Automated misalignment correction method for ultrasonic inspection of CFRP parts

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Abstract

Ultrasonic inspection of large CFRP components requires an accurate positioning of the part with respect to the equipment’s coordinate system to ensure normal incidence during the scan. Fulfilling this condition often implies impractical and time-consuming manual adjustments of the part. A new method is proposed for ultrasonically determining the position of a complex part installed in an inspection system, and automatically correcting the offline-programmed path instead of iteratively and manually adjusting the part’s position. Two application strategies of our method are presented and experimentally tested on a complex CFRP landing gear component. The results suggest that even the simplest strategy using a planar learning scan of a randomly positioned part can produce C-scans of equal quality as those obtained with the manual alignment, in a fraction of the time that this process usually takes.

KEYWORDS: Ultrasound, robotic automation, CFRP, geometry, registration

1. Introduction and background

Carbon-fiber reinforced polymers (CFRP) components are generally inspected by ultrasonic testing (UT) using pulse-echo technique at normal incidence. Significant efforts have been made in the last decades to automate these inspections and automated UT systems dedicated to CFRP components are now widespread in the industry [1]. These systems generally operate with the following steps: an optimal probe trajectory is programmed from the CAD file of the part to be inspected using off-line software. The part is installed and located in the inspection equipment. The probe is then moved to follow the contour of the part according to the generated trajectory while maintaining a constant probe-part distance (called the water column) and, more important, a zero-degree angle between the incident beam and the normal to the part’s surface. This process may seem basic and easy to automate, but it requires a precise positioning of the part with respect to the equipment’s coordinate system, as errors of only a few tenths of degrees on the incident angle are sufficient to generate prohibitive signal loss. In practice, positioning and aligning large or complex CFRP components can be particularly challenging. The simplest methods used to get a proper alignment rely on an accurate positioning of the
part in the equipment using jigs and other mechanical elements containing their own reference. However, unlike machined metallic parts for example, CFRP parts can have significant geometric variability while still being compliant, and these reference elements are often insufficient to guarantee an optimal alignment during the whole scan. Another approach is to ultrasonically locate specific features (such as holes, corners, etc.) during the inspection preparation to find the part’s position and orientation. Nevertheless, this process is often tedious, difficult to automate, and for some parts, it may not be possible to determine singular points that can be easily detected by ultrasound. Other solutions that use sensors to correct the probe’s position and orientation [2-4] have also been suggested. However, a retroactive loop must be added to the inspection process, which makes these approaches difficult to implement. More recent approaches use electronic compensations of the emitted beams such as the Surface Adaptive Ultrasound (SAUL) algorithm [5]. This algorithm recalculates the focal laws of a phased-array probe during the scan according to the interface echoes obtained during previous shots. The angle is adapted so that the next emitted beam penetrates the part’s surface under normal incidence. These compensation methods can give reliable results for some components, but they are only efficient for small misalignments (as it is necessary to get a returning signal at each position to compute the laws corrections) and they only work with phased-array probes.

Because of the lack of systematic and easy-to-integrate solutions, the corrective actions deployed in industry are often limited to impractical and time-consuming manual adjustments. We propose a new method to precisely locate a CFRP part positioned in an automated ultrasonic equipment. The method works on complex shapes and no remarkable geometric features are required. The initial positioning can be approximate and no further adjustment to the part position, nor to the emitted beam are needed.

2. Method

In the proposed method, the part’s position is detected through an additional quick scan that allows to collect partial, but sufficient data to determine its misalignment relative to an ideal positioning, and to modify the inspection program accordingly. Such a solution will be considered valid if the time required by this additional scan is significantly shorter than the manual adjustment process, and if the resulting alignments are comparable in quality. Before starting the actual inspection program, a learning scan is performed, during which a point cloud \((P)\) is extracted from the surface of the part exposed to ultrasounds. A second point cloud \((Q)\) corresponds to points sampled on a triangular mesh representing the surface of a part in its ideal position. Using the point-to-plane iterative closest point (ICP) algorithm [6] implemented within the open3d library [7], the theoretical point cloud \((Q)\) can be registered on the experimental one \((P)\), so that the rigid transformation from the ideal position to the actual one is known. This transformation is then applied to the inspection program. Two different strategies to apply this method were tested, corresponding to different types of learning scans: part-dependant and planar.

The part-dependant learning scan corresponds to the actual inspection program performed on a quickly and approximately pre-aligned part so that the collected data is partial. However, if the probe receives enough echoes to build a 3D point cloud corresponding to the part’s surface, the registration can be performed. The main advantage of such a learning scan is that data can be collected from different sides of the
part, allowing for a more complete point cloud used for registration. The principal drawback is that an initial pre-alignment is required to ensure sufficient returning signal, and to avoid a collision of the probe with the part throughout the scan. The part-dependant learning scan is thus relatively long (compared to the planar learning scan detailed in the next paragraph), but still significantly quicker than the manual alignment process.

