Analysis of Commercial Aeronautics Applications of Laser Ultrasonics for Composite Manufacturing

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Abstract. Laser-based ultrasonic techniques have been investigated for the non-destructive testing of advanced aeronautic composite structures for more than twenty years. Several organizations have evaluated the technology at various levels during this period. In one case, EADS (formerly Aerospatiale) acquired, jointly with Dassault Aviation, a laser ultrasonic system from a now defunct provider. In another case, Lockheed Martin Aeronautics independently developed its own laser ultrasonic technology, named LaserUT®, which is used for the inspection of composites in the manufacturing of advanced military aircraft. After several years of production operation, the LaserUT design has been proven particularly cost-effective for the inspection of complex-shaped composite parts associated with fighters. This paper presents an overview of the current state of the technology and outline future developments. As the next generation of commercial aircraft will certainly use large quantities of composites, an analysis of the anticipated cost saving associated with the laser ultrasonic technology for large commercial aircraft is presented using the example of the LaserUT systems as a basis. Inspection techniques currently used by the commercial aircraft industry are compared with the laser ultrasound technology and experimental results will be presented. As a conclusion, the predicted advantages and limitations of the technology for the commercial aeronautic industry are discussed.

Context

As the market for commercial aircraft expands, the ability of the primary manufacturers to capture significant portions of this market might be limited in the near future by the ability to deliver aircraft at high rates. In this context, any increase in productivity corresponds not only to savings from the manufacturing point of view but also as an opportunity to seize an additional portion of the expanding market.
Non-destructive testing (NDT) is a major element in the aircraft manufacturing process. It represents not only a source of cost but very often also a bottleneck in the overall process. The newly introduced aircraft contain an unprecedented proportion of composites. A fresh look to NDT for those composites is required since conventional approaches were designed for relatively low part volume and complexity, and availability of those systems might become problematic.

Laser-based ultrasonic technology for the inspection of composite structures for the aeronautic industry has been around since the beginning of the 1990's [2-6]. However, only recently has one implementation of that technology, LaserUT® at Lockheed Martin Aeronautics Company, demonstrated real industrial capabilities for military fighter manufacturing [7].
This paper presents an overview of that technology from the point of view of commercial aircraft manufacturing.

Needs

Since the 1980's, airframe manufacturers have been using carbon fibres reinforced plastics (CFRP) in structural parts. The CFRP proportion is increasing steadily every year, leading to parts that now have relatively complex shapes. The challenge we are facing now with the next aircraft generation is a full body CFRP commercial aircraft.
At the end of the nineties, Raytheon launched its Premier full composite aircraft. Early in the 2000's, Airbus started the production of the A380 Centre Wing Box (CWB) with composite material. CFRP will be intensively used also for wing panels and the fuselages in the next aircraft generation. One of the main differences between metallic and composite components is the NDT process. If we are considering fuselage panels, the skin made with metallic material is inspected at the supplier level, before forming, when the shape is flat. The same panel made with CFRP requires NDT after curing, when material is consolidated in its final shape. This new approach will lead to a huge quantity of complex-shape material to be inspected in the case of a full fuselage of a large commercial aircraft.
Alternative NDT techniques are investigated by considering the contactless aspect, the coupling removal, and the low positioning constraints. These points are the main keys for potential cost saving regarding the NDT process.

Background

In the beginning of the 1980's, as laser-ultrasonics emerged from a scientific curiosity into a non-destructive technology mainly for metallic applications [1], General Dynamics envisioned that this technology could fill a need for cost-effective ultrasonic inspection of future composite components. Therefore, a research program on laser-ultrasonics started at the Fort Worth facility in 1983. A fully functional laboratory prototype was built (see figure 1) and the composite inspection concept using laser-ultrasonic was demonstrated in the late 1980's. In the early 1990's, a second more advanced prototype for demonstration of large area scanning was built (see figure 2). This latest prototype led, in 1997, to the construction of the Alpha LaserUT facility that was built as part of demonstration hardware for the JSF competition. In June 2000, a second LaserUT facility began operations as the first production system. A second production system, Gamma, started operations in 2004. In 2005, a 5-year technology development program was initiated. This program aims at in-service applications and improved productivity.

