Robot-operated quality control station based on the UTT method

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Abstract: This paper presents a robotic test stand for the ultrasonic transmission tomography (UTT) inspection of stator vane thickness. The article presents the method of the test stand design in Autodesk Robot Structural Analysis Professional 2013 software suite. The performance of the designed test stand solution was simulated in the RobotStudio software suite. The operating principle of the test stand measurement system is presented with a specific focus on the measurement strategy. The results of actual wall thickness measurements performed on stator vanes are presented.

Keywords: Guide vane, robot-operated quality control station, UTT method measurements

1 Introduction

The turbine rotor guide vanes (the stator) of a turbofan engine are components which shape the engine gas path. The vanes are also highly exposed to dynamic loads from the hot gas stream (reaching temperatures which range from 950°C to 1650°C) [1]. Hence, it is essential to improve the high temperature resistance of rotor blades with ceramic thermal barriers and by cooling the stator during operation. The cooling process of the component requires production of a complex cored casting, where the core forms the internal passages that pass the cooling medium and reduces the component weight. The cooling process gives a temperature gradient across the casting wall section. The temperature gradient induces heavy thermal stress that may contribute to failure of the casting (by fracture) and its protective thermal barrier (by chipping, cracking and flaking). The component weight is reduced and the stator segment and vane cooling system performance is improved by making the vane casting walls thinner. It is then critical to assure dimensional repeatability of wall thickness during the manufacturing process. The measured titanium stators are manufactured by an investment core casting method [1]. Among the available NDT (non-destructive test) methods applied in a wall section inspection, e.g. active thermography [2], CT (computer tomography) [3], and eddy current defectoscopy [4], ultrasonic measurement methods [5] are the most popular. In general, three measurement methods are used during ultrasound measurements: echo [6], shade [7] and resonance [8]. The method selected for the measurement depends on the workpiece size and material. The solution described here uses the echo method, with two sensors being used to deal with the complex workpiece design.

The choice of test medium is also important, and depends on the measurement method used and the environmental conditions. Manual defectoscopy uses gels [9], while robotic or automated systems tend to use water and oils [9, 10]. However, if the measurement temperatures are low, silicone gels are used [11]. In this paper, water was used as the medium.

An industrial plant currently performs vane wall thickness inspections by manual application of ultrasonic testing. This is done by applying the measurement points on the inspected pieces with a graphic marker. The locations of the points are determined with special templates. The next step of the process is to manually measure the vane wall thickness at the marked points with a handheld flaw detector tool. The measurement results (thickness) are fed with the individual measurement point numbers to a PC workstation which generates the measurement report. The solution has a long processing time. One guide vane seg-
ment takes approximately 6 hrs to inspect. This generates a risk of errors from operator’s fatigue at work.

The need for continuous quality control increases the process time, which in turn results in higher costs, hence leading to the search for automated [12] or robotic solutions [13]. We were able to find solutions involving 2-axis [10], 3- and 4-axis dedicated robots and dedicated mobile robots for special non-destructive testing [14]. In addition to the dedicated robotic structures, there are also a small number of systems based on standard 6-axis robots [15].

An alternative stator vane wall thickness inspection method is a process automated with a robot unit and explained below.

2 Robotic measurement test stand

The robotic test stand was designed with a set of guidelines. A CAD model of the stator to be inspected and a known stator weight were used to select a grab and to design its jaws, and a fixture cassette for the inspected detail. A docking station was also designed to fix four stators. The type of the robot to be used on the test stand was determined by the input weight of the stator, the grab and the fixture cassette, and the required motion range. Based on the available processing documentation, the positions of the measurement points across the stator vane surfaces were input into the design. The couplant selected was water.

![Figure 1: Test stand (a) RobotStudio software (b) Actual test stand.](attachment:figure1.png)

The accepted design guidelines were a basis for a series of simulations of the robotic test station configurations in RobotStudio. The simulations facilitated establishing the robot positions that permit reaching all measurement points of the test piece. The simulations helped determine

The dimensions of the liquid couplant bath, the test stand frame arrangement, the layout of all test stand components (the docking station, the loading door, the safety components, and the locations of the PC workstation and the robot controller). The simulation stage revealed that it was not possible to reach all measurement points with a single UT probe, and thus two such probes were included in the design. The generated 3D model of the test stand served as an input for the test stand baseframe, designed in Autodesk Robot Structural Analysis Professional 2013. The structure had its workshop drawings and a 3D model developed.

