Advanced Ultrasonic NDT of Aero Engine Components Using Validated Simulation Techniques

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Abstract. The use of simulation tools is essential for the improvement of currently applied inspection techniques and the development of new approaches. This contribution presents results elaborated in recent studies where the application of validated simulation techniques has led to optimized ultrasonic inspection performance on relevant aero engine components.

Introduction

The use of high-performance components as well as the application of new manufacturing processes in aeronautics increases the need for advanced inspection techniques. This especially holds for ultrasonic NDT of complex components which generally suffers from loss of sensitivity, beam distortions and beam disorientations, if the transducer is not perfectly matched to the inspection conditions. The use of respective simulation tools is therefore essential for the improvement of currently applied techniques and the development of new approaches.

This contribution presents results elaborated in recent studies where the application of validated simulation techniques has led to optimized ultrasonic inspection performance on relevant aero engine components. Two (semi-) analytical approaches [1-3] are at hand which are described and illustrated by recently acquired validation results. An example for the application of these simulation methods to improve the defect detectability in aero engine components is then presented, which refers to the elaboration of optimal probe arrangement for the inspection of spin test disks.

1. Simulation Approaches

To simulate ultrasonic immersion testing, the various physical processes involved have to be modeled, which are (i) the radiation of ultrasonic waves by circular, flat or focused transducers and the propagation through the respective medium, (ii) the reflection and refraction process at the water/solid interface, and (iii) the scattering of the waves incident on defects, which e.g. may be modeled as flat-bottomed holes (FBH). Figure 1 shows the principal set-up of probe, component and the coordinate system in considering the transmission problem in view of immersion testing.

1.1 Gaussian Beam Superposition For Field Calculation (GBS_field)

As previously described in [1], the beam field of a circular piston in a single medium can be
formulated as a superposition of $N$ Gaussian beams according to

$$| u_{s}(R) | = \sum_{n=1}^{N} \frac{U_{n}}{1 + M_{n} v_{\alpha} z} \exp \left[ j \omega \frac{M_{n} r^{2}}{2(1 + M_{n} v_{\alpha} z)} \right],$$

where the complex amplitudes $U_{n}$ and the beam waist parameters $M_{n}$ characterize the individual beams. $\omega$ designates the circular center frequency and $R=(x,y,z)$ the spatial coordinates (with $r^{2}=x^{2}+y^{2}$). In modeling rectangular transducers, a formulation given in [4] can be applied, which reduces the Fresnel field integral to the superposition of a set of two-dimensional Gaussian beams. A rectangular piston transducer of side lengths $a$ and $b$ is thus described according to

$$| u_{r}^{red}(R) | = \sum_{n=1}^{N} \frac{U_{n}^{x}}{1 + M_{n}^{x} v_{\alpha} z} \exp \left[ j \omega \frac{M_{n}^{x} x^{2}}{2(1 + M_{n}^{x} v_{\alpha} z)} \right]$$

$$+ \sum_{n=1}^{N} \frac{U_{n}^{y}}{1 + M_{n}^{y} v_{\alpha} z} \exp \left[ j \omega \frac{M_{n}^{y} y^{2}}{2(1 + M_{n}^{y} v_{\alpha} z)} \right].$$

Here, $U_{n}^{x,y}$ and $M_{n}^{x,y}$ are sets of coefficients characterizing circular piston transducers of diameters $a$ and $b$, respectively. In view of immersion testing, expressions similar to Eqs. (1) and (2) have been derived for the beam fields transmitted through the fluid-solid interface [5]. While many authors rely on the set of Gaussian beam coefficients determined for a ten-beam solution [6], the results presented here are obtained using sets of coefficients for five-beam solutions, individually determined in view of the transducers under concern [5].

1.2 Generalized Point Source Synthesis For Beam Field and Defect Signal Calculation (GPSS_field and GPSS_defect)

As a second method, a point source superposition technique is used which assumes that the transducer is acting as a piston source. The method is briefly summarized here, a detailed description can be found in [2] and [3]. While the GBS technique is based on a summation of a small number of Gaussian beams, the GPSS approach exploits the numerical evaluation of a surface integral according to

$$u(R, \omega) \simeq - \int_{S} \sum_{\alpha} \left[ t(R', \omega) \cdot g_{\alpha}(K(\Delta R)) \right] \cdot \bar{u}_{\alpha}(K(\Delta R)) \frac{e^{j|\Delta R|/c_{\alpha}(\Delta R)}}{4\pi |\Delta R|} \mathrm{d}S'.$$

Equation (3) depends on the tractions and the point source directivities at the transducer (surface $S$), as well as on the wave polarizations and velocities of the wave type $\alpha$ under concern. Similar surface integral representations have been derived for interfaces and scattering surfaces. In the calculations, equidistant distributions of grid points within the transducing, refracting and scattering surfaces or interfaces, respectively, are used in accordance with the sampling-theorem. In modeling transient signals the harmonic (continuous wave) solutions at many frequencies are calculated and then numerically Fourier transformed into the time domain, assuming a respective frequency spectrum function for the transducer input signal of the probe.

To model the reflection and refraction process at the water-solid interface the continuity of
the normal tractions and the displacements is used to calculate the particle displacement distribution on the solid surface. This distribution is then applied to determine the propagation of the ultrasonic waves into the component. Finally, in modeling defect responses the resulting displacement on the defect is calculated using Kirchhoff’s theory as described in [3] for the case of anisotropic media. The time-domain signal detected by the transducer is eventually 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 [7], in frequency domain, the time-domain signal is obtained using subsequent inverse Fourier-transformation. For illustration, Figure 1 also shows two simulated A-scans in comparison with experimental ones, obtained for flat-bottomed holes inspected in an immersion set-up [8].

