LASER ULTRASONIC TECHNOLOGY IN EUROPE FOR INNOVATIVE INSPECTION OF AIRCRAFT STRUCTURES

E. Guilliorit and H. Trétout
Dassault Aviation, France

Abstract: The major European aircraft companies are engaged in a common project INCA* to investigate laser ultrasonic technology in order to get the maximum performances of such a non-destructive testing (NDT) system. The INCA project was established to advance the state of the art of NDT to enable the aeronautic industry to manufacture aeronautic structures with new materials, new technologies, and new structural geometries with a quality assurance system using the best, fastest, safe, reliable and cost efficient NDT methods. A review of the laser ultrasonic developments undertaken and of the results achieved by the different partners of the INCA project is presented. The scientific approach is based in the setting-up of an evolutionary laser ultrasonic test platform, and the development of defined sub-systems in order to tackle several applications dealing with composite materials as well as metallic one's.

Introduction: European aircraft industry has achieved a key role in the world market. To reach and to maintain this position it has been constantly introducing innovations especially in the field of structure design. Successful introduction of new structural technologies into the European aeronautic industry demands that quality control and maintenance tools are developed in due time fulfilling adequate performances. The objectives of the INCA project are focused on the development of NDT methods well suited for adaptation to tomorrow's needs, as a composite fuselage for instance. In this respect, major efforts are put on the development of laser ultrasonic technology. This NDT method has already been widely studied in many laboratories [1,2,3], in North America and in Europe [4]. Two partners of the INCA consortium, Dassault Aviation and EADS CCR, bought an industrial system 10 years ago for evaluating the technique on aeronautical applications. This system called LUIS (Laser Ultrasonic Inspection System) has proved to be highly performing on the foreseen applications, covering production and maintenance inspection of composite parts [5]. LUIS capabilities have been above all unmatched for the testing of parts with a complex geometry, either monolithic, stiffened or sandwich ones. However its commercialization suffered the lack of support for its maintenance and evolution. More and more composite structures are being developed for aircraft programs as they enable to include several capabilities in one part and hence reduce production costs. For these reasons, the major European aircraft companies started the INCA project to complete the evolution of the laser ultrasonic NDT method in order to get the maximum performances out of such a testing technology and to set-up European industrial capabilities for its dissemination.

The scientific approach is based on the set-up of a test platform in the one hand, and the development of defined sub-systems on the other hand. The sub-systems are addressed to improve cost-efficient and wavelength adapted ultrasonic generation lasers, based on the CO_2 technology as well as on the innovative Yb:YAG disc-laser that is combined with an Optical Parametric Oscillator. Other laser systems are investigated for ultrasound generation in metallic materials such as UV lasers and X-ray lasers. On the detection side of the laser ultrasonic system, long-pulse detection lasers and interferometers are optimized and under development within the project. A low-cost flash-lamp pump oscillator is developed to illuminate the sample and the interferometer, whereas photorefractive interferometers based on single channel and new multi-channel design are promising to be powerful devices for ultrasound detection. Finally, improved ultrasonic board and signal analysis software and hardware are developed for acquisition and processing the ultrasonic data coming from the laser ultrasonic test platform. These developments are aimed to tackle within the project several applications for which improvement are expected in terms of sensitivity, frequency bandwidth and speed of inspection. These applications to be undertaken in the last phase of the project will among others specifically deal with:

- Large composite structures
- Thick parts (RTM manufactures)
- Glare composite, sandwich and metallic parts

Several important issues will be addressed such as crack and corrosion detection in metallic materials, attenuation and debonding assessment in composite materials. The INCA project involves for the Laser Ultrasonic workpackage the following partners:

- 6 aircraft manufacturers: AIRBUS Deutschland (D), AIRBUS España (E), BAE Systems (UK), ALENIA (I), DASSAULT Aviation (F), SAAB through CSM Materialteknick AB (S).
- 3 technology companies: MYOS (D) specialized in optical systems, TECNATOM (E) and NUTRONIK (D) both entirely involved in the development and commercialization of NDT systems.
- 8 research centers and universities: EADS CCR (F), CESI (I), Universitat Stuttgart (IFSW-D), ONERA (F), Laboratoire Charles Fabry (LCFIO-F), University of Central Lancashire (UCLAN-UK), General Electric Companu (USA), Institut des Matériaux Industriels (IMI-CA).