Figure 1. Late 80's lab prototype at GD for concept demonstration of inspection of composites.

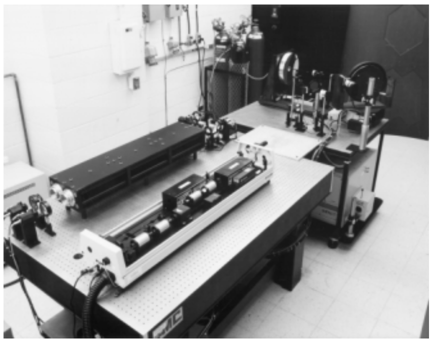

Figure 2. Early 90's laser-ultrasonic prototype at GD for demonstration of large area scanning.

In the early 1990's, mainly three groups [2, 3, 4] were investigating the laser-based techniques for the ultrasonic inspection of polymer matrix composites: Rockwell International Science Center [2], the National Research Council of Canada [3] and General Dynamics [4]. The first group stopped work in this field in the late 1990's without any significant implementation of the technology. The second group contributed to two semi-industrial systems named LUIS. The first LUIS system was for Dassault-Aerospatiale [5] that it is still operational in EADS' laboratories. The second LUIS system was for the US Air Force [6] and was later abandoned as the base on which it was installed closed. General Dynamics, Fort Worth Division, that later became part of Lockheed Martin Aeronautics, developed the LaserUT technology and is the only laser-based ultrasonic system in use today in an industrial environment.

The lack of a commercial provider for the laser-based ultrasonic technology led to an European project inside the 5th Framework. The 4 year INCA project ended late 2005. It contributed to the survey of the technology and investigated different axes for improvement of both generation and detection of ultrasound especially on composite materials [7]. EADS CCR, Airbus and Lockheed Martin Aeronautics, through its research partner, GE Global Research, were members of the INCA partnership.

The LaserUT technology was developed for Lockheed Martin's own internal needs [8, 9]. However, as the LaserUT technology matures, it appears that the technology can fulfil needs for applications other than military fighters. At the time of writing, Lockheed Martin Aeronautics is actively interested in seeing the LaserUT offered for commercial applications. In this spirit, technical exchanges were initiated with Airbus and EADS to evaluate the economical advantages of LaserUT for applications specific to the commercial aeronautic market.

LaserUT description

Lockheed Martin (LM) has built three LaserUT systems, referred to as the Alpha, Beta, and Gamma facilities. These three systems are similar in design, but the inspection envelope of the Alpha gantry robot is the largest while Beta's is the smallest. The Alpha system is currently dedicated to research and development while Beta and Gamma handle production tasks. All systems use a short-pulsed TEA CO_2 laser to generate the ultrasound and a long-pulsed diode-pumped Nd:YAG laser with a dual differential confocal Fabry-Perot interferometer for ultrasound detection. These lasers are not eye-safe and the inspection cell is interlocked to protect the operators. The two lasers are optically combined to produce a coaxial beam that is about 5mm in diameter at the composite surface. Inspection depth-of-field is fairly large and allows the part standoff distance to vary between 1.5m and 2.5m

from the optical scanner. Beam indexing (optical scanning) is done using a high-speed two-mirror galvanometer scanner with a 50mm clear aperture. A five-axis gantry robot moves the inspection head to the best position for scanning each region of a part. Scan coverage can be as large as 1,3m × 1,3m for a single inspection view. Parts with significant contour are typically sectioned into a series of smaller regions so each subsection remains within the constraints of the system. Scanning constraints are based on the generation efficiency and optical scattering properties of the material, but typical values are ±45º angle of incidence and a typical working distance of 1.8m from the surface.
All ultrasonic waveforms are digitally captured, processed and permanently stored while the inspection point is indexed over the composite surface. Real-time data analysis tools are available to the operator that greatly speed the inspection/analysis process. Data management is performed with an automated archival system and an Oracle database. The current LaserUT system operates at a maximum inspection rate of 400 points per second and is limited by the pulse rates of the lasers. As faster lasers are developed, the scan rate will improve accordingly. The inspection coverage rate is related to the index step size required for the material under test, which is usually based on the size of defect that must be found. A 400Hz scan rate with 2 mm steps equates to an area coverage of about 5,8m^2/h. Future laser improvements should increase the pulse rate to 1000Hz or over 14m^2/h. The LaserUT systems are especially well suited for the inspection of complex-contoured parts found on fighters. Figure 3 shows an example of such contoured part.

