HIGH SPEED INSPECTION OF COMPOSITE PROFILES

Vincent BISSAUGE, Guillaume ITHURRALDE
NDT EXPERT / TESTIA France
18 rue de Marius Terce | BP13033 | 31024 Toulouse Cedex 3 | France
e-mail : vincent.bissauge@testia.com

ABSTRACT

Carbon Fiber Reinforced Plastics are now widely used in aeronautic components. The advantage of this material is that it allows the airframe designer to save weight and thereby reduce fuel burn (fuel costs being the highest single factor in airline operations today). The components used in stiffening the overall airframe are constructed profile beams. Their common shapes are: T, L, H, Ω, etc.

Dedicated ultrasonic and thermography inspection solutions were developed to capture the critical quality requirements without causing any slowing down to the production rate. These solutions are based on using ultrasonic phased arrays and associated automated guiding mechanisms. The ultrasonic data obtained is automatically processed.

KEYWORDS:

ultrasound, phased arrays, infrared thermography, aerospace, carbon fiber composite, profiled beams
INTRODUCTION

The most recent programs of the international aircraft manufacturers use composite materials on the large scale. The composite parts composing these structures are partly shaped with a nearly-constant section such as T or (omega) stiffeners C or Z frames L angles or cylindrical shaft (cf. Figure 1). Those particular shapes require the implementation of dedicated testing machines given that the parts are submitted to quality requirements and increasing production rates. A 100% inspection is in most cases required.

Figure 1 : examples of profile sections

NDT EXPERT has acquired a strong experience in dealing with inspection solutions by semi-automatic ultrasound, which comply with supplier’s and primes requirements for this type of elementary composite parts (cf. Figure 2). The NDT equipments and machines now developed by NDT EXPERT are automated and dedicated to answer two main problems: in one hand the respect of the quality requirements and on the other hand the adapted automation of the inspection process. These two elements are taken into account from the beginning of the development of the control methods, which conception is carried out according to the shape of the inspected parts, whereas other systems are only adapting themselves: it is called “design to control”.

Figure 2 : Example of a profile inspection by semi-automatic ultrasound

This intrinsically optimized conception leans on a detailed and methodical analysis of the requirements and the objectives of the method. At the same time it insures an optimal repeatability and an adaptation to the production rate. The technological bricks constituting the testing machine are flexible and completely supervised by NDT EXPERT and its network of partners.

The purpose of the document is the presentation of this approach in the context of industrial applications.
1  DESIGN TO CONTROL: UNIQUE PRODUCT, UNIQUE EQUIPMENT

The inspection requirements of a manufactured part rely on three main input data of which the detailed analysis will allow to define the optimized solution (cf. Figure 3): the quality requirements, the part definition and the cycle times.

![Diagram: Main constraints related to the inspection process]

The primary data are all the applicable quality requirements. They depend on the security class of the product and on the prime’s normative system. It allows directing the first choices of the design, in particular the choice of the method. The second datum is the part’s definition and in particular its shape which will guide the sensors and the mechanism definition. Finally the cycle time is the requirement which will mainly define the degree of automation of the system and the number of required sensors. The analysis approach adopted by NDT EXPERT follows reverse process logic, starting from the indication to detect, and so directly related to the CND, towards an overview of the integrated solution in a full manufacturing process. The approach guides the main options of the designed solution.

1.1 Quality requirements

Quality requirements, particularly detection and acceptance criteria, represent the core of the definition of the non-destructive process. The analysis of these requirements allows to guide the first choices and identify the main constraints (see Figure 4).

![Diagram: Main parameters guided by the quality requirements]

This article specifically deals with stratified composite parts (carbon layers or carbon fabric) typically in which possible defects are planar (delamination, foreign objects) and porosity type. For this category of parts and defect, the ultrasound inspection and methods are generally imposed by the client. For non-critical parts and/or outside of the aeronautical field,
the porosity detection (at low rates) is not systematically required thus the choice of methods can be broadened such as infra-red thermography. The knowledge and analysis of these requirements determine the choice of methods used.