INCA Laser US Test Platform: The test platform architecture was defined from end-users experience in laser ultrasonic inspection with the LUIS system. Preliminary specifications and requirements lead to establish an evolutionary Laser Ultrasonic platform as a basis for validations and developments of defined sub-systems. The mechanisms of laser ultrasound generation indicate that the CO_2 laser is well suited for typical composite materials. This type of laser is well established and currently used in two existing laser ultrasonic systems [5,6]. It offers the benefit of having a high damage threshold on composites and generates ultrasound by a buried thermoelastic source mechanism providing strong longitudinal wave generation. The pulsed CO_2 laser can provide typical levels of displacement in composite materials, which can be detected by a wide range of optical detectors used in laser ultrasonic systems. On the detection side of the laser ultrasonic system, there are two important components: the high power and long pulse detection laser that illuminates the sample, and the interferometer converting the light's frequency fluctuations into an electrical signal. The long pulse (at least 50 ms) is needed because the flying time of the ultra-sound echoes inside the composite materials lasts this amount of time: within the whole period, the detection laser must continuously interrogate the surface of the sample. High power (at least 1 KW) is required by the high attenuation of the laser beam, due to the diffusion of the surface of the sample under inspection. To-date laser ultrasonics systems have used interferometric detection techniques based on the Michelson or Confocal Fabry-Perot interferometers. These are highly sensitive but relatively complex devices. Recently, photorefractive interferometers have been demonstrated to be powerful devices for detecting ultrasound with sensitivity approaching the ultimate sensitivity of optical detection [7,8]. The potential of these photorefractive sensors is very high and justifies investigating this approach in the frame of the INCA project. The INCA test platform is composed of five main units:

- *SDI* CO_2 *TEA* generation laser (400 mJ multimode, 200 mJ monomode, rep. rate 200 Hz maximum)
- *Tecnar PDL* long pulse detection laser (1 kW peak power, pulse duration > 50 µs, monomode, rep. rate 50 Hz, fibre coupled)
- *Tecnar* TWM photorefractive interferometer (fibre coupled, bandwidth 100 kHz - 90 MHz, sensitivity better than 2.10^{-7} nm $(W/Hz)^{1/2}$
- *Newport* two axis XY scanner (600 mm translation stage, 0.1 mm resolution). This type of motion system, however less versatile than an optical scanning mirror, is sufficient to validate most of the applications foreseen in the project.
- *Nutronik* motion controller and *Utxx* acquisition module

The INCA Laser US test platform is presented in Figure 1. In order to ensure mobility of the system and to prepare validation tests at partner's industrial site, the whole platform has been integrated into a transportable shelter.