Figure 3. LaserUT system inspecting a complex-contoured composite part.

Between the introduction of LaserUT in production in June 2000 and May 1st 2006, more than 13 000 parts have been inspected (see Figure 4). As the composite production increased by nearly ten-fold, the NDT labour assigned to composite inspection remained constant.

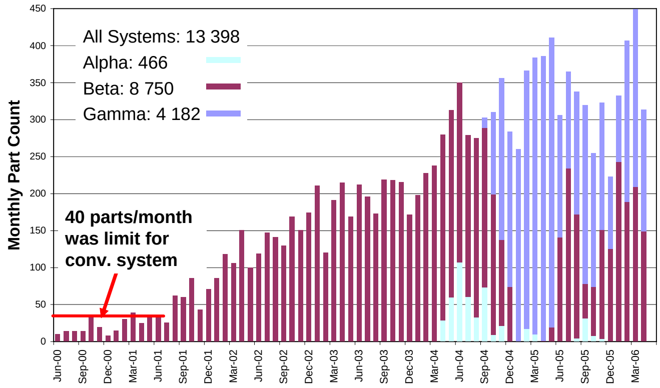

Figure 4. Number of parts by month inspected by LaserUT systems at Lockheed Martin Aeronautics at the Fort Worth, Texas facility since the technology was introduced in production in June 2000 as of May 1st 2006.

Approach

With more than 13 000 parts inspected by the LaserUT technology, several problems were encountered and solved. Reliability is one of the most important characteristic of a production system. Early after the introduction of Beta in production in June 2000, the conventional system previously used for inspection of complex contoured composite parts was retired, leaving no backup plan to the LaserUT technology. Early problems were rapidly solved and had little or no impact on production.

The biggest challenge to the reliability and maintenance schedule is the laser technology. Important efforts were put into testing and improving the reliability and performance of the generation and detection lasers. These efforts led to lasers and systems that have a very high reliability with 2 to 3 days of maintenance over one year of operation. The efforts are still going on to increase the maintenance interval to 3 years, even with the expected increase in repetition rate to 1 kHz in the next few years.

These figures are illustrating the maturity of the technology and show that the industrialisation requirements are strongly considered in the technological developments.

In order to evaluate the ultrasonic capabilities of the LaserUT system, several typical samples were inspected during a short period, involving EADS CCR, AIRBUS and LM personnel. We performed a real-time result analysis in terms of UT signal characteristics as well as preparation and scanning time, handling, system operation policy and all environmental characteristics.

The inspection process is very similar to the one used with conventional ultrasonic inspection. LaserUT systems have a very high level of automation in order to exactly repeat the sequence for the inspections of all similar parts. A great advantage for all laser-based ultrasound system is the positioning tolerance of 2 cm or larger. The components can be inspected on their transportation tool without precise positioning.

The part to be inspected is delivered with its traveller sheet. It is identified using a radio-frequency (RF) terminal, equipped with a bar code reader, by reading the part and serial numbers from the traveller sheet. The operator then reads the instructions for part positioning automatically displayed on his computer screen. Visual aids also accompany instructions. After part positioning, the button “Begin Scan” can be selected. There are no knobs to turn or any adjustments to make.

During the ultrasonic inspection, only the small mirrors of the 2D scanner actually moves, scanning a maximum area of 1,3m x 1,3m but typically smaller than 1m^2, at a speed of 5,8m^2/h. For large or complex (or both) parts, the LaserUT head will move to one position, scan an area, then move to another position to scan a different area of the part and so on

until the part is completely covered. Each robot position and its associated scanning area is called a region. Usually, for each part, the first region is an inspection reference panel containing standard defects. Typically, gantry movements take between 2 and 3 minutes using a safe-gantry-move approach.
Different regions are used to maintain the incidence angle below a maximum (typically ±45°). The regions for a given part are defined by a one-time operation called teaching. This operation typically takes 5 to 6 minutes per region. Once a given part has been taught, the inspection only requires the steps mentioned earlier. For a new part that is relatively flat, no teaching is needed and only approximate dimensions are required. The number of regions is then automatically defined by the system. The LaserUT inspection process is very easy for the operators, and preparation and positioning consume very little time. LM operators are UT level 2 certified.
The figure 5 is presenting processed LaserUT ultrasonic data. It corresponds to a 44 mm thick CFRP with inserted defects. The backwall echo is clearly detected and can be precisely analysed.

