ABSTRACT: The increasing use of composites in aircraft industry leads to the need for non-destructive testing systems that are effective in the inspection and evaluation of these structures. Since there is currently a lack of effective systems for inspecting composites, a system that is able to inspect not only composite flat panels but also parts with complex geometries autonomously was developed. This system consists in an instrumented tank that can perform inspections by immersion of complex geometries with a system of five degrees of freedom, which is able to cover a scanning area of approximately 3m².

In order to validate the project a flat composite plate, with embedded and previously known defects, was inspected with ultrasonic phased technique, using a LabVIEW program with pre-defined trajectories. This program was developed especially for this system. The final results demonstrate the efficiency the inspection obtained through this system in terms of inspection sensitivity.

KEY-WORDS Automated inspection system; Aeronautic industry; Composites; Nondestructive testing; Phased Array; Inspection by immersion

1. INTRODUCTION

Non-destructive testing (NDT) is a procedure that allows parts inspection without affecting their functionality. According the type of material, these tests need to be adjusted order to prevent damage. (1) (2) Ultrasonic inspection technique is usually the most appropriate type of inspection for difficult defects. (3) (4) Phased Array is an advanced variant of the ultrasonic technique and it can be applied in any scenario where traditionally conventional ultrasounds are applied. This method allows the user to control parameters such as the emission angle of the beam and the focal length, there by increasing the probability of detection defects. (5) (6) The inspection technique by contact is specific for manual testing, and the inspection by immersion is specific for tests by automated systems. In this type of inspection, the probe and the part to be inspected are both immersed to ensure an optimal and uniform coupling. This type of inspection can achieve faster productivity in terms of quality control and can be automated, and a single probe can be used with various angles of incidence. Since there is no direct contact between the workpiece and the probe the probe wear does not exist. (2) (7)

Some constraints are still found when trying to perform a NDT inspection with Phased Array. Among these restrictions the complexity of the geometry of the components play an important role, because they lead to poor performance of probes since the characteristics of the beam cannot be preserved. The thickness variation during the examination can be problematic because there will be the need of different inspection setups to ensure the inspection effectiveness.

To tackle this problem, a technique based on an iterative process of data acquisition by measuring the times of flight of the wave was implemented. A law of delay is calculated through these times and is applied to all the elements of the probe. This technique is called Adaptive Surface Ultrasounds (SAUL). This technique allows using the same probe to analyze various structures of complex
geometry through an iterative algorithm. With this approach a normal incidence of the beam in any point of is achieved surface without the need of an adapted probe to the profile of the geometry. (8)

The most common defects of composites are debonding and delaminations. Delaminations usually occur in the manufacture of the composite when some undesirable element lies between layers. Debonding may come from an inefficient adhesion between of the composite layers or by the lack of resin between the same elements. To detect these type of defects it is convenient that they are oriented parallel to the plane of the probe.

Given these limitations abovementioned to the aim of the present work is to develop a flexible system that will be adaptable to different inspection scenarios depending on its restrictions. The system will be fully adjustable to complex geometries, as for example variations in the curvature radius along the geometry profile.

2. PROJECT

Aiming to build an inspection immersion system where it could be possible to inspect materials with the Phased Array technique, it was proposed to design the following elements:

- A stainless steel tank with dimensions of 2500x1300 mm, with an area of 3 m², able to support a head of water of 500 mm to inspect components using ultrasonic techniques;
- An autonomous system of water recirculation using a water pump and appropriate filters;
- A centralized control system, with all the electronics required for the handling of the probe;
- A system of linear actuators responsible for the movement of the X, Y and Z axes which could achieve a speed of 100 mm/s with an accuracy of 0.1 mm;
- An arm, 700 mm long, connected to the vertical Z axis with the capacity to hold and adjust the probe with two automated degrees of freedom.

In parallel to the tank design several structural simulations, using Solidworks modeling tool, were done, considering the appropriated load profile in order to obtain results about the performance of the designed tank.
The final tank is presented in the following figures.

