Real-time 3D-Simulation Tool for Ultrasonic Transducers Used in Aeroengine Component Inspections

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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 a 3D simulation code based on the Gaussian beam method, addressing the simulation of circular and rectangular, flat and focused transducer beam fields and their visualization. Due to its computational efficiency this tool is particularly suitable to perform a-priori evaluation of complex inspection problems.

1. Introduction

Beam field modeling using Gaussian beam superposition (GBS) is highly efficient due to low computation times. Thus, respective simulations allow for a fast evaluation of even complex inspection situations. Here, we present a 3D simulation code based on the GBS method, addressing the simulation of circular and rectangular, flat and focused transducers. In our approach, only a small number of Gaussian beams is required to synthesize the transducer beam field so that the resulting three-dimensional data fields can be calculated in real time. The coefficients characterizing the beams are specifically determined for each transducer or transducer element under concern using the lateral field profile data obtained at the near-field length or in the focal point. These reference profiles can be determined in experiments or by exact simulation techniques, such as the Generalized Point Source Superposition technique (GPSS) used in our study. To visualize the 3D datasets we have used efficient software (MeVisLab) which provides various techniques and views for beam field representations. We exemplarily illustrate the efficiency of our approach by simulations of (monochromatic) beam fields with emphasis on a specific disc geometry of interest in turbine engine component inspection. For a commercial transducer applied in immersion technique we show the principal procedure used for transducer characterization. Further, we present validation results and 3D beam field representations which allow for a-priori evaluation of such complex inspection problems.

2. Simulation Approaches for 3D Transducer Beam Fields

To simulate ultrasonic transducer beam fields, the respective physical processes have to be modelled. These are (i) the generation of waves by flat or focused transducers and the propagation through the original medium and (ii) in the case of immersion testing the reflection and refraction process at the water/solid interface to calculate the beam fields transmitted into the inspected component. In this contribution, we concentrate on the experimental set-up displayed in Figure 1 which shows the principal arrangement of the probe and the component to be inspected; further details are given in Chapter 2.
2.1 Generalized Point Source Synthesis For Reference Beam Profile Calculation

To efficiently apply the GBS approach, the Generalized Point Source Superposition technique (GPSS) is used for reference. Here we give only a brief summary, a detailed description of the method can be found in [2] and [3]. While the GBS technique is based on the summation of a small number of Gaussian beams, the GPSS approach exploits the numerical evaluation of a surface integral according to

\[
    u(R, \omega) \approx - \int \int_S \sum_{\alpha} [t(R', \omega) \cdot g(\hat{K}(\Delta R))] \cdot \hat{u}_\alpha(\hat{K}(\Delta R)) \frac{e^{j\omega |\Delta R|/c_\alpha(\Delta R)}}{4\pi |\Delta R|} \, dS'
\] (1)

Equation (1) depends on the tractions \( t \) and the point source directivities \( g \) at the transducer (surface \( S \)), as well as on the wave polarizations \( \hat{u} \) and velocities of the wave type \( \alpha \) under concern; \( \omega \) designates the circular frequency and \( R=(x,y,z) \) the spatial coordinates. Similar surface integral representations have been derived for interfaces and scattering surfaces. In the calculations, equidistant distributions of grid points within the transducer aperture as well as the refracting and scattering surfaces or interfaces, respectively, are used in accordance with the sampling-theorem. As the discretization, i.e. the number of grid points depends on the wavelength, it increases with the transducer frequency. To model transient signals the harmonic (continuous wave) solutions at many frequencies are calculated with a respective frequency spectrum function for the transducer input signal of the probe and then numerically Fourier transformed into the time domain.

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. The GPSS simulation method is applicable to a large variety of transducer types and component geometries. Over the years, validation has been performed on isotropic and anisotropic materials; inspection data acquired in the course of an international UT Benchmark have also been used for validation [4-6].

