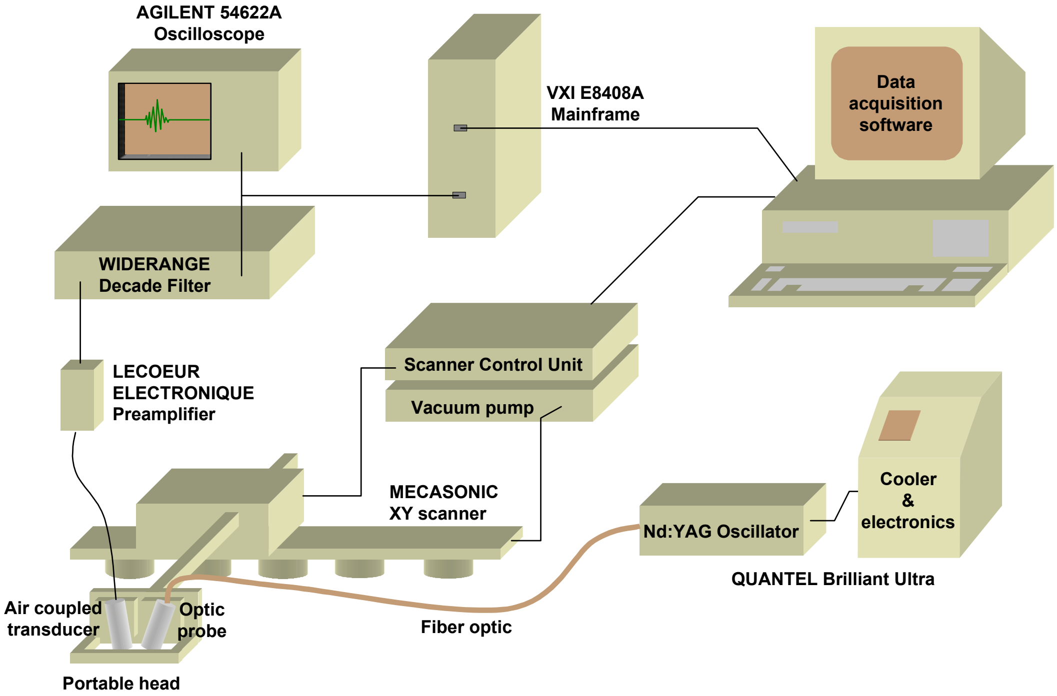

Figure 2: Experimental set-up

The portable head was integrated with a *MECASONIC* XY scanner. This scanner moves the probe holder above the sample and keeps a constant gap between the transducer/optic probe block and the sample. The ultrasonic signal is amplified with a 25 dB *LECOEUR Electronique* preamplifier, and filtered with a *WIDERANGE* Decade Filter module. A digital *AGILENT* 54622A oscilloscope displays the ultrasonic waveforms, and the data are transferred and stored into a PC using an *AGILENT* E8408A VXI mainframe. A software was developed on *HP VEE* to control the generation laser, the XY scanner and the VXI board. Finally, the signal processing and the plot of the C-scan are performed with a dedicated PV WAVE software. The experimental set-up is presented in Figure 2.

Results and Discussions: The performances of the portable head are evaluated on representatives composite samples manufactured for the aeronautic industry. For each inspection test, the laser energy is set between 3-4 mJ/pulse in order to raise a sufficient ultrasound signal to noise ratio without damaging the surface of the composite sample. The optic probe and the air-coupled transducer are arranged as close as possible (separation between laser line illumination and center of transducer ≈ 12 mm) to minimize the acoustic attenuation in the sample. The transducer is rotated by a precise angle (around 10° for CFRP composite materials) to detect the Rayleigh surface mode owing to Snell's law: $\sin(\theta) = V_a / V_R$, where V_a is the ultrasound velocity in air, V_R is the Rayleigh wave velocity and θ is the rotation angle. The A-scans are recorded with a scanning step of 1 mm, and a temporal window is adjusted to select the Rayleigh mode in the A-scan representation. Finally, the C-scan is displayed, starting from the maximum peak to peak amplitude of the Rayleigh wave for each step of the probe holder.