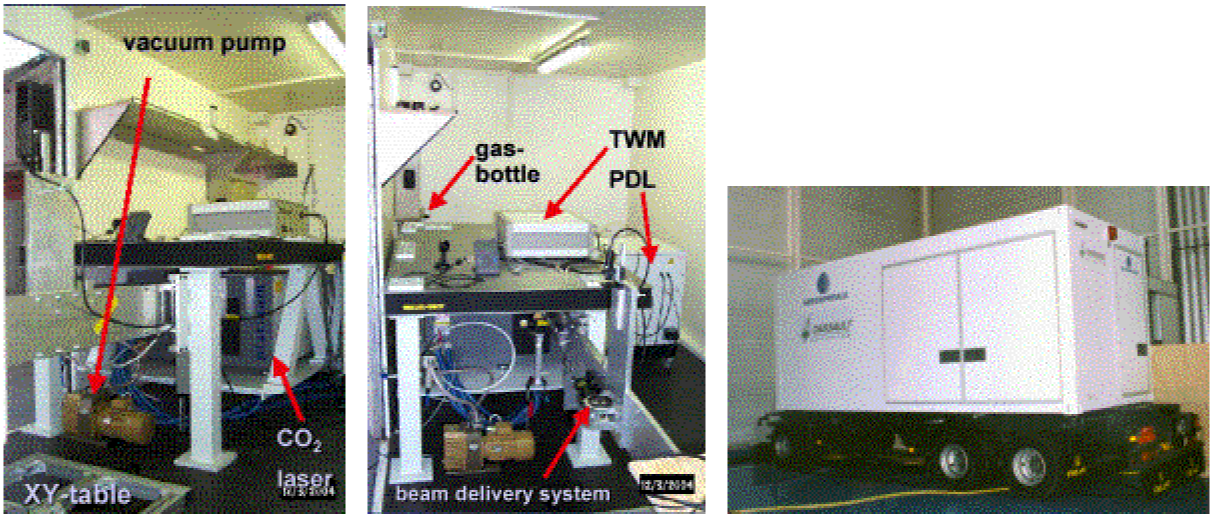

Figure 1. INCA Laser US test platform integrated into the shelter

INCA Laser US Developments: In parallel, the development of generation and detection subsystems to improve performances in term of sensitivity, band-width and speed are in progress. Concerning the development of generation lasers to improve efficiency on composite, two ways are investigated. One is to improve industrial laser already existing but requiring modifications: BAE Systems also acquired an SDI CO_2 laser as well as Airbus D, and has shown that reducing the Nitrogen content in the gas mix has a beneficial effect in avoiding heating and possible damage to the test material, while Industrial Material Institute (IMI) is investigating the modification of the CO2 laser resonator with a variable reflectivity mirror. The second axis of investigation involves a new original laser called "thin *disk lase*r". IFSW (Universitat Stuttgart) is in charge of the design and experimental realization of an adapted diode-pumped Yb:YAG pulsed thin disk laser, delivering pulse energies of 100 mJ with pulse duration < 50 ns, repetition rate of 1 kHz and $M^2 < 2$. The advantages of this new technology are efficient cooling, small thermal lens, small depolarisation losses (< 0.2%) and power scalability at constant high efficiency. This disk laser will be used as a laser pump for an Optical Parametric Oscillator (OPO) and for a UV module. The concept of the disc laser and the thin disc module are shown in Figure 2.

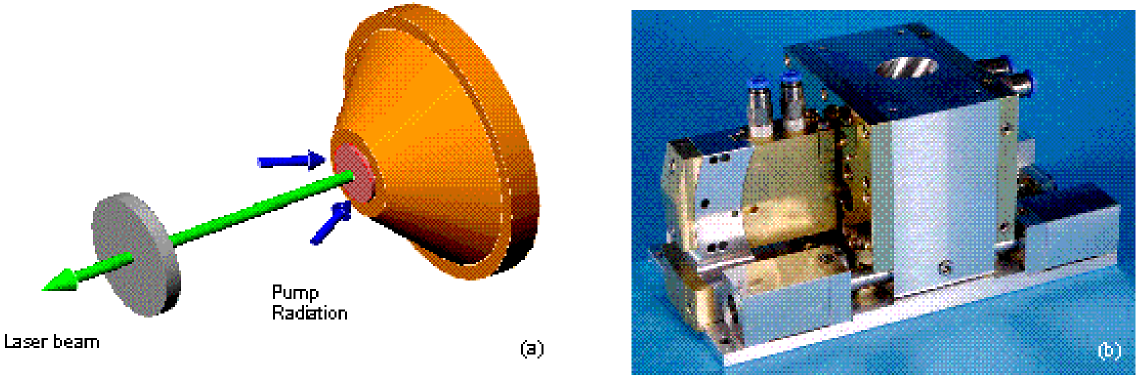

Figure 2. (a) Disc laser concept and (b) thin disc module from USTUTT

An Optical Parametric Oscillator (OPO) operated in the mid IR wavelength range (between 3.1 and 3.4 µm) is being developed by ONERA, to be coupled to the disk laser. A study on wavelength selection and requirements has proved that the OPO operating between 301 µm and 3.4 µm is a very suitable solution to improve generation efficiency in composite materials, because the ultrasound generation efficiency values are high and the damage threshold of composite materials too (in the mid-IR range). The objectives of the OPO development in the INCA project are to obtain 10 mJ in the mid-infrared range with 100 mJ pump laser from the thin disc laser. Calculations are performed by ONERA to optimize the OPO conversion efficiency versus the pump pulse duration, and a new original cavity is designed and tested to improve the OPO. Figure 3 presents the ONERA experimental set-up, and the OPO cavity.