In the same way, the minimum detectable defect determines the choice of the used sensors. For the phased array ultrasonic testing, the sensors are chosen according to the focusing and step parameters which are determined by the minimal detectable size and the tolerances for the sizing.

To complete the inspection chain, to face the increasing complexity to process and analyze the information being collected (position of indications, clustering, surface indication, porosity type, indication density) and to comply with traceability requirements, it has become necessary to call upon specific software for this analysis. Moreover, specific NDT analysis software lead to save time thanks to powerful automated data processes.

1.2 Product definition

Beyond the choice of the CND method, the machine design is also directed by optimized definition, positionning and trajectory of the probes compared to the parts definition (cf. Figure 5).

![Figure 5: Main parameters guided by the product definition](image)

Some testing techniques will be preferred depending on the access to the different areas of the part. Thus concerning ultrasounds and thermography the pulse echo or reflection mode is planned when the access to the opposite side is limited. For ultrasound testing method, reflector plate inspection technique will be preferred on areas which are thin and flexible, or on areas where sides are non-parallel. In the same way, specific part geometries will orientate the choice of sensors towards more adaptable shapes. A current example is the inspection of radii with curved phased array probes.

By definition, a profiled structure presents a constant section (or quasi constant) and generally the dimension of the extrusion axis is bigger than the other two. The main scanning direction of the sensors along this generatrix will be naturally preferred to avoid complex trajectories thus to optimize cycle time. However the choice of components to be moved will depend upon the volume of the part to be tested, of the complexity of the measuring system and the shape of the generatrix. It could be interesting to move the part rather than the inspection system if it is not too large or too heavy. In other cases some generatrix shapes can define the choice of the manoeuvring system, for example a turntable for an elliptical generatrix. To sum up, the scanning choice will define the blueprints of the solution and allow integrating the manoeuvring problems of parts and equipments.

Finally numerous profiles show slight variations in sections along their lengths: thickness changes, width of certain areas, radii etc.. Moreover, the same inspection solution must be able to adapt to groups of parts, among which the sections are similar but not identical. The
robustness of a system is defined by its capacity to remain performant despite variations of the external parameters. It can be optimized by different choices. In the first place, some inspections procedures are naturally more tolerant to shape variations than others. For example; inspection by infrared thermography is less sensitive to misalignment of the detector axis in comparison to ultrasonic inspection. As well, the reflector plate technique of ultrasonic testing is more tolerant of slight shape variation or non-parallel sides than pulse echo technique. A second lever to increase robustness is the definition of a more tolerant sensor. For inspection by ultrasonic submersion the optimisation of the ultrasonic probe and the focal laws is preponderant for tolerance to water height variations and for signal amplitude stability drop-offs and slight distortions. Finally robustness is guaranteed by the automatic compliance of the mechanical system similar to the dexterity of manual inspection operator.

### 1.3 Takt time

Within the different obligations, the aim of the takt time is generally the most delicate aspect of the cost of the inspection solution. So it remains necessary to find the appropriate level of performance of the machine and procedure to reach the required cycle time. The characteristics of the means allowing to reduce the duration cycle are the “parallelism” (increase of the number of parallel sensors), the global level of automation (which covers all the inspection steps from the handling to the information analysis) and within a larger framework, the inclusion of other phases and process of the manufacturing sequence (cf. Figure 6).

![Figure 6: Main parameters guided by the cycle time](image)

In the same way as IT architects parallelize their processors, the measurement chains (generally composed of a sensor, an electronic system and a computer) will be multiplied to increase the coverage on the profiled section and decrease the number of scanning trajectories. In the extreme, the global architecture of a inspection die is obtained when the amount of scans are reduced to one. This imposes as many sensors as necessary for the coverage of the section to be complete. The balance between increase of equipments and the number of scans necessary is a compromise.