During the planar learning scan, the probe moves above the part and follows a simple planar raster path. The ultrasonic beam aims in a predefined direction and collects a point cloud which might be strongly incomplete depending on the returning signal. The interest of this approach is its implementation simplicity: planar paths are easy to build, fast to perform, do not depend on the part’s geometry, and do not require a precise initial positioning. The main drawback is that an incomplete point cloud will be collected for parts with few “well-oriented” (i.e., perpendicular to the incident beam) surfaces.

3. Results and discussion

The method was tested on a real CFRP landing gear drag brace (Fig. 1). The part is half of the full component (it was cut after being submitted to a destructive tensile test). It is of particular interest to evaluate our method: it is a full-scale component made of aerospace grade composite, with a complex geometry (multiple radii of different curvatures, a center portion including a slope and complex curved surfaces).

![Figure 1: Isometric view of the drag brace used for the experimental validation.](image)

The automated UT equipment used for the inspections is a 5-axes immersion tank designed and manufactured by TD NDE. A conventional 5 MHz Ø0.375-inch probe (Olympus V326-SU) with a theoretical near field distance of approximately 85 mm was used for availability reasons at the time of the tests. With a phased-array probe and an inspection system with at least 6 axes, the proposed method would be even more efficient as the learning scan would be 10 to 20 times faster. The ultrasonic instrument used during the tests is a Topaz32 by Eddyfi. An optimal inspection trajectory was automatically generated from the drag brace CAD file using CAD2UT/flatten software [8].

A manual alignment process that took 150 min was used as a reference for comparison with the two automated alignment strategies detailed in section 2. The NDT technician performed iterative measurements of the water column and the entry echo amplitude followed by alignment corrections of the part. Then, the part’s origin was found by detecting its contour and the center of the hole in the lug region through amplitude drops when the probe moved above these regions. The 150 min delay could be reduced using mechanical reference elements. It also depends on the technician’s skills and the aimed alignment precision. However, it still constitutes a realistic reference since it was performed by an experienced technician.

The first alignment strategy is based on the part-dependant learning scan which requires a coarse pre-alignment. After placing the drag brace on a flat support in the immersion
tank, the operator made some quick adjustments: he aligned the longest dimension of the part with the x-axis of the immersion tank, used shims to correct important angular offsets, evaluated the water column, and roughly located the center of the part’s hole. This procedure took about 10 min. A learning scan using the full inspection trajectory with a 2 mm resolution was then performed (duration of approximately 30 min). The times of flight (ToF) of the entry echoes on the part’s surface were recorded and converted into a point cloud. The developed algorithm was used (about 2 min) to determine the rotation and translation offsets, and corrections were made to the inspection program which was executed a second time. The overall 42 min alignment time is still significantly quicker than the 150 min required for a complete manual alignment for this part.

For the second strategy, the operator simply put the drag brace on a flat support with no particular orientation in the immersion tank. This positioning only took 2 min. The probe than realized the planar learning scan, a 600 mm × 250 mm rectangular raster scan with a 2 mm resolution. The ultrasonic beam was normal to the learning scan plane. The scan took about 10.5 min. With an equivalent 32 elements phased-array probe, the same scan would have taken less than 1 min. The ToF of the entry echoes on the part’s surface were recorded and converted into a point cloud. The proposed algorithm was then applied, and rotation and translation corrections were calculated (taking about 30 s), before applying the corrections and executing the complete inspection program.

Figure 2. ToF and Amp C-scans before alignment with strategy #1 (a, b) and #2 (c, d), after manual alignment (e, f), after alignment with strategy #1 (g, h) and #2 (i, j).

Fig. 2 presents the C-scans obtained during the learning scans of strategy #1 (pictures a, b) and strategy #2 (c, d), and after the final inspection of the part aligned by a manual process (e, f), strategy #1 (g, h) or strategy #2 (i, j). The ToF C-scans represent the water column, and the Amplitude (Amp) C-scans show the first echo obtained on the part’s surface. Table 1 presents the time required to perform each step of the alignment methods and some quantitative results about the quality of the scans. In this table, 0.5% of the larger ToF C-scan values were removed to get rid of possible outliers before calculating water column intervals and standard deviations (SDs). A scan on an aligned part should
have a small number of points with “low amplitude” on the Amp C-scans of the entry echo. Every point with an amplitude of 6 dB below the average amplitude was considered as a low amplitude point (LAP). The ratios of LAP were calculated for each inspection (see table 1). Tight water column intervals centered on the target value of 85 mm, small water column SDs and low LAP ratios are quantitative indicators of a good alignment.