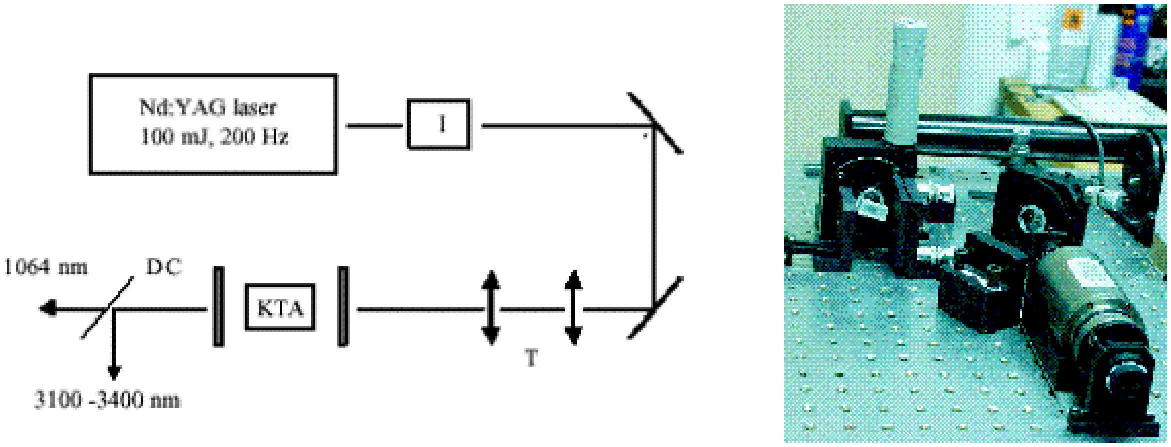

Figure 3: (a) experimental set-up and (b) OPO cavity from ONERA

Generation lasers applied to metallic materials require different characteristics compared to the one used for composite materials. Two approaches have been investigated: on the one hand a theoretical model developed by GE shows the potential of X-ray lasers for thermoelastic generation in metallic samples. Such a laser source is being evaluated by CESI. On the other hand, CESI is investigating a 3ω and 4ω optical device allowing the operation of the disk laser (developed for composite materials) in the UV range. This device including both the 3ω and 4ω harmonics must provide a switching from the former to the latter with no loss in energy. The output values of the relative harmonics are 20 mJ @ 0.343 µm (3ω) and 10 mJ @ 0.257 µm (4ω) if the IR disc laser input is 100 mJ @ 1.03 µm. The crystals chosen for generating second, third and fourth harmonics are BBO (b-BaB2O4: beta-Barium Borate). The crystal must be thermally controlled by ±0.1 °C to maintain the energy stability of the 4ω harmonic within ±5%. The 3ω and 4ω generation system is shown in Figure 4.