![Figure 1](image.png)

**Figure 1.** Principal set-up of probe, component and the coordinate system in considering the transmission problem in view of immersion testing (left). Comparison of calculated and measured transient signals obtained in an immersion set-up for two FBHs in 0.25 in. and 0.5 in. depth, respectively [8].

### 2. Validation Using MTU Experimental Data

Previously, the two simulation approaches have been verified using experimental data obtained from various UT applications. Further verification has been performed recently, where inspection data acquired in the course of an international UT Benchmark have been used for comparison with the GPSS approach [8,9]. In view of UT inspections in aerospace industries, comparisons have been performed using experimental data obtained at MTU Aero Engines, Munich, Germany [10].

At MTU, experiments have been performed on a specific test block which simulates the inner contour of a turbine disc. In the test block, 0.2 mm flat-bottomed holes (FBH) have been manufactured under depths from 2 mm to 15 mm, and from 12 mm to 40 mm. These model defects have been interrogated by two different transducers, whose features are given in Table 1. The two probes are used according to the FBH depth: the first probe
(TLC IS1010GA) is used for the FBHs located close to the inner surface of the component. The spherical focusing radius of this probe has been calculated in water, in order to focus at 75 mm depth as measured. The MTU calibration block has been scanned with this probe, aiming only at the 0.2 mm and 0.3 mm FBHs ranging from 2 mm to 15 mm depth. The same has been done with the second probe (Harisonic I2LRA), aiming at the FBHs ranging from 12 mm to 40 mm depth. The probe has its focal point at a depth of 52 mm (as measured).

<table>
<thead>
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<th>Table 1: Transducer features.</th>
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<tr>
<td>TLC U IS 1010GA</td>
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<tr>
<td>10 MHz</td>
</tr>
<tr>
<td>0.375&quot; element diameter</td>
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<tr>
<td>Focus in water: 3&quot; spherical</td>
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<td>Water path: 75mm</td>
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Figure 2 shows the simulated on-axis beam amplitude profile for both transducers in comparison with the measured amplitude values. Deviations between the simulated and measured results evolve with longer travel paths in water, since here the sound attenuation in water affects the measured amplitudes. This effect has not been included in the simulation procedure, as it is negligible for smaller water paths, which are of general interest. To exemplarily illustrate the good agreement between the measured and simulated beam fields in water, Figure 3 displays the C-scans at distances from 50 mm to 70 mm for the TLC probe, using linear scaling. Considering that the simulation results are obtained assuming monochromatic sound excitation, while broadband measurements have been performed, the agreement is excellent. It has also to be obeyed that the simulation results are performed for a point reflector, while the experimental determination of the beam field has been performed using a Ruby sphere of 2.5 mm diameter.

![Figure 2](image)

**Figure 2.** On-axis amplitude beam profile (solid curve) in water for the TLC (left) and the Harisonic (right) transducers in comparison with the measured amplitude (dotted curve).
With respect to the experimental C-scan results obtained for the interrogation of the 0.2 mm and 0.3 mm FBHs, GBS and GPSS simulations have been performed. In the first case the FBHs are modeled as point-like defects, which is a valid assumption for the wavelength-to-reflector diameter ratios involved (frequencies are 10 MHz and 15 MHz). In the case of the GPSS calculations the actual geometry and dimensions of the scatterers are taken into consideration. Figure 4 displays the simulated amplitude profile of the signals obtained for the 0.2 mm FBHs in different depths under the surface of the test block, in comparison with the measured FBH values. A strong deviation can be seen for the 2 mm depth, which is to be further investigated. The deviations for the 12 mm, 14 mm and 15 mm depth are less than 2 dB and thus within the usually acceptable range. Exemplarily, Figure 5 shows the simulated C-scans for the TLC probe for FBHs in a depth of 14 mm. It has to be noticed, that in the experimental C-scans the signals for the 0.3 mm FBHs are over-amplified in order to also obtain a clear indication of the 0.2 mm FHB signals. Taking this into account, the agreement is again excellent.

Figure 4. Defect signal amplitude profile (solid curve) for TLC IS1010GA and measured values (dotted).
3. Application Example: Optimal Probe Arrangement For Spin Test Disks

Turbine engine disks are highly loaded and life-limited parts. For safe life the highest level of quality assurance is therefore necessary. Respective quality assurance procedures at MTU include a material characterization program, finite element 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 [11]. Spin tests provide the most realistic fatigue and life data and give additional input for advanced risk analysis. 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.

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. 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 6. 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. The inspection set-up has been investigated and optimized in view of the inspection area to be covered, the influence of the transducer near-field at the interface, the achievement of optimal focusing, the selection of the frequency as well as in view of the optimal insonification angle and probe position. For a similar component geometry Thompson et al. [12] used an approximative approach to model the response of a small crack, applying a far-field approximation to model the transducer beam field and Kirchhoff theory to model the scatterered field. Here, we have adapted this approach, employing GPSS in order to get rid of the restriction to the probe's far-field.
FIGURE 6. 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.

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 6 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 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 [11]. 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.

4. Summary

The validation and the application of the two superposition approaches GBS and GPSS in view of ultrasonic NDT of aero engine components have been addressed in this contribution. Due to its computational efficiency the Gaussian beam method allows for a quick evaluation of transducer beam fields, while the Generalized Point Source Synthesis method can be employed in view of more sophisticated UT configurations. In this respect, the latter has been applied for optimization and simulation in complex inspection set-ups, including single- and multiple-element transducers [13] as well as mirrors for improved the defect detectability [14].
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).

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References

[7] Auld, B.A., Wave Motion 1, 3-10 (1979)