The analysis of ultrasonic cartographies and thermograms takes up a large part of the cycle time and often introduces repetitive tasks of preprocessing and editing of inspection reports. Part preparation, handling tasks and cleaning monopolize qualified staff and also increase the duration cycle. The automation of physical tasks or data processes can be accomplished as support to mechanization or to robotization (conveyors, robots...) and automation software (cf. Figure 7). The automation choice can be progressive and can be applied to different stages of the inspection cycle (until almost 100%) according to the needs.
Finally, an approach of mutualization of industrial means allows to save time on the global cycle of the manufacturing of a product. This principle will apply especially to solutions with an already highly automated and thus partially autonomous for example the use of a conveyor a sector or a robot. The processes most commonly associated with non-destructive testing are other processes such as thickness measurements and visual and dimensional checks (cf. Figure 8). For the more complex solutions it is possible to integrate processes such as machining (trimming, deburring drilling) or edge sealing.

The approach introduced leads to the architecture of an optimized inspection solution as it arises from the product and the inspection requirements and is built gradually in response to different constraints until a larger view is achieved. In the same way, to fit with the choices of design, the construction of the solution is made by the assembly and exploitation of technological bricks.
2 ASSEMBLY OF TECHNOLOGICAL BRICKS

Like all systems, NDT equipments consist of various subsets which interact with each other (cf. Figure 9). We identify as first subset the detection equipment established by exciters (heating in infrared thermal imaging X-ray tube) and sensors (ultrasonic translator, thermal camera. This first block communicates with the system of acquisition consisting generally of an electronic system and a monitoring software. Once processed, the data are transmitted to the analysis system. The mechanical and automated system puts in reference the part and testing equipment and communicates with the other sub-systems for the definition of the inspection sequence.

The nature and type of the constitutive components of the sub systems and their interactions reflect the choices made during the response to the initial need. It is necessary to adapt each elementary component to the conclusion of the analysis. The principle is based on the exploitation and assembly of homogenous and flexible bricks.

2.1 The modularity of the brick construction

Using bricks allows flexibility therefore the possibility to adapt the whole system with the same technological base and equipment. This principle offers a greater flexibility than with monolithic systems. The application of this principle to inspect high speed ultrasonic profiles with CND equipment is the parallelism of the measurement chains (package including a probe, an electronic card and a computer). In this example, the assembly of elementary bricks contributes to the adequacy of the head of control to the section of the product, provides the possibility to parallelize acquisition and calculation, but also brings the
advantage of upkeeping the mean by keeping spare bricks available, immediately exchangeable.

2.2 The possible automation of all testing steps

The overall degree of automation of the system allows answering to the required takt time. The principle of this modular system allows a sharp adjustment of the automation degree as each brick or group of bricks is managed separately. In particular, various degrees of automation can be defined for each sub-system.

The automation of the mechanical system allows the guidance of the part or the detection equipments. In the less automated dye systems, the elements of the mechanical system will be reduced to clamping tools, guiding rails, turntable or probe handler. On the other hand, on the most automated systems the handling, the clamping and the trajectories can be performed by a robot. For each case, according to the needs of robustness towards the geometry variations of the product, mechanical compliances are defined.

On the NDT machine for manufacturing, the analysis of cartographies is essential to respect the quality requirements and the traceability issues. The analysis is then assisted by image processing software (for ultrasonic C-scan or thermograms for example). This software will be exploited either as an assistance tool for the operator to perform simple operations on the images, or as an autonomous program capable of realizing processes, defect detection and creation of reports according to the qualified written instructions. The results from this automated analysis can also be used to communicate with the other sub-systems and allow then the automation of more complex sequences as, for example, checking the calibration on a reference standard, displaying a pre-sanction in the form of a Go/No Go indication for the operator [1] or the integration in the report of data coming from other control processes.

2.3 Use of bricks to integrate other processes

The components set for the inspection solution can be also adapted and exploited for the integration of other manufacturing processes. In particular, the dye mechanical system, either based on a robot or based on a conveyor, can be used to handle the part and bring it from a point to another, or to implement the various process on a common scanning trajectory. In the second case, the dye principle is applied to the other processes.

