Ultrasonic Techniques and Industrial Robots: Natural Evolution of Inspection Systems

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Abstract. The current tendency in the Aerospace industry is to save weight in the manufacturing of components, in order to reduce costs and ensure environmental friendliness. The world of today is constantly improving, as fast as technology allows. As a result, the presence of composites in structures is increasing every year, with new materials and new geometries emerging. This has made it necessary to innovate in the development of ultrasonic techniques, from conventional ultrasounds to phased-array technologies (pulse-echo and through transmission) and of new innovative techniques, such as laser ultrasonics. In parallel to this evolution, mechanical manipulators have evolved from gantries and bridge concepts to industrial robots such as those developed by Tecnatom, with the collaboration of KUKA, which are bringing accuracy, reliability, availability and good maintenance programs to inspections. This article describes the evolution of ultrasonic techniques and mechanical manipulators in a company that has more than 50 years of experience in non-destructive testing. This evolution has led to the current systems, where a perfect combination of innovative ultrasonic techniques and robots is satisfying customer requirements in the Aeronautical Industry.

1. Introduction

This paper describes the evolution of Non-Destructive Testing (NDT) systems for aeronautical components. Tecnatom is a company with more than 50 years of experience in NDT in the nuclear field and holds more than 700 NDT certificates. Fifteen years ago Tecnatom decided to widen its strategy and to extend its activities to other markets, with priority given to the field of aeronautics. Both fields of application of NDT techniques, aeronautical and nuclear, share many synergies, such as their rigorous approach to manufacturing processes, their stringent demands as regards quality control, both in manufacturing and in service, and the fact that both are based on strict quality codes and standards. These synergies facilitate the task of Tecnatom vis-à-vis the adaptation of its know-how, capacities, experience and especially its way of working to new developments in the aeronautical sector.

Throughout these fifteen years, during which Tecnatom has developed different items of equipment and systems for aeronautical applications, there has been a natural evolution, both of the mechanical systems, whose scope and accuracy of movement have improved, and of the non-destructive tests, in which from the use of mainly conventional piezoelectric ultrasounds with single elements there has been an increase in the number of elements involved, leading finally to the possibility of configuring them electronically, optimising the focusing and orientation of the ultrasonic beam (Phased-array). To the above are added the different ultrasonic methodologies: transmission and pulse-echo. The
latest breakthroughs in the field of non-destructive testing arise from the generation of ultrasounds by laser, which as we shall see provides major advantages in the inspection of aeronautical components, or the contributions made by other technologies such as air-coupled ultrasonics or Thermography.

All of these breakthroughs, the result of continuous research and optimisation in materials, geometries, manufacturing processes and inspection systems, have implied a process of natural evolution that has led to more accurate and efficient solutions, increasing the scope of inspection.

2. Increasing Presence of Composites in Aircraft

One of the parameters that influence the definition of non-destructive tests is the material of the components to be inspected. The current trend in the aeronautical sector is to reduce the presence of metals in the manufacturing of aircraft to the extent possible, increasing the presence of composites. [1] [2] [3] This allows for an important reduction in the weight of the aircraft (approximately between 20-50%), which has an impact on fuel savings. It also allows improvements to be achieved in other properties, such as resistance to corrosion or fatigue, as well as a reduction of assembly costs. However, consideration should also be given to the disadvantages that this increasing use of composites produces, fundamentally as regards increasing recurrent and non-recurrent costs in the manufacturing of aeronautical components, the appearance of repair methods different from those used for metals and the need to prevent the galvanic corrosion of adjacent components made of aluminium.

From 1970 the presence of composites materials in aeronautical structures has increased from 5% up to almost 50% of composite structural weight and consequently there has been a corresponding decrease in the use of aluminium, from almost 100% up to 50% of metallic structural weight. This progressive incorporation of composites may also be seen in different aircrafts, being the composite presence higher in new aircrafts programs.

In addition to solid laminated parts of different thicknesses, the inspection of other types of materials is also contemplated, such as sandwich components (single or double) in which one or two aluminium or paper honeycomb structures are included between two solid laminates.

When defining the inspection of these components, it is first necessary to look at their behaviour with respect to ultrasounds, bearing in mind the attenuation they cause, the possibility of obtaining a signal with air-coupled ultrasonics or Thermography, and even if the surface can facilitate the inspection carried by Laser Ultrasonics.