Figure 2 - Isometric view of the tank

With a water mass of about 2500 kg, the boundary conditions were defined in each face of the tank in terms of the correspondent pressure. To the side metal sheets and the acrylic, the force applied was based on the concept of hydrostatic pressure. In addition, the gravity force was applied and the supports of the tank were constrained in all directions.

The materials used in SolidWorks were:

- AISI 304 - Yield Stress = 206.8 MPa for all reinforcing bars and plates used
- Acrylic (Medium-high impact) - Yield Stress = 45 MPa for the acrylic used in the front of the tank.

From the simulation, the following results were obtained:

Figure 3 - Distribution of stresses in the tank

Figure 4 - Distribution of deformations in the tank

The maximum stress value in the tank was 96.7 MPa and the maximum deformation was 1.49 mm, obtaining an overall safety factor of 3.21.

Another element designed was the coupling arm of the probe which is presented in the following figures:
Through a set of bearings, as it can be seen in Figure 6, the independent movement in each degree of freedom was achieved, obtained from the rotational motor and the tilt motor of probe.

To fix the probe was necessary to use dedicated concepts, as is seen in Figure 7, not only to have a system fix the probe but also to allow a precise lateral adjustment to perform the inspection.

The final design on the complete system is shown in the following figure:
3. CONSTRUCTION

After the material and components acquisition they were connected using welding processes. The main process was the Tungsten Inert Gas (TIG) (9). Other processes such as Shielded Metal Arc Welding (SMAW) (9) or Stud Welding (SW) (10) were also important during the construction of the tank.

As TIG is very efficient to weld thin metal sheet, this process was extensively used for the majority of the welds since it allows a more precise control of heat input obtaining high quality welding beads. For the present case, weldings of 2 mm stainless steel sheets, it is desirable to use direct current with direct polarity. In general the welding parameters were an Intensity 80 A, with gas rates of 10 l/min using rods of filler material specific for the AISI 304 steel.

The welds were made with the back stepping welding technique, i.e. with limited advancement and intervals in order to prevent a large heat input in the base material and thus to reduce the welding distortion. (11)

To develop the water filling and recirculation system, different devices were purchased and assembled. In Figure 10 is presented the recirculation system and its different elements.
Figure 10–Recirculating water system and pump

Table 1 - Legend of components in the recirculating water system

<table>
<thead>
<tr>
<th>Item</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16/12 BulkheadPush-to-Connect</td>
<td>Water input from the tank for recirculation.</td>
</tr>
<tr>
<td>2</td>
<td>16/12 BulkheadPush-to-Connect</td>
<td>Water input</td>
</tr>
<tr>
<td>3</td>
<td>Tap ½”</td>
<td>Tap to open and close the flux of water from the tank.</td>
</tr>
<tr>
<td>4</td>
<td>Water filter</td>
<td>Removes the impurities in the water..</td>
</tr>
<tr>
<td>5</td>
<td>16/12 Push-in ElbowSwivel</td>
<td>Accessory that leads the flux of water to the tank.</td>
</tr>
<tr>
<td>6</td>
<td>Check Valve</td>
<td>Valve that allows the water to flow through it in only one direction</td>
</tr>
<tr>
<td>7</td>
<td>16/12 BulkheadPush-to-Connect</td>
<td>Water exit to the sewer.</td>
</tr>
<tr>
<td>8</td>
<td>8/6 BulkheadPush-to-Connect</td>
<td>Water output for the probes.</td>
</tr>
<tr>
<td>9</td>
<td>Pump</td>
<td>Device that moves the water by mechanical action. Can recirculate the entire water volume in about one hour.</td>
</tr>
</tbody>
</table>

The electrical system followed the same idea of the previous system, but having a special attention in handling the components due to electric current flow.