In the same way, the bricks forming the data analysis system can also be adapted and exploited to manage and report the data from the other processes.
3 APPLICATIONS

The practical cases of the following sections illustrate the analysis approach followed by NDT EXPERT to bring inspection solutions, built from technological bricks.

3.1 Un moyen CND optimisé : filière de contrôle de cadres de fuselage à haute cadence

DUQUEINE Rhône-Alpes supplies Z-frames for the A350XWB program. These frames are made by bending profiles in prepreg carbon/epoxy. They must be 100% inspected by ultrasound testing to find structural delamination, foreign bodies and porosity. They present general characteristics of profiles: semi-constant section and extrusion generatrix. The takt time should be such that one machine can accept the amount of parts given by the production rate.

The detection criteria imposes an ultrasonic testing method to detected planar defects such as delaminations and porosity. The quality requirements necessitate characterization and traceability of the indications requiring the assistance of powerful ultrasonic data processing software such as ULTIS [2], [3].

Taking into account the overall shapes of the parts the dye solution was quickly retained. However, the section variations of length and curvature of the generative are significant and require certain robustness to guarantee an homogeneous and reproducible testing. As the section is composed of radius areas and flat areas, two types of elementary probes are defined, which will make two of the bricks of the complete system.

The short cycle time imposes the maximization of parallelism and automation. A manual thickness measuring operation resulting from CND must be included with this solution.

From this need analysis, NDT EXPERT has defined a dye solution allowing the acquisition of a part in one scan with an automatic analysis in concurrent operation time, an inspection report and a display of a pre-sanction to sort the parts. (cf. Figure 10).
The center of the system is a set of 8 fixed phased array probes in local immersion covering the section of all parts. These probes are optimized for the detection of small sized parts (under 16 mm²) and for their tolerance of misalignment of the probe on the surface of the part (in ply drop-off areas). A complex system composed of drive rollers, rudder bar and actuators insures the local reference of the part above the probes as well as the scrolling of the part.

Each of the probes is connected to an ultrasonic Smart U32 card of the range Smart NDT tools [4] and to a PC. These measurement chains are monitored by a master PC which transmits the data to an analysis PC embedding the ULTIS software. The monitoring of the Smart U32 has allowed the development of automatic setting and calibration of the entire system in a homogeneous way. The automatic merging of elementary C-scans of each chain makes the use of a phased array probes system transparent for the user.

The analysis carried out by ULTIS in ghost mode leads to the creation of a inspection report (Figure 11) in which only the certified operator’s validation is missing. The choice of parallelizing the data analysis on a supplementary PC ensures the takt time by hiding this process which is managed in a totally autonomous and invisible way. Finally, in order to ensure the flow’s continuity an automatic pre sanction is displayed for the operator, based on the principle of the computer aided diagnosis solutions industrialized by NDT EXPERT [1]. This pre-sanction appears to the operator on a dedicated user interface as a LED associated with each inspected part, whose color indicates the diagnosis.
The ultrasonic thickness measurement is carried out at the same time as the flaw detection. Therefore this test becomes completely transparent in the cycle’s complete takt time and the exploitation of the same technological bricks (dye mechanical system, Smart U32 and ULTIS) enables the creation of a second inspection report, specific to the thickness measurement.

### 3.2 Others concepts of dye-shaped NDT equipments

The concept of the testing means is globally built from the same technological bricks as the testing solutions of the Z-frames. The differences appear on the overall architecture of the dedicated means and thus arise from detailed analysis of the requirements.

The first concept answers to the need for a compact inspection solution by ultrasound of small sized frames with two various shapes, with a takt time of a few minutes by part (Figure 12)
To limit the handling of ultrasound probes and to smoothen the control, the stationary probe solution has been chosen. A number and a specification of phased array probes have been defined to cover with one scan the largest surface of the frame. The set of probes is immersed and the mechanism helps to ensure in all points the perpendicularity of the acoustic beams to the part surface. The part is clamped on one arm tied to a guiding axis helping the operator during the movement.