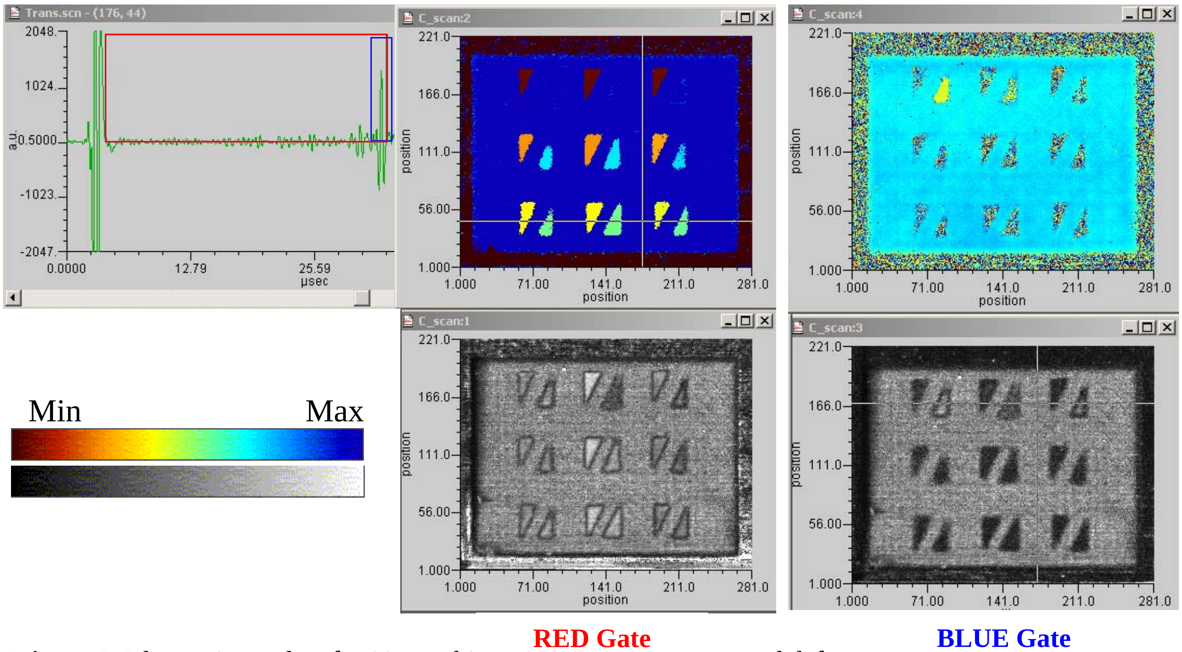

Figure 5. Ultrasonic results of a 44 mm thick CFRP block with inserted defects with the LaserUT system. Time of Flight C-scan (Top) and Amplitude C-scan (Bottom).

Note that the laser-ultrasonic LUIS system currently owned by EADS is not powerful enough to achieve equivalent results on the same part. However, the LUIS is a very efficient tool for thinner components inspection. As an illustration the figure 6 is presenting the results with a spar with flat bottom holes in the radius.