The final design of the electrical and electronic engine control system, after the assembling of the different components, is presented in Figure 11:
### Table 2 - Legend of the electrical system

<table>
<thead>
<tr>
<th>Item</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RCD</td>
<td>Device that disconnects a circuit whenever it detects a electrical leak.</td>
</tr>
<tr>
<td>2</td>
<td>Circuit Breaker 16 A</td>
<td>Automatic electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit.</td>
</tr>
<tr>
<td>3</td>
<td>Analog Timer</td>
<td>Allows activation of the water pump over a certain time interval</td>
</tr>
<tr>
<td>4</td>
<td>Circuit Breaker 6 A</td>
<td>Automatic electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit.</td>
</tr>
<tr>
<td>5</td>
<td>Current transformer 220V AC - 24V DC</td>
<td>Produces a reduced current accurately proportional to the current in the circuit</td>
</tr>
<tr>
<td>6</td>
<td>+24V/-24V DC</td>
<td>Terminals for voltage supply to the digital positioning controllers and other elements that works with voltages of 24V.</td>
</tr>
<tr>
<td>7</td>
<td>Relay</td>
<td>Allows control a circuit by a low power signal (with complete electrical isolation between control and controlled circuits).</td>
</tr>
<tr>
<td>8</td>
<td>Cable connectors</td>
<td>Used to connect the cables inside the enclosure</td>
</tr>
<tr>
<td>9</td>
<td>Digital positioning controller</td>
<td>Allows controlling each motor individually through a PC.</td>
</tr>
<tr>
<td>10</td>
<td>Ground Bar</td>
<td>All ground connections are done by this bar.</td>
</tr>
</tbody>
</table>

The final version of the integrated system, after being assembled and calibrated for the required operations, is presented in Figure 12.

![Figure 12 - InspectionSystem](image)

### 4. SYSTEMVALIDATION

The Carbon Fiber Reinforced Polymer (CFRP) panel used for validation of the system intended to simulate a section of aircraft fuselage with longitudinal stiffeners. This component consists of a monolithic panel of carbon, in which three reinforcements were bonded in order to increase its resistance to bending loads.
During the panel inspection and the system validation, the panel was subjected to several mechanical tests of fatigue and impact and nondestructive testing was performed between each testing phase. Five impacts were made on the plate with different loads. These impacts as well the strain gauges are shown in Figure 14:

In Figure 15 and Figure 16 acquisitions made by a 10 MHz Phased Array probe are presented, which represent the background echoes of the composite panel after the first cycle fatigue, and after the last cycle fatigue, respectively.
In the two figures squares are represented to assess the evolution of defects in the panel. These squares represent:

- In squares 1 to 5 area number of pin-hole areas due to small lacks of resin;
- In square 1 and 5, there are flaws of delamination around the sensors
- In square 5 a defect due to the impact test can be seen.

Through the analysis of the two acquisitions, and due to the inspection system sensitivity, is possible to verify that there is an increase in the monitored areas.

5. CONCLUSION

Regarding the different developments, it is worth noting that they have been implemented successfully and on schedule.

Apart from to the acquired knowledge derived from the complete development, including all stages, of a system capable of addressing the requirements initially defined, several contacts with various suppliers of all elements required for the system were made, in order to compare the various options and choose the best supplier in terms of cost and quality of the components.
Concerning the system manufacturing the main conclusions are the following:

- A Stainless steel AISI 304 immersion tank with external dimensions of 1320mm by 2500mm was successfully built.
- The recirculating water system was successfully assembled achieving a water recirculation time for the entire tank of 1 hour.
- The electrical system was one of the components that required more effort due to its complexity. It was possible to successfully manage the control system from a set of six motors which are part of the inspection system.
- The linear actuators X, Y and Z are all very important to the system due to its accuracy and function. With the actuators and the engines mounted it was found that the overall module complies with the required precision and speed.
- The arm attached to the vertical axis Z was one of the most complex elements to design, manufacture and assemble, due to its functional specifications. At the end this was able to rotate and tilt the probe and it has a fine-tuning adjustment for the probe.

Although it was not originally planned, some acquisitions were made in composite pane in order to prove the overall capability of the system developed. To make this task possible a program in LabVIEW was developed in parallel that was able to operate the mechanical part of the phased array inspection system. This program has several features, allowing the predefinition of different types of customized scanning trajectories in order to inspect parts with complex geometry.

6. Bibliography