The parallel connection of the acquisition systems (probes, smart U32 and PC) and the analysis system (PC and ULTIS) allows again to hide the time of analysis and compilation of the inspection report.

This solution offers a high level of software automation with an almost complete reduction of the analysis time and the waiting of the report by the operator. The mechanism and the electronic are simplified for an optimization of the dimensions of the equipment and maximum flexibility for the control of the varied shaped parts.

The following concept was proposed by NDT EXPERT and its partner ACTEMIUM for the inspection of large dimension curved profiles, with the possibility to control other parts of large dimension with various shapes (panels for example). The defined solution relies on an ultrasonic control effector optimized for the control of the profiles associated to a robotic arm with a seventh axis providing flexibility for the inspection of various shapes (cf. Figure 13).

![Figure 13: Solution concept of automatic control of large profiles and parts with various shapes](image)

The frame testing is performed by ultrasound in immersion. The tanks and the clamping systems of parts are parallelized to allow the handling and positioning of the parts in one tank, in time hidden by the inspection by the robot in the other tank. The effector is studied to adapt to the frames section with a parallelization of the probes and of Smart U32 used to decrease the number of scans. The system’s compliance to balance the shaped variations of the parts is given at the same time by: the robot, the mechanical part of the effectors and by the choice of phased array probes and settings less sensitive to the angle from the surface perpendicular angle. A tool changer with effectors non dedicated to frames is added to the solution for the inspection of the various shaped parts.
The evolution capacities of the robot solution on a seven axis allows to consider other kinds of manufacturing processes.

Finally the analysis system incorporating ULTIS and communicating with the rest of the system allows automating analysis tasks and reporting editing.

The last concept presented complies with AEROFONCTIONS needs for a control of spinner A400M components, in particular stiffeners. The characteristics of the stiffeners are a length which is more important than the two other dimensions and a very variable section : from omega to plane section. The flaws detected are only delamination type or foreign object type.

The inspection solution by dynamic infrared thermography has been chosen for its high tolerance for the inspection of surfaces which are non-parallel to the detector (unlike the standard ultrasound testing) and for the speed of the inspection. Furthermore, the application of this method is possible because of the absence of porosity within the detection criteria.

The system allows the inspection of revolution elements composing the spinner on turntable and the inspection of the stiffeners moved by a linear axis (cf. Figure 14).

![Figure 14 : Stiffeners inspection solution by infrared dynamic thermography (translation of the stiffeners)](image)

The robustness of the system is mainly due to the high stability of the control process compared to the different disturbances (variable section, deformation of the work piece, possible variations of the environment such as the temperature, etc.). Besides, the reproducibility is guaranteed by the automation of control sequences, parameters included. In particular the movement of the part, the ignition of the heating and the trigger of the camera are synchronized. According to the modularity principle and the use of bricks, the solution has been defined with a low cost compact and strong microbolometer camera. The analysis system is linked to the rest of the system by the transfer of the inspection data which allows hiding or deferring the analysis work. The software allows the automation of image processing sequences and the use of analysis tools for the positioning of the indications in hidden time (cf. Figure 7) [5].
For this application where the rhythm is not critical, one camera is used and the part is moved twice in front of the heater/camera couple with two different angles of view for the camera. In case of an increase of the rhythm, the takt time can be divided by two on the stiffeners simply by adding a second thermal camera.

4 CONCLUSION

On one hand the described analysis approach leads to the definition of some architectures of dedicated and performant equipments, in particular for the inspection of parts with a constant or nearly constant section. On the other hand the exploitation of adaptable and modular technological bricks allows a flexibility of conception and an adaptation of the automation degree, suiting the customer needs and the requirements of the prime.

The association of these two principles leads NDT EXPERT to propose and to supply many various testing methods (from semi-automatic compact systems to the multi-processes robotized mean) based on the same technological bricks, according to the needs in high rhythm composite profiles testing.

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