OPTIMAL PROBE ARRANGEMENT FOR ULTRASONIC
INSPECTION OF SPIN TEST DISKS

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ABSTRACT. This paper presents the results of combined experimental and theoretical studies performed to develop an efficient inspection procedure to detect small cracks of radial orientation in turbine engine disk components. After selecting an optimal transmit-receive probe for proper coverage of the inspection area, further work has dealt with the maximization of the small-defect response in view of the inspection parameters. Experimental and simulation results are presented.

Keywords: Transducer, Simulation, Semi-analytical Model, Scattering, Defect
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INTRODUCTION

Non-destructive ultrasonic inspection of aero engine disk components is essential for the acceptance of manufactured parts as well as for the extension of the life of parts after a period of service. Therefore, inspection systems have to be implemented to evaluate components both during production and at periodic intervals after delivery. As an example for such a technique, the inspection of spin test disk components from the inner bore using immersion technique is presented. In the specific case under concern, concurrent experimental and simulation studies have been employed to elaborate an efficient inspection procedure to detect small cracks of radial orientation. In a first step, a selection has been made on the transducer to be operated in transmit-receive mode to ensure a proper coverage of the inspection area. In the second part of the study, an appropriate model has been derived and implemented to optimize the inspection parameters, such as angle of insonification, water path and frequency. Here, emphasis has been on the maximization of the scattering amplitude of a ‘small’ penny-shaped crack in a depth from 1 mm to 10 mm below the surface. Experimental and simulation results will be presented to illustrate the methodology and the efficiency of the elaborated inspection procedure.

SITUATION

Turbine engine disks are highly loaded parts, on each blade root attachment acts a force of several tons (Figure 1). High temperatures and huge alternating centrifugal forces lead to fatigue; this is the reason why turbine engine disks are life-limited parts.
For safe life the highest level of quality assurance is therefore necessary. Respective quality assurance procedures include a material characterization program, finite elements calculations, spin tests, billet inspection, forging inspection, process monitoring, surface inspection and overhaul inspection. In particular, spin tests are needed for the validation of new materials, new designs and manufacturing technologies. A typical spin-test set-up is shown in Figure 2.

Spin tests provide the most realistic fatigue- and life-data and give additional input for advanced risk analysis. One of the high-level risk analysis tools is called DARWIN (Design Assessment of Reliability with Inspection), developed by the Southwest Research Institute, Texas [1]. The input variables are stress concentration, inspection schedule, cycle usage, probability-of-detection and crack growth data; the output is the probabilistic life.
OBJECTIVE

There may be tiniest inclusions in the turbine spin disks which are not detectable even by high resolution ultrasonic inspection methods. This means that the size of the defects is less than 0.1 mm in diameter. After a long incubation time (tens of thousands of cycles) crack initiation and crack growth may appear. The location of crack initiation and the speed of crack growth are beneficial for risk analysis of new disk designs. Therefore it is necessary to find these cracks as early as possible.

ADAPTATION OF UT INSPECTION

Preliminary Examinations

Conventional ultrasonic inspection procedures are based on the reflection of ultrasonic waves at inclusions or voids. However, cracks with radial-axial orientation, generated during spin tests in the disks, are not detectable in this way, when perpendicularly insonified from the inner bore. Therefore, the selected approach to detect such cracks is to use backscattering of shear waves at oblique incidence. Preliminary tests on a glass/IN718 test block have shown that this backscattering approach works.

For the parts to be inspected, obliquely incident shear waves are generated by shifting the probe off the central axis, as schematically indicated in Figure 3. Due to the vast variety of inspection parameters, which are decisive for the performance of the new approach, modeling has been applied, taking the material properties and the component’s interface geometry into account. Figure 4 displays the part to be inspected and a simplified CAD model. The inspection set-up has been investigated and optimized in view of the inspection area to be covered, the influence of the transducer nearfield at the interface, the achievement of optimal focusing, and the selection of the frequency as well as in view of the optimal insonification angle and probe position.

FIGURE 3. Illustration of the conventional UT inspection set-up (left) and the new approach (right).
Modeling Approach

For similar component geometry Thompson et al. [2] used an approximative approach to model the response of a small crack, applying a farfield approximation to model the transducer beam field and Kirchhoff theory to model the scattered field. In this study, we have adapted this approach, employing a point source superposition technique in order to get rid of the restriction to the probe's farfield.