3. Geometries of Aeronautical Components

Another aspect that has a fundamental influence on the NDT inspection of aeronautical components is the geometry of the latter. In this respect we may have to deal with the complex geometries generated by parts of great size and length. Generally speaking, the geometries to be inspected are no more than the sum of a series of defined profiles of the L, T, U, H and closed H type. These are combinations of flat and curved surfaces. The most evolved geometries are of the omega and delta types. Figures 1 and 2 show conceptual and actual examples of the aforementioned geometries.
The geometric parameters that are essential to define an adequate inspection technique are the thicknesses, radii and angles. These parameters may vary considerably, as a result of which it will be necessary to study each case individually before defining the inspection solution to be applied.

- Thicknesses: 1-50 mm
- Radii: 3 mm – without limit
- Inner angles: between 80º and 180º. (Influences the physical space available for the probe)
- Outer angles: between 0º and 180º.

4. Evolution of NDT Techniques

The presence of different materials and geometries, as well as of different defects to be detected in accordance with different standards, means that whenever an inspection is planned it is necessary to adhere to a protocol for the definition and development of the non-destructive testing techniques to be applied.
The natural evolution of non-destructive testing started fundamentally with the use of ultrasounds generated by a single piezoelectric element, with two possible configurations:

- **Through Transmission**: this is generally used for high attenuation materials, since the sound passes through the material once only. The disadvantage is that access is required to both sides of the component to be inspected and that no information on the position in depth of the defect is provided.

  ![Figure 3. Through Transmission configuration.](image)

- **Pulse-echo**: access is required from one side only of the component and information is provided on the exact position of the indication, including depth. This is not suitable for high attenuation materials since the sound passes through the material twice.

  ![Figure 4. Pulse-echo configuration.](image)

The evolution that has taken place in this field in recent years has been the result of in-depth research. From inspections using ultrasounds generated by single piezoelectric elements in a transmission configuration, pulse-echo inspections were developed, providing more detailed information on the depth of defects. This was subsequently extended to include multiple element piezoelectric probes in which several probes inspected simultaneously, but without electronically combining their beams. The next step in this evolution was the ability for the different piezoelectric elements to interact electronically, providing a control of the orientation and focussing of the beam (Phased-array); in other words, configurable ultrasonic beams are achieved, improving the capabilities of these systems enormously. Mainly complex geometries inspections have been optimized increasing productivity. Manufacturing and maintenance costs are also greatly reduced compared to previous systems, since a lower degree of mechanical complexity is achieved, along with simpler wiring and reduced space requirements.

Likewise, improvements are achieved that have a direct impact on the quality of ultrasonic inspections. The beams obtained are more homogeneous, since the physical differences between the crystals are very small. Phased-array ultrasonic probes are more versatile and are not limited to a single application. There are also improvements in venting and in the supply of water, this providing better coupling of the part, generating a better ultrasonic signal and increasing the scope of the inspection, for example in the inspection of edges. Overall an important reduction in inspection times is achieved.

Once phased-array technology was incorporated in inspection systems, the challenge was to gradually increase the number of elements in order to achieve versatility and, especially, inspection speed. At present Tecnatom possesses equipment developed in-house that makes it possible to have up to 2,048 phased-array elements operating.
The research and development process to which Tecnatom subjects non-destructive tests means that there is an in-house evolution in all fields, for example in the development of ultrasonic data configuration, acquisition and evaluation software, the optimisation of conventional and phased-array ultrasonic probe specification, based on Tecnatom’s capacities and experience, and simulation programmes such as CIVA, which help to simulate ultrasonic beams and their interaction with the defects to be detected, as well as the optimisation of the focal laws to be configured. [5]

Another of the results of research and development activity in relation to non-destructive testing is the optimisation of other more innovative techniques, such as laser-generated ultrasonics, air-coupled ultrasonics or Thermography.

4.1. Laser-generated ultrasonics. (LUS)

Figure 6 shows schematically how a pulse of energy from a CO₂ generator laser instantly heats a given area of the composite part, causing an increase in temperature and in volume that produces elastic stresses that push on the adjacent material. This generates ultrasounds in the component, which are detected by the detector laser associated with an interferometer. The result is a C-Scan with the ultrasonic data of the inspection. [6]

In May 2011, Tecnatom delivered an inspection system based on laser ultrasonics, the configuration of which is shown in Figure 7. This means that LUS is finally available for industrial composite inspection and is a new option for the NDE needs of composite parts.