The inspection scan showed that the alignment obtained with the manual process was quite good: the ToF C-scan (Fig. 2e) shows small variations of the water column limited to 3.7 mm, with a SD of 0.4 mm. The Amp C-scan (Fig. 2f) has a relatively homogeneous amplitude, and the ratio of LAP is only 10%. However, some alignment problems persist and lead to low amplitudes on one of the curved surfaces (zone circled in red on Fig. 2f). This alignment can still be considered as sufficient to perform a decent NDT inspection of the part. It is worth noting that the part considered here has large flat portions and various remarkable features facilitating the detection of its origin. The manual alignment process would probably be much longer, if not impossible without using external fixtures, for parts with fewer or no clear geometric references.

### Table 1. Duration and performance of each alignment strategy

<table>
<thead>
<tr>
<th></th>
<th>Manual alignment</th>
<th>Automated strategy #1</th>
<th>Automated strategy #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time to install / align the part in the immersion tank</td>
<td>150 min</td>
<td>10 min</td>
<td>2 min</td>
</tr>
<tr>
<td>Duration of the learning scan</td>
<td>0</td>
<td>30 min</td>
<td>10.5 min</td>
</tr>
<tr>
<td>Algorithm computation time</td>
<td>0</td>
<td>2 min</td>
<td>0.5 min</td>
</tr>
<tr>
<td>TOTAL alignment time</td>
<td>150 min</td>
<td>42 min</td>
<td>13 min</td>
</tr>
<tr>
<td>Initial alignment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water column [Min, Max] (mm)</td>
<td>unknown</td>
<td>[79.1, 89.4]</td>
<td>[86.7, 131.5]</td>
</tr>
<tr>
<td>Water column SD</td>
<td>unknown</td>
<td>2.1 mm</td>
<td>13.7 mm</td>
</tr>
<tr>
<td>Low-amplitude points ratio</td>
<td>unknown</td>
<td>29%</td>
<td>36%</td>
</tr>
<tr>
<td>Final alignment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water column [Min, Max] (mm)</td>
<td>[83.7, 87.4]</td>
<td>[83.9, 85.7]</td>
<td>[83.6, 86.1]</td>
</tr>
<tr>
<td>Water column SD</td>
<td>0.4 mm</td>
<td>0.3 mm</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Low-amplitude points ratio</td>
<td>10%</td>
<td>10%</td>
<td>9%</td>
</tr>
</tbody>
</table>

The automated correction method used in strategy #1 required about 42 min. The ToF and Amp C-scans generated during the learning scan (Figs. 2a and 2b) show that the quick pre-alignment results in a 10.3 mm variation of the water column (with SD of 2.1 mm) and a LAP ratio of 29%, indicating an approximate initial alignment, coherent with the positioning requirement of strategy #1. After the misalignment correction, ToF and Amp C-scans were obtained (Figs. 2g and 2h), and these values decrease to 1.8 mm, 0.3 mm and 10%, respectively. Combined with the relatively homogeneous amplitude of the Amp C-scan (Fig. 2h), this indicates that the quality of the automated alignment is comparable to that of the manual alignment but 3.5 times faster. Such a correction method could be used in inspection systems equipped with machined jigs or other mechanical reference elements which provide a rather good initial positioning. The misalignment correction strategy #2 was even faster (overall time of approximately 13 min). The learning scan ToF and Amp C-scans (Figs. 2c and 2d) showed a 44.8 mm water column variation with a SD of 13.7 mm, and a LAP ratio of 36%, overlying that the part initial positioning was far from ideal. After the misalignment correction, the same values extracted from ToF and Amp C-scans (Figs. 2i and 2j) become 2.5 mm, 0.6 mm and 9%, respectively. These
results are comparable to those of the manual alignment and of strategy #1. It is worth noting that the registration was done with a partial point cloud (compare Figs. 2c and 2a, for example) since a returning signal is only possible for small angles between the ultrasonic beam and the normal to the surface. Nevertheless, it has been possible to correct the part’s misalignment without the need of remarkable geometric features. Since planar regions of the part could potentially return an echo, the ultrasonic beam aimed perpendicularly to the learning scan plane of strategy #2. From the part’s CAD, a theoretical shooting angle that optimizes the returning signal for the whole part could be calculated and used instead as the fixed orientation of the beam.

4. Conclusions

A new method was proposed for ultrasonically determining the position of a complex part installed in an inspection system, and automatically correcting the offline-programmed path accordingly. Two strategies were presented: a *part-dependant learning* scan which requires a coarse pre-alignment of the part, and a *planar learning scan* that works for a quasi-random initial positioning. Experimental validation on a complex CFRP landing gear component showed that both strategies give misalignment corrections comparable to a careful manual positioning. The *part-dependant* and the *planar learning scans* strategies respectively took less than a third and less than a tenth of the time required for the manual alignment process. A method to optimize the shooting angle to collect more complete experimental point clouds during the planar learning scans will be developed and evaluated.

Acknowledgements

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References