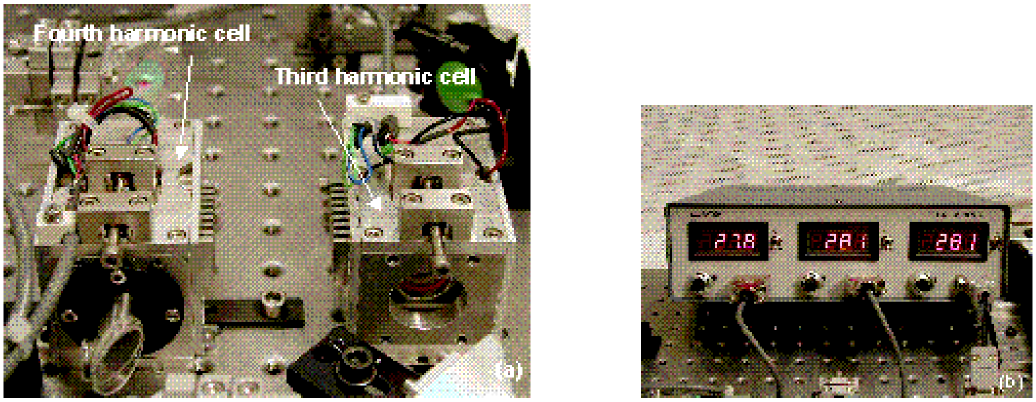

Figure4: (a) 3ω and 4ω cells and (b): thermo-electric controller from CESI

Another main task is dedicated to the improvement of detection lasers. This component is the weakest point of a laser ultrasonic system as it required specific characteristics (power, long pulse duration and stability) that no other application need therefore leading to an expensive dedicated system. The work of IMI is concentrated on a flash-lamp pumped oscillator, instead of the usual scheme of a small single frequency oscillator followed by an amplifier. A stable mounting of the ring configuration is completed and gives satisfactory results. The detection limit with photorefractive demodulator detection is found in agreement with expectations. A second system developed at the IMI, inducing generation + detection could lead to a new compactness and extremely low cost Laser Ultrasound NDT system (see Figure 5).

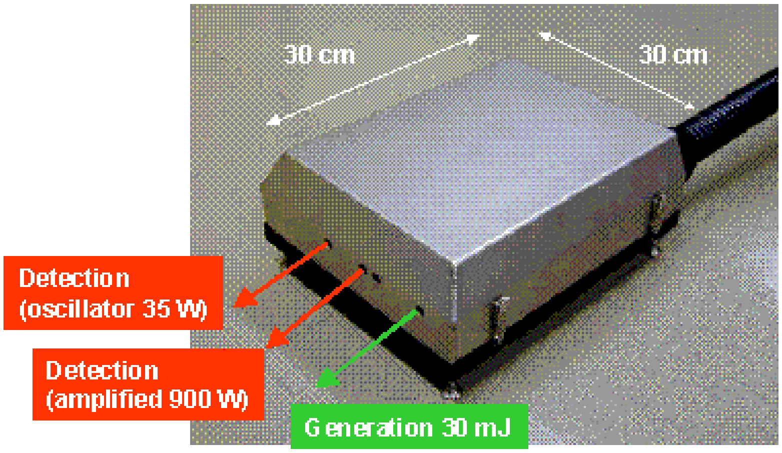

Figure 5: Compact laser ultrasonic system prototype from IMI

IMI has also carried-out a theoretical study on the advantages and drawbacks of pre-amplification and post-amplification scheme for laser detection. Pre-amplification scheme requires a single mode detection laser with a long pulse and a high peak power (at least 1 kW).This type of laser has a high cost, especially if the required repetition rate (essential to reduce the inspection time of a component) is more than 100 Hz, that makes necessary to pump the laser with laser diodes, instead of flashlamps. To develop a more cost-effective detection laser, CESI works on a diode-pumped fiber optic amplifier for post-collection amplification (It must be pointed out that every amplification process ads noise to the input signal). The fiber optic amplifier is inserted in the path of the collected light; the gain of the optical amplifier should allows the use of a less powerful detection laser, decreasing the cost of the system which is essentially linked to the number and high price of the laser diodes.

For improving the sensitivity of interferometric detection, the work is focused on photorefractive laser ultrasonic sensor. The laser ultrasonic detection requires a detection laser with a high power and a good spectral quality (high coherence length, low amplitude and phase noise, …). In order to obtain this high spectral quality, spectral filtering elements have to be inserted in the laser cavity. The work of LCFIO in this task consists in evaluating the capabilities of a new kind of spectral filter to improve the quality of the source on the laser cavity architecture developed by IMI. The adaptive dynamic holographic filter in the case of the Nd:YAG laser is analyzed, and its operation is modeled.

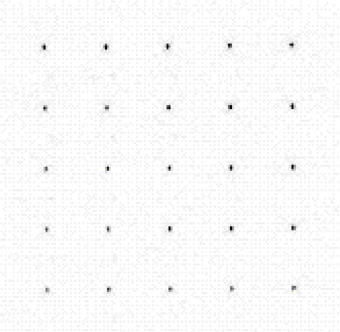

Figure 6: Image of the array of spots in the target plane from LCFIO

Another promising field of interest is the study of a multi-channel photorefractive sensor by LCFIO. The aim is to develop a multi-point detector and a proper optical system, to make the measurement on several points on the target. LCFIO is continuing the implementation of the sensor set-up of the sensor that will be used for its characterization and its evaluation. The image of 25 spots array in the target plane is shown in Figure 6.