EADS and TECNATOM have won JEC Europe 2012 Innovation Awards with the LUCIE Project (LUS system).
The fundamental benefits of laser-based inspections are a reduction of the complexity of the mechanical system and tooling, the removal of the need for coupling for generation, which does away with the need for water in inspection, the promising results obtained for both slopes and edges and the considerable increase in inspection speed for large and small components.

Figure 8 shows the results of an inspection performed using laser ultrasonics on a double curvature part. The benefits of the inspection may be appreciated in the resolution obtained in the slope area.

4.2. Air-coupled ultrasonics

Air-coupled ultrasonics use Lamb waves to detect defects in composite materials, using air as the coupling medium, this also making it possible to do without water for inspection. A preliminary study is required to determine the frequencies at which the work may be performed, in order to obtain the resonances of the modes of the Lamb waves in the part. It is also necessary to determine the optimum angle of the probes in order to optimise the resulting ultrasonic signal. Difficulties arise in parts with changes of thickness or of curvature, since in these cases it is advisable to orient the part to obtain a wave resonance in order to achieve a good signal to noise ratio. Furthermore, the existence in the material of mechanically disengaged elements (for example cardboard honeycomb) implies a signal loss that may considerably limit reception. [7]

The following figures (Figure 9 and Figure 10) show the two air-coupled ultrasonic configurations existing: transmission and pitch & catch.
4.3. Thermography

Thermography evaluates the infra-red radiation of bodies following their excitation by different media (mechanical, thermal,...) with a view not to determining their temperature but of obtaining variations in their thermal behaviour, allowing detection of the presence of defects in the material. Foreign bodies or porosities (air) present in the material behave differently in response to heating or cooling to the composite material itself. If these variations are controlled, information may be obtained on the defects present in components. [7]

Figure 12 shows the results of thermographic inspections. The two components are ladders (blocks with different thicknesses steps) with defects at different depths. The difference between the two ladders is the material, the one on the left is a sandwich type component with honeycomb and the one on the right is of a solid laminate material.
The knowledge and use of these innovative inspection techniques (laser-generated ultrasonics, air-coupled ultrasonics or Thermography), along with the optimisation of inspections using piezoelectric generated ultrasounds (transmission and pulse-echo) - where the progress made with phased-array ultrasonics, the optimisation of focal laws, etc. is particularly noteworthy – mean that overall inspection solutions may be proposed depending on the components to be inspected, including one or several non-destructive testing techniques.

After years of research, TECNATOM is now in a position to answer aeronautical customer requirements, giving solution with different NDT combinations. Examples of this are the latest systems delivered by Tecnatom, and that includes sophisticated Phased Array systems for complex geometries like omegas stringers, or Laser Ultrasonic system for big components with double curvature and radius inspection.

5. Evolution of Mechanical Inspection Systems

The tendency in recent years has been to automate the entire process of manufacturing aeronautical components, including inspection. The fundamental objective of automation within the inspection process is to reduce inspection times thanks to the high speed achieved and the length scanned in each run, and in parallel to achieve the inspection of 100% of the surface, including all edge areas. Faster, more repetitive and reliable inspections are achieved, covering a larger percentage of the surface inspected.

The early mechanical systems considered typical gantry or bridge designs that allowed at least six degrees of freedom and provided access to different areas.
The next step in the evolution of mechanical systems was the incorporation of sophisticated industrial robots, allowing for implementing flexible inspection cells, increasing productivity and flexibility.

RABIT is the solution developed by TECNATOM in collaboration with KUKA that makes it possible to incorporate the use of industrial robots in NDT inspection systems.