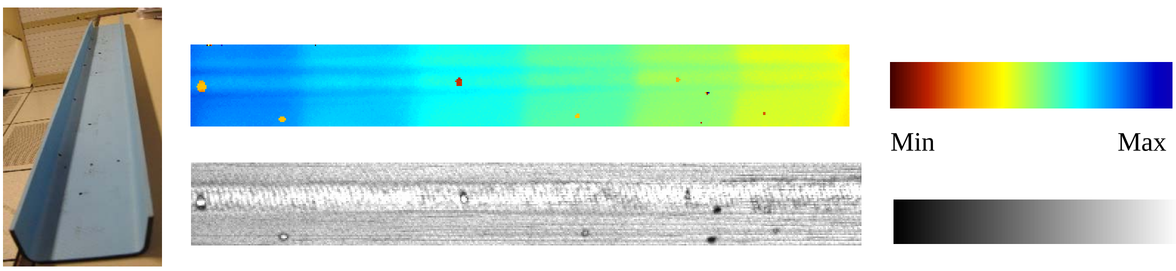

Figure 6. Ultrasonic results of a CFRP spar with flat bottom holes (ø 2 – 3 – 4 mm)with the LUIS. Time of Flight C-scan (Top) and Amplitude C-scan (Bottom).

In the case of a very large and complex shape part, like it is now envisaged for the next aircraft generation, the laser ultrasonic technique can be considered with the UT capabilities that were observed with the LaserUT system of LM. This system, designed for LM components, has been evaluated on many different types of parts gathered from several EADS plants. Results have demonstrated a high level of sensitivity and a significantly better efficiency in ultrasound generation and detection compared to the LUIS system.
With an adapted LaserUT system, and when the type and aspect of material at the top surface are suited, it could lead to a really efficient combination system-structure providing high quality results.
When the technical comparison is done between conventional UT and laser ultrasound, the evaluation criteria are only based on the costs.
The non recurrent cost, capital expenditure including

- The system (UT system + mechanics + computers)
- The building
- The training

The recurrent costs are:

- The labour: preparation, inspection and analysis
- The maintenance: labour & spare
- The supply: water, power, gas

In a first approximation, we identify the main differences only for the system and the labour costs. A single LaserUT system appears to be approximately 1.7 times more expensive than a single conventional multi-channel UT system. Today, conventional multi-channel UT systems have scanning speeds up to 3.5 times faster than LaserUT systems. Considering the preparation time (scraping, positioning, geometry teaching) there is no ratio between the different technologies as it is linked to the component. The main point to highlight is that these tasks are reduced to a minimum time (few minutes) in the case of the LaserUT inspection.
The comparison should then be done for each considered application. If we consider a relatively flat panel there is obviously no interest at all to invest in a LaserUT, for which the capital expenditure is larger than a conventional multi-channel UT system. However, as soon as manual testing is extensively required for very large and complex shape parts, like wide fuselage panels with stringers, the overall LaserUT inspection speed is definitely competitive and could save time and costs. In addition, the raw scanning speed is expected to be significantly increased in the near future as laser technology will progress.

Parallel investigations

One significant advantage of LaserUT and of laser-ultrasonics in general, is the consistency of the results over similar parts. This advantage makes it an ideal tool to track part conditions over usage. One extension of the LaserUT technology that is currently in development is the inspection of aircraft components in service. As a very large proportion of aircraft components at Lockheed Martin Aeronautics were inspected by LaserUT during manufacturing, in-service inspection using the same technology would provide a one-to-one comparison. An in-service LaserUT system demonstration is targeted for 2010.
The non coupling advantage of the laser ultrasonic technique makes it also suitable for on-line monitoring of composite material. This is under investigation at EADS CCR especially where on-line NDT has a very high added value and where the results can influence the process parameters in real time.

Conclusion

For Lockheed Martin Aeronautics, the LaserUT technology will save several hundred millions dollars in capital and lower labour costs compared to other competing ultrasonic technologies over the life of the F-22 and F-35 programs alone. These huge savings are due to the type of parts found on fighters that are relatively small and highly contoured and easily justify the massive development and implementation investments made by Lockheed Martin Aeronautics.

In the case of commercial aircraft manufacturing, composite parts are usually larger and smoother and consequently more compatible with multichannel conventional ultrasonic techniques. However, those multi-channel systems are usually dedicated to one specific type of part. For relatively large and complex parts, when comparing the performances of those systems with those of LaserUT systems, the whole inspection cycle time needs to be analysed. When considering the flexibility to handle very different parts and the very short positioning and preparation times, LaserUT systems seem to provide real economical advantages. Finally, in addition of those advantages, future LaserUT systems with kHz-scanning speeds will seriously challenge dedicated conventional multi-channel systems even for the inspection of large and less-complex parts.

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