Concerning data acquisition and signal processing, an adapted ultrasonic board is being developed by TECNATOM. This UT hardware is designed in a modular way (PCI based): the carrier board, the A/D converter board and the DSP board. The A/D converter is probably the key element of the UT board. Taking advantage of the new electronics under development in TECNATOM, the new UT board is designed in a versatile way, allowing the possibility to use different A/D converters. The board will include a 120 MHz, 14 bits A/D converter (2x120 MHz is under research and could be integrated in the INCA board).

As the laser generated ultrasonic signal is transient in nature and embedded in severe noise, UCLAN is developing a real-time digital signal processing system (based on wavelet transform) for restoration, detection and extraction of the noisy laser generated ultrasonic echoes. To improve further the performance, a new method is developed by UCLAN to design a better wavelet function. The new method yields a new type of wavelet that is adaptive to the waveform shape of the ultrasonic echoes to be detected. Initial evaluation based on simulated data shows improvement in performances in terms of automatic attenuation estimation.

As a result of a QFD (quality function deployment) carried-out by GE with the participation of the INCA consortium, the main requirements and criteria for an optimal system have been elaborated. The last development is dedicated to an original concept of low cost and portable equipment for 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 is designed, and integrated with an *XY* scanner system provided by CSM to move the probe above the sample. The field of application is surface and subsurface defect detection in composite and metallic materials. The portable head equipment is presented in Figure 7.

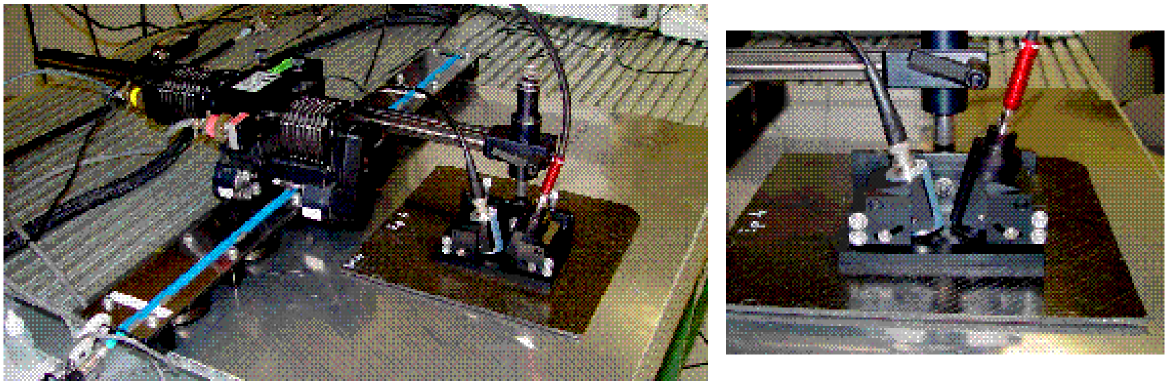

Figure 7: Portable head equipment from Dassault Aviation

Conclusions: A review of the developments undertaken and of the results achieved by the different partners of the INCA project was presented in this paper. The scientific approach of the INCA project is based on the setting-up of a test-platform, and the development of defined subsystems to evaluate the performances of the laser ultrasonic technology on new composite and metallic applications. New developments and major improvements concerning ultrasonic generation (thin disc laser, mid-IR OPO, UV module...), detection (new laser design, photorefractive interferometers…) and signal evaluation are the major goals within the INCA project as well as the reduction of the system's overall costs. Some significant achievements have already been obtained and some promising ones are expected to push forward the current limits of this technology. A better understanding of the involved phenomena on the one hand, and a more versatile offer on the other hand should be the major end-results of the project. However, an important issue is remaining at that stage, it concerns the necessary integration and support capacities in Europe to enable a large dissemination in the aeronautic industry and in others such as the steel one.

(*) **I**mproved **N**DE **C**oncepts for Innovative **A**ircraft Structures and Efficient Operational Maintenance

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