To predict the amplitude of the signal scattered at the (small) defect, the various physical processes involved have been modeled. These are (i) the radiation of ultrasonic waves by the (commercial) immersion transducer and the propagation through water, (ii) the reflection and refraction process at the water/metal interface, taking into account the specific component geometry, and (iii) the scattering of the waves incident on the small defect. The point source superposition technique accounts for these processes, assuming that the transducer is acting as a piston source. The method is described in detail in [3].

To model the reflection and refraction process at the water/metal interface, the continuity of the normal tractions and the displacements is used to calculate the particle displacement distribution on the component's surface. This distribution is then applied to determine the propagation of the ultrasonic waves into the inspected part. Finally, the resulting displacement on the defect is calculated using Kirchhoff's theory as described in [4] for the case of anisotropic media. In the calculations, equidistant distributions of grid points within the transmitting, refracting and scattering surfaces or interfaces, respectively, are used in accordance with the sampling-theorem. The time-domain signal detected by the transducer is finally determined using Auld's reciprocity theorem for traction-free scatterers. It exploits the displacement and traction at the scatterer's position in presence and absence of the scatterer, respectively [5], in frequency domain; the time-domain signal is then obtained using subsequent inverse Fourier-transformation. Since for the problem under concern the harmonic (continuous wave) solution can be considered to be sufficient, the evaluation has been performed for a highly narrow-band signal as an approximation of the monochromatic solution.
MODELING RESULTS

For the spin disk components to be inspected, a set of optimal parameters has been elaborated for the inspection from the inner bore. These are: frequency 5 MHz, cylindrical lens focusing at 2.5 inches (63.5 mm) in water, water path 15 mm, probe shift 8 mm off the center (generating a shear waves at ~ 58° incidence). As an example for the performed simulations, Figure 5 shows the beam fields of the selected transducer in the radial plane of the disk, where the probe’s has been shifted off the center by 7 mm and 8 mm, respectively. The selected angle of shear wave incidence is also backed by Figure 6, where the backscattering amplitude from a #1 crack (perpendicular orientation with respect to the surface of a planar component, depth 10 mm) is plotted versus the insonification angle in water.

The modeling approach has also been checked against experimental results for validation. Figure 7 shows a comparison between the measured and the simulated defect responses. Here, the focused probe (5 MHz frequency) has been modeled, assuming a water path of 12 mm and 15 mm, respectively, insonifying on a penny-shaped crack of 0.4 mm diameter, radially oriented, positioned at a depth of 10 mm. A respective test specimen to perform reference experiments had been fabricated at MTU Aero Engines. In the measurements, the cylindrical specimen has been rotated and the maximum defect responses have been recorded, with the simulation performed correspondingly. The results agree well and also indicate the influence of the water path on the performance of the inspection procedure.

![Figure 5](image)

**FIGURE 5.** Calculated beam fields of the 5 MHz focused transducer, shifted by 7 mm and 8 mm off the component's rotation axis; and sound field in the disk.
FIGURE 6. Calculated backscattering amplitude for a #1 crack in dependence of the insonification angle in water. The maximum amplitude is obtained at approx. 23°, corresponding to shear waves at 58° in the planar component.

FIGURE 7. Detected maximum amplitude of a penny-shaped 0.4 mm crack in a reference specimen, plotted versus the probe shift off the center. The simulated results are given by the solid (12 mm water path) and the dashed curve (15 mm water path).
INSPECTION RESULTS

Figure 8 shows the experimental set-up for the inspection. On a test disk with side-drilled holes the sensitivity of the calculated sound field was checked. Figure 9 shows the scanning result obtained with the 58° shear wave on the test defects, which are comparable to #1 flat-bottom holes (area = 0.12 mm²).

Until now, four spin disks were inspected and no crack indications were found in these spins.

FIGURE 8. Experimental set-up for the UT inspection.

FIGURE 9. Test disk with flat-bottom holes (left) and C-scan result, clearly indicating the three FBHs (right).
OUTLOOK

The spin test monitoring will continue; in addition, doped disks will be spinned and inspected. If there are findings a detailed metallographic analysis will be done. These data will give additional credit for quality assurance of life-limited parts.

REFERENCES

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