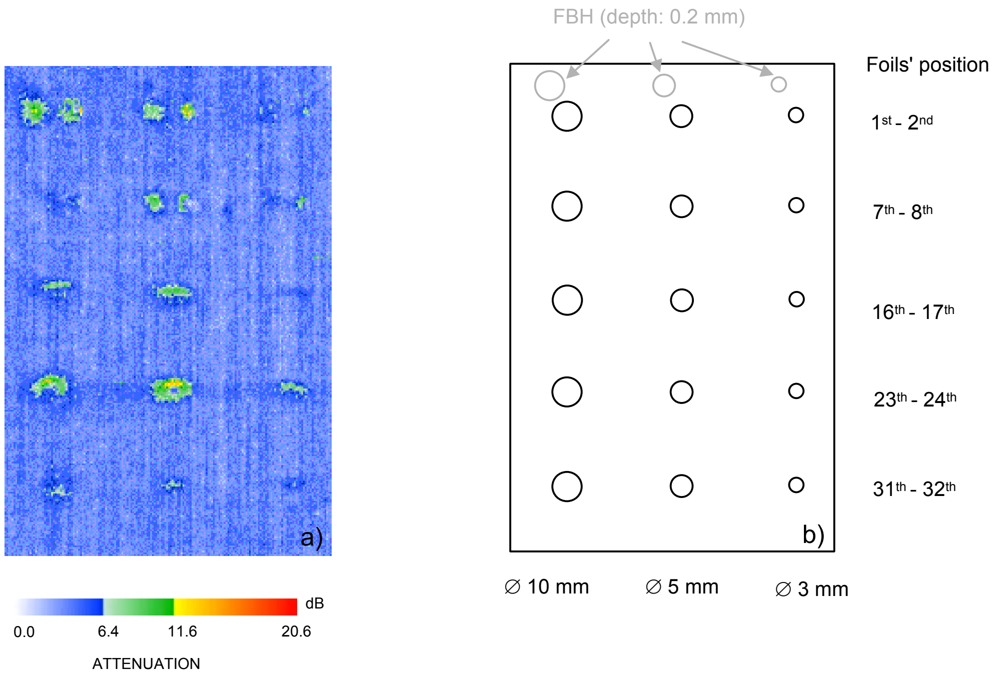

Figure 3: (a): Portable head C-scan of a 4.6 mm thick CFRP composite sample with Teflon foils, and (b): detail drawing of the sample

Figure 3(a) shows the C-scan performed with the portable head and a 0.5 MHz air coupled transducer on a CFRP composite sample (T300-914, 32 layers, 4.6 mm thick) with artificial defects. The defects are teflon foils of 10 mm, 5 mm and 3 mm diameter, set between 1^{st}-2^{nd} and 31^{st}-32^{nd} layers in the depth of the CFRP sample (the detail drawing is given in Figure 3(b)). Furthermore, 3 Flat Bottom Holes (FBH, 0.2 mm depth) are present on the top of the sample (see Figure 3(b))

From the C-scan in Figure 3(a) it is clear that the portable head has identified most of the Teflon foil defects. The penetration depth of surface waves and the sensitivity are not important enough to detect the 0.2 mm depth Flat Bottom Holes on the opposite side (4.6 mm) of inspection. However, such defects should be detected within thinner test samples.

This results shows the ability of the equipment for non contact NDT of surface and subsurface defect detection (up to 3-4 mm depth). A limitation of the portable head is the resolution, depending on the diameter of the transducer. The resolution could be improved by reducing the diameter of the transducer, but the detected acoustic energy and so the signal to noise ratio will be reduced too. Another limitation is the defect image distortion caused by the double image effect. This is because every point on the test sample is scanned twice: once by the laser generation beam and once by the receiving air-coupled transducer. Consequently, the final image (see Figure 3(a)) consists of two identical images that are superimposed but shifted by an amount which is equivalent to the separation between the laser line illumination and the center of the transducer. A simple way to remove the double image is to compare the amplitude of pixels which are separated by the equivalent of the laser/transducer separation, and to choose the highest amplitude to create a new pixel.