Further simulations were processed in RobotStudio with the developed test stand model to design the robot grab TCP trajectory. All components of the test station were simulated and control signal relations were defined to permit control of the robot grab movements. The mode of communication was proposed to handle the data exchange between the robot controller and the measurement module board, a device managed by the Sonic software tasked for measurement performance and reporting. Once the test station structure, electrical interfaces and communication mode were produced, a program for the robot controller and the measurement environment software were developed.

The problem with the design of robotic NDT inspection systems is that, despite the advances made with this casting method, the manufactured details may vary by several percent in terms of geometry. This is due to the casting solidification process and several other effects that occur as the casting cools. The potential for geometrical deviations of the individual castings from the original CAD model requires that the design of the robotic test station and its software must consider the actual dimensional differences and their random variations. For correct measurement, the measuring header must be set in the normal axis to the casting plane at the set point. In the presented solution, an algorithm based on information from the feedback loop changes the orientation of the workpiece being measured until the maximum value is reached. This provides an automated UTT inspection of the stators, including the random geometrical variances of the stator details. This approach is a genuine copyrightable solution, and the authors have not encountered any similar solutions in the literature available to them. The solution has been verified by comparison with the manual UT measurement method carried out using a Novascope 5000.

The last design and production stage of the robotic test stand was to equip the deliverable with safety components, light barriers, and latched locks. The accuracy of the developed solution was verified by a series of demonstra-
tion measurements, where the measurement results were compared to the results produced by an industrial plant Quality Control.

3 Station software

The controller’s software uses a RobotStudio environment and VirtualRobot™ technology, by which the robot simulation is controlled by the operating system deployed in the actual robot controllers. This ensures full compatibility of the developed robot programs with the actual operating environment. The designed software was assumed to have a robot operating on a fixed object, i.e. the inspected stator, with the robot tools being UT scanning probes (Fig. 2). This assumption is critical to the programming of the solution and greatly facilitates the design process.

Having a solution by which the scanned work object and its coordinate systems are in motion, with both tools being fixed, helps to design the motion paths faster and to modify them with greater ease.

Each of the six stator vanes has to be measured at seven sections and 28 measurement points. This operation is performed with four robot wrist paths. The robot software was designed to tie two of the paths with the right UT scanning probe and the other two with the left UT scanning probe.

Geometrical differences in the castings randomly vary by several millimetres in different planes. These geometrical differences prevent the UT sensors from measuring the wall thickness values at certain measurement points. For those points, the echo amplitude registered in LabView is too small, preventing measurement from taking place or affecting the measurement accuracy.

Due to this, the station software carries out a “point sweep”, finding the correct alignment of the stator relative to the UT sensor at the pre-set measurement point location. In this position the echo amplitudes exceed the minimum thresholds that ensure a good measurement.

The sweep procedure was designed with the RAPID language emergency situation handling functionality. The UT measurement follows, and the echo amplitudes are recorded. The tests completed on various castings of stators allow the conclusion that the sweep and good orientation location procedure are unnecessary in 70% of all cases. In the remaining cases, the designed sweep procedure allows a correct measurement to be made despite the dimensional deviations of the scanned details.

4 UT measurements of stator casting quality

The application of UT measurements for the determination of material section thickness is based on the physical phenomena of wave propagation, i.e. the reflection (echo) of the wave incident to a medium of which its physical and chemical characteristics are different from the tested material. The reflection (echo) point is the interface between the test material and the medium. The phenomenon is caused by the change in the acoustic resistance of the wave. The reflected wave amplitude is increasing with the wave resistance difference between the two media. Hence, if an echo of the sound waves is present in the investigated medium, there is a discontinuity within the medium. If the time from transmitting the sound wave in the tested medium to the return of the wave reflected by that discontinuity can be measured, the wave propagation velocity in the given material is known. This way, the distance covered by the wave can be established and the material thickness can be determined.

The produced robotic test station application uses a UT wave transceiver formed by two piezoelectric elements. The location of the piezoelectric elements was determined by the form of the inspected casting. The location of the piezoelectric transceivers was determined by simulation in RobotStudio. The concept of measuring the cast vane wall thickness is shown in Fig. 3.

Figure 2: Layout of the coordinate systems and tools on the test stand.

Figure 3: Measurement concept.
The robotic measurement of vane wall thickness involves a verification of the casting section thickness across a sequence of measurement points. The couplant applied in the solution is water. An example of the measurement signal is shown in Fig. 4. The visualised wave trend features three characteristic areas. Area 1 is the wave echo caused by the design of the UT probe. This trend fragment has no relevant measurement data. Area 2 is the echo at the interface between the couplant and the outer casting surface. Area 3 is the echo at the interface between the casting and the couplant.