Figure 1. Immersion testing set-up with the probe and the Titanium test block, as applied in an internal qualification procedure for disc inspection at MTU Aero Engines [1].
2.2 Gaussian Beam Superposition For Field Calculation

The computational efficiency of the GBS method is due to the fact that only a small number of Gaussian beams have to be considered to synthesize the beam field, even in the case a high frequencies. This is most beneficial in view of the calculation time and makes the method particularly suitable for fast 3D simulations. As previously described in [7], the beam field of a circular piston in a single medium can be formulated as a superposition of N Gaussian beams according to

\[
| \mathbf{u}_n^{\text{circ}}(\mathbf{R}) | = \sum_{n=1}^{N} \frac{U_n}{1 + M_n v_\alpha z} \exp \left[ j \omega \frac{M_n r^2}{2(1 + M_n v_\alpha z)} \right],
\]

where the complex amplitudes \( U_n \) and the beam waist parameters \( M_n \) characterize the individual beams; \( \mathbf{R}=(x,y,z) \) designates the spatial coordinates and \( r^2=x^2+y^2 \). In modeling rectangular transducers, a formulation given in [8] 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

\[
| \mathbf{u}_n^{\text{rect}}(\mathbf{R}) | = \sum_{n=1}^{N} \frac{U_n^x}{\sqrt{1 + M_n^x v_\alpha z}} \exp \left[ j \omega \frac{M_n^x x^2}{2(1 + M_n^x v_\alpha z)} \right] \times \sum_{n=1}^{N} \frac{U_n^y}{\sqrt{1 + M_n^y v_\alpha z}} \exp \left[ j \omega \frac{M_n^y y^2}{2(1 + M_n^y v_\alpha z)} \right].
\]

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 Eq. (2) and (3) have been derived for the beam fields transmitted through the planar or curved fluid-solid interface [7]. While many authors rely on the set of Gaussian beam coefficients determined for a ten-beam solution [10], we use sets of coefficients for five-beam solutions, individually determined for the transducers under concern from either measured or simulated references beam profiles [9].

3. Inspection Scenario, Simulation and Validation Results

3.1 Experimental

In view of UT inspections in aerospace industries, we focus on an experimental set-up applied in an internal qualification process at MTU Aero Engines, Munich, Germany [1]. Here, experiments have been performed on a specific test block which simulates the inner contour of a turbine disc with a radius of 50 mm (Fig. 1). In the test block, 0.2 mm and 0.3 mm flat-bottomed holes (FBH) have been manufactured under depths from 2 mm to 15 mm (Volume No. 1) and from 12 mm to 40 mm (Volume No. 2). These model defects have been interrogated by two different transducers. In the following, we concentrate on Volume No. 1, which has been inspected using a 10 MHz, spherically focused probe (TLC IS1010GA) with a focus depth in water of 3 inches (76.2 mm) and an element diameter of 0.375 inches (9.5 mm). For the reference profile calculations we have determined the spherical focusing radius of this probe in order to focus at 75 mm depth in water as measured.
3.2 Determination of GB Coefficient Sets

The reference profile used in evaluating the GB coefficients individually for the TLC transducer has been determined using the GPSS technique. While the coefficients presented in [10] have been determined for a prescribed amplitude distribution within the transducer aperture, the procedure applied here is based on the profile at the transducer focal length. Thus, the reference profile includes side lobe structure information, so that the number of Gaussian beams necessary for an appropriate description of the beam field can be reduced to less than ten. In Figure 2 (left), the resulting on-axis field profiles are displayed; the solid curve represents the GBS calculation with 5 Gaussian beams while the dotted curve shows the calculation exact GPSS result. Noticeable, but irrelevant differences exist in the near-field structure. This is well-known for the GBS approach; since it is based on a paraxial approximation differences also occur in the outer side lobe structure [10].

![Figure 2](image_url)

**Figure 2.** On-axis amplitude beam profiles in water for the TLC transducer. Left: GBS and GPSS calculations; right: comparison of the amplitudes measured using a Ruby reflector sphere (dotted curve) with the GBS-calculations without (solid curve) and with attenuation (dashed curve).

3.3 Validation of Simulation Results – Beam Field in Water

With the coefficients $U_n$ and $M_n$ specifically determined, beam field simulations have first been carried out for water. Figure 2 shows the GBS-simulated on-axis beam amplitude profile for the transducer in comparison with the GPSS-calculation (left) and in comparison with the measured amplitude values (right). It has to be obeyed that for the latter 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. Deviations between the simulated and measured results evolve with longer travel paths in water if the sound attenuation in water is neglected. The effect of attenuation is negligible for smaller water paths, but should be considered for longer paths as shown by the dashed curve in Fig. 2 (right). The difference of about 2 dB at 300 mm between this curve and the measured results may be attributed to the fact that the Ruby sphere has a diameter of approximately 15 wavelengths, while in the simulation we have assumed a point reflector.