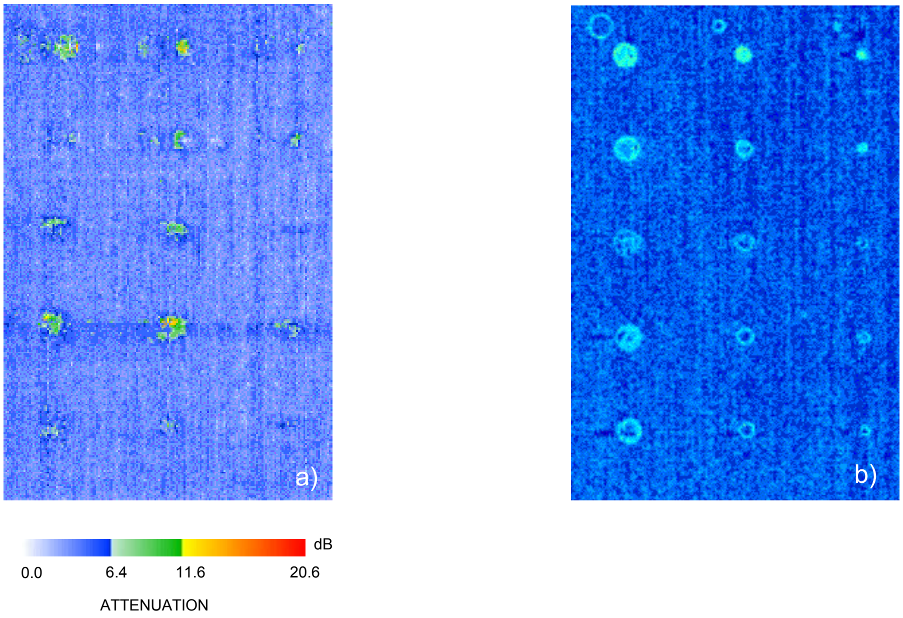

Figure 4: (a): Processed C-scan with the portable head, (b): C-scan with LUIS system

The previously described process was applied to the C-scan image in Figure 3(a), the result of this simple processing technique is shown in Figure 4(a). The defect resolution is highly improved because the double image distortion is almost removed. However, the image processing reduces slightly the contrast between a defect and a sound area. The C-scan performed with the portable head is compared with the C-scan performed with a full laser ultrasonic inspection system (LUIS system, see ref.[10] for details) in Figure 4(b). Although the performances of the portable head are inevitably limited compared to the performances of the LUIS system (CO_2 generation laser, Fabry-Perot interferometer coupled to a long pulse Nd YAG laser for the detection of the longitudinal waves), the portable hybrid equipment is a very cheap and compact system that can be sufficient for quick and easy surface and subsurface defect detection.

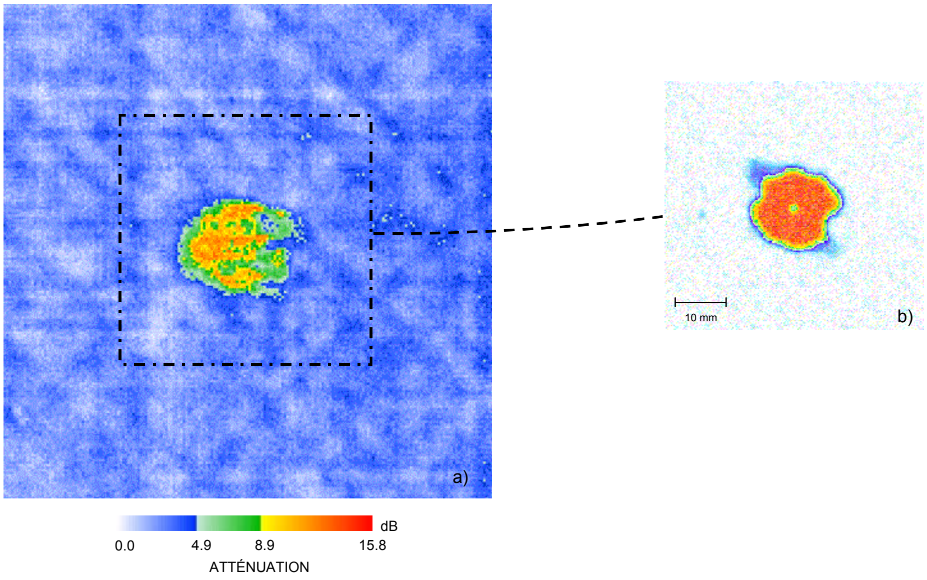

Figure 5: C-scan of a 35 J impact damage on a 2.3 mm thick CFRP sample performed with (a) :portable head, (b) conventional focused 5 MHz water immersion method (closed view)