![Figure 4: Example of the measurement signal with characteristic areas.](image)

The thickness is measured with upper signal amplitudes, which eliminates the measurement of the distance between the upper and lower halves of the amplitude. The measurement is performed by determining the time of signal transition between echo 1 and echo 2. Three level indicators, or gates (Fig. 5) are applied in this measurement. The gate no. 1 is the detection of the echo maximum and it automatically determines the signal analysis area on the x-axis. Based on the yellow gate position value, the coordinate x of the blue gate is dynamically determined. This facilitates locating the echo 1 amplitude value within gate no. 2. In the next step, the gate no. 2 value is used to automatically determine the coordinate x value of gate no. 3. This facilitates locating the echo 2 amplitude value within gate no. 3. Thanks to the dynamic gate positioning, the measurement system is immune to the effects of changes in the distance of the UT transceiver probe from the test item.

The coordinate y values of gates 1 and 2 were selected experimentally to have the echo values higher than the values assumed for the gate level. The lower limit must be higher than the signal variation amplitude. During the experiments, the y value was 20% of the maximum signal amplitude. The applied measurement method requires calibrating the UT wave propagation velocity in the test item material. The calibration process for the test stand discussed herein is automatic: when a standard item thickness is input, the calibration function automatically determines the coefficient of wave propagation velocity.

There are several factors that influence the measurement accuracy of casting wall thickness. The first is the time measurement accuracy of the echo occurring at the location of the echo centers. The calibration accuracy of the unit depends on the resolution of the electronic measuring systems. Device calibration is carried out by determining a proportionality factor based on the measurement of a calibration plate of a known thickness under conditions analogous to those found during the measurement process. In the proposed solution, a 1.05 mm thick template plate was produced, made of the same material as the tested stator, and placed in the mounting case intended for the casting. Correction of the proportionality factor in the calibration procedure has to be carried out each time before starting the measurement. In conclusion, one calibration procedure per thickness measurement must be carried out for all points on the workpiece. The error sources cited above can be calculated mathematically. The accuracy of the whole method is further increased by the random error of inaccuracy of perpendicularity of the signal from the probe in relation to the tangent to the plane of the detail at the measuring point of the robotic system. It is random, as it is not only related to the precision of the algorithm used to determine the maximum signal strength but also to the accuracy and rigidity of the robot. The measurements obtained using the presented solution were then compared with measurements made of the thickness of the cast wall using a micrometer gauge of accuracy XYZ. Checking the accuracy of the presented solution required the destruction of several cast rotors. The accuracy obtained with regard to the thickness measurement adopted as a standard was +/-5% of the measured value. In addition, the robotic measurement system for the stator casting solution was verified by comparison with a manual UT measurement method carried out using a Novascope 5000. The software suite of the test stand features an ad-
advanced UT defectoscope functionality and digital connectivity with the robot controller. The application level allows managing the UT signal parameters. The software can save the recorded measurement results to a HTML report and the settings to an *.ini file.

![Figure 6: Measurement software: user panel view.](image)

The software allows adjustment of the UT transceiver probe output pulse frequency, the pulse generation repeat interval, and the pulse generation voltage. The software also permits selection of: analysed signal range, signal recording start delay, signal gain (dB) value, frequency band, signal attenuation, and signal averaging method. Fig. 6 shows an example of the ImageSonic software user panel.

![Figure 7: Example of a measurement report.](image)

The report is generated as a HTML file at the end of the measurement. Fig. 7 shows an example of the measurement report. The output measurement report features test item identification, thickness values at individual measurement points on the vanes, statistical data (mean, standard deviation, min and max values per data line, and minimum values in the comparison of the measured point values).

5 Conclusions

The paper presents a robotic test stand for UTT quality control. The design process of the test stand and the operating principle of its measurement system are presented with a specific focus on the measurement strategy. The results of actual wall thickness measurements performed on stator vanes are presented.

The innovative element of the solution presented here is undoubtedly the method for evaluating the perpendicularity of the signal from the probe in relation to the tangent with the workpiece plane of the detail at the measuring point. This was accomplished by an iterative process based on changes in the orientation of the robot around the measuring point. A correct measurement is one having the shortest path for the measurement signal. This is the robot position in which the thickness of the stator vane wall is determined using the calibrated method. This strategy has a behavioural illustration, and the measurement is performed manually in the same way. The correctness of the developed solution has been proven with a series of demonstration measurements. The measurement time was reduced from 6 h to 15 minutes. Currently, the presented test stand is based at the Research and Development Laboratory for Aerospace Materials. Its design development continues, especially in the areas of EHS compliance and IT compatibilities required at an industrial plant.

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References