3.4 Validation of Simulation Results - Test Block Inspection

The MTU calibration block has been scanned with this probe, aiming at the 0.2 mm and 0.3 mm FBHs ranging from 2 mm to 15 mm depth. Exemplarily, Figure 3 shows the simulated C-scans for the FBHs in 14 mm depth. 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 obtain a clear indication of
the 0.2 mm FHB signals. Taking this into account, the agreement is excellent. With respect to the experimental C-scan results obtained, GBS and GPSS simulations have been performed. In the first case the FBHs are modeled as point-like defects, a valid assumption for the wavelength-to-reflector diameter ratios involved (the center frequency is 10 MHz, the FBH diameters are in the order of the wavelength). In the case of the GPSS calculations the actual geometry and dimensions of the defects 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 values. A strong deviation can be seen for the 2 mm depth, but in all other cases the differences are less than 2 dB and thus within the usual, acceptable range.

Figure 3. Experimental (left image with FBHs 0.2 mm (left) and 0.3 mm (right)) and simulated (right) C-scans obtained for the FHB in 14 mm depth. The shape of the energy distribution is properly simulated [1].

Figure 4. Simulated defect signal amplitudes for TLC IS1010GA and measured values (dotted).

4. Three-Dimensional Beam Field Calculation and Visualization

Addressing the inspection of complex parts such as aero engine components, several features have to be taken into consideration. The influence of the curved component surfaces leads to a focusing or defocusing of the transducer beam fields. These effects lead to even more complicated beam fields if spherically or cylindrically focusing probes are used [11]. Therefore, it is advisable to look the beam fields in three dimensions. Also, in many cases it is not necessary to simulate the complete inspection procedure, since the main features affecting the ultrasonic inspection of the components under concern can be already extracted from the 3D beam fields. This especially holds if the defect dimensions are small in comparison with the wavelength, as previously illustrated in Fig. 3.
For the TLC probe, Figure 5 shows visualizations of the three-dimensional beam fields calculated for the immersion medium (water, a) as well as the beam fields generated in the component to be inspected. We present results for components with a planar surface (b), a concave surface (c, which corresponds to the test block shown in Fig. 1) and a convex surface (d), obtained for a water path of 75 mm. The 50 mm radius of curvature leads to a focusing (c) and a defocusing (d) of the beam fields as compared to the planar case. These effects are also apparent if cuts through the 3D datasets are plotted as displayed in Fig. 6 for the x-z- and y-z-plane. In Figure 6 a), we have plotted the beam field representations for the concave component (corresponds to Fig. 5 c). In Figure 6 b), we refer to a component with a hyperboloidal surface (convex/concave curvatures in x-/y-direction, radii of curvature 50 mm). Using efficient software, the 3D datasets can be visualized according to the user’s preferences. Here, we have used MeVisLab [12], which offers various techniques of data preparation and representation. Other commercial software packages are of course available as well and can be applied to the 3D datasets.

The use of the GBS simulation tool in combination with a separate graphical visualization software is one option. We are currently working on an alternative approach, where the GBS code and appropriate visualization tools are integrated in one graphical user interface. Figure 7 shows a preliminary representation, further details will be presented in due course [13].

**Figure 5.** Three-dimensional beam fields of the 10 MHz focused transducer for water (a), water and the inspected component (75 mm water path) assuming (b) a planar surface, (c) a concave surface as in Fig. 1 and (d) a convex surface (radii of curvature are 50 mm). The visualizations are performed with MeVisLab [12].
Figure 6. Two-dimensional representations of the 3D transducer beam fields showing the x-z- and y-z-planes. The plot on the left corresponds to Fig. 5 c); on the right, the insonification into a component with a concave curvature in x-direction and a convex curvature in y-direction is considered. The visualizations are performed with MeVisLab [12].

Figure 7. Screenshot taken from the Beam Field Simulation Tool in a preliminary version [13]. The plots correspond to Fig. 5 c) and 6 a) and show the beam fields in the Titanium test block. The x-y-plot is taken at 14 mm depth and thus relates to Fig. 3.

5. Conclusion

We have addressed the simulation of transducer beam fields with emphasis on the inspection of aero engine components. The two validated superposition approaches GBS and GPSS offer different features and complement each other. 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 transducer configurations and in view of the consideration of defect interaction.

We have shown that the GBS approach is particularly beneficial for real-time 3D simulations. The 3D datasets presented in this contribution for ultrasound propagation paths of 300 mm have been calculated within a few seconds on a standard PC. Since the application of phased-array transducers has become an important NDT issue also in aerospace industries, we are currently extending the GBS method accordingly. Here, again the 3D beam fields are of interest, especially in the case of 2D arrays applied e.g. to perform volume focusing [14].

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References