The potential of the portable head to detect impact damages in aeronautic structures was demonstrated on a 2.3 mm thick CFRP sample (T300-914, 16 layers). Figure 5 illustrates the C-scans performed closed to a 35 J impact damage in the case of (a): portable head equipment with 0.5 Mhz air coupled transducer and (b): focused 5 Mhz conventional ultrasonic water immersion method. The Figures show that the portable head has sufficient resolution and sensitivity to image impact damages in such composite structures.

Portable head C-scan image was also obtained on a composite honeycomb sandwich sample with structural inserts. The test sample is made of a 12 mm thick NOMEX honeycomb structure bonded between 2 CFRP skins (2 mm thick each). The 8 composite structural inserts fill the depth of the honeycomb. The C-scan image performed with the portable implemented with a 1 MHz air-coupled transducer is shown in Figure 6(a). The C-scan obtained using a whole focused QMI 400 kHz air-coupled transducer equipment (generation + detection) through transmission mode is shown in Figure 6(b). The structural inserts are imaged in both cases with a better resolution for focused air-coupled system through transmission mode. However, the portable head is a unilateral system (only one-side access necessary), in opposition to the transmission air-coupled equipment (two-side access are necessary) that can be a drawback for inspection of limited access components.

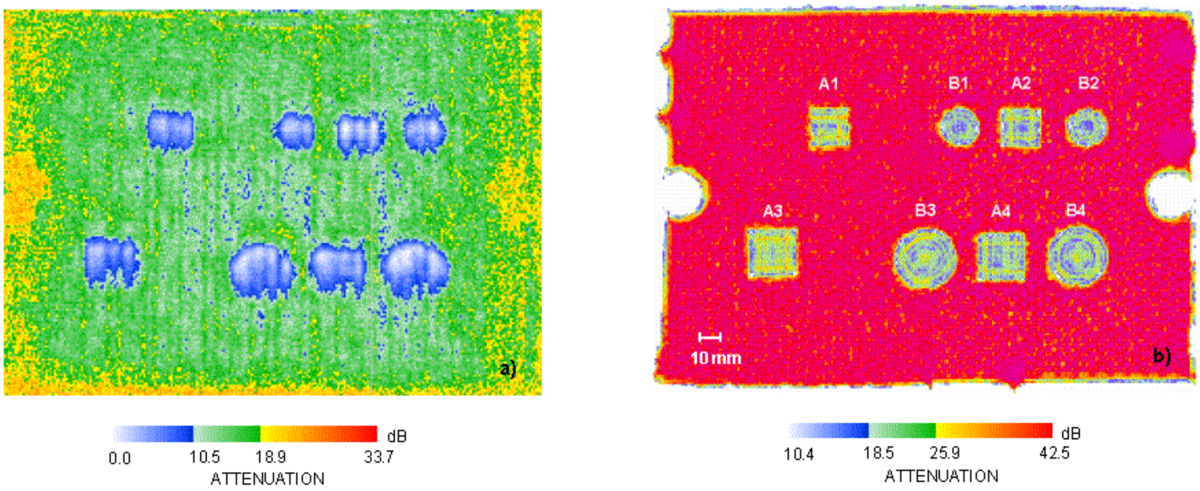

Figure 6: C-scan of a composite honeycomb sandwich sample with structural inserts. (a): Portable head equipment, (b): Through transmission air-coupled equipment

Conclusions: This paper has discussed the design and development of a compact and low-cost non-contact instrument, using a hybrid laser generation/air-coupled detection system for ultrasonic non-destructive inspection. The performances of the portable head have been evaluated over a large panel of composite test-samples manufactured for the aeronautic industry. The equipment has successfully detected artificial defects (such as teflon foils), impact damages and structural inserts in honeycomb structures. The defect detection limit in the depth of common composite samples can be up to 3-4 mm, and the resolution is limited by the transducer size and the double image distortion. However, a simple image processing can be used to improve the resolution by removing the double image. Further testing will be performed to evaluate the system performances under industrial operating conditions.

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