These RABIT systems adapt the characteristics of industrial robots and incorporate them in an overall inspection system bringing together all the hardware and software required to plan and to configure ultrasonic inspections (specification of probes, definition of the part to be inspected obtaining also geometries by 2D Laser, definition and generation of focal laws, definition of inspection parameters, ultrasonic calibration), the aim being to calculate and to generate inspection trajectories (OLP: Offline Programming Tools: Trajectories generation and also 3D simulations and Post Processing), control the safety of all the elements of the inspection cell, automatic change of probe-holder modules, robot/s control (flexible cells), acquisition of ultrasonic data with on-line monitoring, and obtain results from ultrasonic data with a view to being able to analyse and assess them, including automatic evaluation of ultrasonic data, using predefined criteria, all the above forming part of a common system, completely integrated. [8]

For these developments to be possible, collaboration between TECNATOM and KUKA has been necessary, such that all developments on KUKA robots were to make them adaptable to the entire HW-SW configuration of the Tecnatom system, allowing for control from a global system and facilitating ultrasonic inspection.

The hardware used is 100% standard and a high programming and automation capacity has been obtained. This allows for remote operation via Ethernet of the inspection cell with access to all robot / inspection cell resources. The development undertaken has allowed us to obtain mechanical systems using Tecnatom in-house control software and capable of executing complex inspection trajectories, providing the position and orientation of the Tool Centre Point to Data Acquisition System in real time and using no auxiliary encoders.

For the generation of inspection trajectories, only information on the skin over which the probes are to move, generally the aerodynamic skin or the surface of the stringers, is of interest.

The flexible and powerful inspection system incorporates safety elements that range from laser sensors to 3D simulation of the inspection trajectory allowing verification of its feasibility, controlling possible collisions during robot movements before initialising them.

The final result, RABIT, is a highly flexible system that incorporates one or two KUKA industrial robots integrated with linear tracks, gantries and/or turntables. That allows for adaptation to different non-destructive testing configurations, transmission (2 robots), pulse-echo (one robot), using conventional or phased-array technology and providing the possibility of automatic exchanging ultrasonic modules (with different phased-array probe configurations). This allows the system to be prepared for different kind of inspections in the same inspection cell.

With RABIT systems it is possible to configure automatic exchanging not only of ultrasonic modules but also other tools and devices that are automatically picked up and interchanged when exchange is needed or convenient. An automatic charger reduces the scanning time-out periods, improving productivity.

Using industrial robots in RABIT systems, final costs are reduced, as well as delivery time of the overall inspection system. Maintenance programs are assured in any place all over the world with answer in a very short period of time. Additionally this concept for inspection systems has lower space requirements.

Figure 14 shows a multiple element ultrasonic probe module for the inspection of omega components (left) and on the right a tool storage stand located in the robot work area.
Figure 14. Optimisation of inspection modules. Exchange of modules

Figure 15 shows RABIT system with two robots performing a transmission ultrasonic inspection using single element conventional probes.

Figure 15. RABIT Inspection system with two robots operating in transmission mode.

6. Natural Combination: NDT + Robots

The final result of this joint evolution of techniques and machines is a combination that allows us to offer accurate solutions adapted to the inspection of each component and to the defectology to be detected.

The following figures show examples of specific solutions based on client requirements.

Figure 16. RABIT Inspection system operating in transmission mode, based on one robot with yoke.
7. Conclusions

In the wake of all the developments described in this paper like study of aeronautical material and geometries, optimisation of NDT (phased-array ultrasonics, laser ultrasonics, Thermography, air-coupled ultrasonics) and of the improvements in mechanical & control systems (achieved in collaboration with KUKA), Tecnatom is in a very good position to NDT market with RABIT inspection systems for the automatic inspection of complex aeronautical components (and others) by means of updated NDT techniques and industrial robots.
We have developed a powerful HW-SW technology that allows for the integration of the complete inspection process: teaching/probing, scan path generation, post-processing, 3D simulation, control of robots, acquisition, evaluation, reporting and auxiliary devices, in a unified environment that can be operated by one person.

Furthermore, our technology contemplates the use of different types of flexible configurations based on 1 or 2 robots on linear tracks and/or gantries, working simultaneously on one or several parts and using pulse-echo or transmission techniques.

Likewise, the developments and improvements made in non-destructive testing, not only in conventional piezoelectric ultrasonics (including Phased Array), and also in laser-generated ultrasonics, as well as in other innovative non-destructive testing techniques such as air-coupled ultrasonics or Thermography, have permitted that Tecnatom has increased efficiency of the systems developed in-house, and also have reached an strategic positioning in the Aviation Industry.

8. References

[1] Low-Cost Composite Materials and Structures for Aircraft Applications Dr. Ravi B. Deo, Dr. James H. Starnes, Jr., Richard C. Holzwarth