The Essential Role of Simulation in Optimizing Probes and Inspection Strategies

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Abstract
Examples from industrial applications are used to illustrate how simulation is used to design and optimize phased-array probes and inspection strategies. The extensive design options for probes and controllers mandates the use of modelling, and BERCLI uses CIVA simulation software to perform parametric studies that along with laboratory measurements are the basis for determining optimal probe and inspection configurations. Qualitative and quantitative results are presented to demonstrate how simulation is used to characterize the beam radiated into structures undergoing inspection, as well as the response of the radiated field to defects. This allows resolution limits and the minimum size of a detectable defect to be determined. Results are also used to evaluate tradeoffs between performance and cost.

Keywords: CIVA simulation, ultrasonic phased array, composites, weld, aerospace, nondestructive inspection

1. Introduction

Compared to conventional ultrasonics, phased-array systems provide tremendous flexibility derived from the ability to perform electronic focusing, beam steering and scanning. These features in turn enable inspection procedures that are often faster, easier, and more reliable. While the extensive capabilities of phased-array systems promise to improve inspectability and resolution for many nondestructive inspection applications, they also make it more difficult for users to optimize inspection procedures and determine their probe and controller requirements. Simulation is, therefore, an increasingly important tool for both specifying hardware and for determining optimal inspection strategies [1-4].

The examples below illustrate how simulations performed with CIVA software are used to characterize the beam radiated into structures undergoing inspection, as well as the response of the radiated field to defects. This allows resolution limits and the minimum size of a detectable defect to be determined, as well as the coverage zone. Although simulation and modelling do not eliminate the need for experimental validation, they can reduce the number of required tests. Moreover, both qualitative and quantitative characteristics of an NDT procedure can be evaluated (see Figure 1). These modelling and parametric studies are often a necessary step in designing probes and inspection procedures, including green-light/red-light solutions used in the field. Simulation also helps to find the optimal tradeoffs between performance and cost, while also meeting industrial constraints.

2. Phased-array principles

Phased-array probes are composed of several piezoelectric elements that can transmit/receive independently at different times. Each element radiates a spherical wave at a specified time. To focus and steer the ultrasonic beam, time delays are applied to the elements to create constructive interference of the wavefronts, allowing the energy to be focused at the desired location in the test specimen undergoing inspection. Because thousands of signals are captured at once, sophisticated data-visualization techniques can be employed to greatly ease interpretation of results including detection and sizing of defects.
3. Inspection optimization

Optimization of NDE procedures means ensuring that requirements for coverage, detection and sizing resolution are met, while also meeting cost, speed, and reporting specifications. Inspection challenges include complex shapes; joints; composite, heterogeneous and attenuative materials; highly contoured components and rough surfaces. The probe design, ultrasonic beam radiated into the part and scanning strategy must be evaluated simultaneously, and the large number of parameters mandates the use of simulation.

As described below, BERCLI uses CIVA simulation software to characterize the beam radiated into structures undergoing inspection, as well as the response of the radiated field to defects. For ultrasonic applications, CIVA can simulate the acoustic beam radiated by conventional transducers and phased-array probes, used in contact or immersion, and can simulate wave/defect interactions for most geometries (canonical as well as complex shapes) and most engineering materials including isotropic/anisotropic and homogeneous/heterogeneous materials. CIVA is used to design probes that are optimal for one or more applications, to optimize inspection strategies, to verify inspection parameters, and to help in the analysis of results. Using the wave/defect interaction toolbox, it is possible to quantify the response to expected defects, and different inspection strategies can be compared with regard to detection and sizing capability. CIVA is also a tremendous help in understanding what are often complex signals. The modelling takes into account mode conversion, and identifies the response associated with each mode.

The probe parameters that can be iteratively optimized include the frequency, probe shape (e.g., flat, cylindrical, spherical); probe size (total aperture); number and size of elements; and the spatial arrangement of elements (linear, matrix, annular, sectorial). For each probe configuration and set of focal laws, the inspection procedure can be evaluated with respect to the shape of radiated beams, zone coverage, presence of blind zones, sizing resolution, focal-spot size, and the presence of side lobes, which indicates undesirable beam directivity. An essential step in the optimization is to simulate wave-defect interactions for the full range of conditions expected in practice. These parametric studies are designed to explicitly examine the influence of defect type, size, location and orientation. The predicted signals for each case are analyzed, and the qualitative and quantitative results are used to evaluate defect detection and sizing capability.

4. Validation

It is, of course, essential to validate simulation results. Reference standards with calibrated defects are generally used to establish baseline data. The sensitivity of proposed inspection protocols is determined by quantifying the defect response in terms of gain compared to the reference case; i.e., if the gain required to identify the defect is within the dynamic range of the phased-array controller, then it should be possible to detect the defects in question. A series of parametric studies is often carried out, for example, to study the dependence between detectability and the size of the defect, its orientation, and/or its geometry. The images and graphs in Figure 1 allow comparison between experimental measurements and simulation results obtained using CIVA. In this case, the test specimen is an aluminum block containing side-drilled holes. The results displayed were obtained using a focused, sectorial scan that utilized 40 elements of a 64-element Imasonic probe. The scans and dynamic-echo curves displayed show excellent agreement.
Figure 1. Sectorial scans (top images) and dynamic-echo curves (bottom pictures). Laboratory measurements made with an M2M phased-array controller are displayed on the left, and the results of the corresponding simulations are shown on the right (performed using CIVA). Excellent agreement is achieved between simulations and experimental results.

5. Probe design and evaluation

The goal of the simulations shown in Figure 2 was to determine the resolution capabilities of a “daisy” probe used for the inspection of fastener holes. The concept is to put the probe on top of the test specimen and to detect cracks that tend to radiate out from the fastener holes. Using CIVA, several inspection strategies (varying the number of elements used and their delay laws) were investigated. In addition to resolution, the client’s industrial constraints included the size and cost of the probe, which affected the number of elements that could be used in the probe design. The simulation results allowed the tradeoffs among cost, size and performance to be evaluated, along with the characteristics of the radiated beam. A second example is shown in Figure 3 where simulation was used to design a radial probe and inspection strategy that utilized dynamic-depth focusing to provide consistent resolution throughout the thickness of a thick-walled cylinder.

Figure 2. Beam simulation when all elements of the probe are fired in parallel. The beam profile and a horizontal slice of the radiated acoustic beam centered at a depth of 20 mm are illustrated (left-hand and right-hand pictures, respectively).

Figure 3. Results of a simulation designed to demonstrate the feasibility of maintaining resolution through the entire thickness of the thick-walled cylinder.
6. Optimizing the beam radiated into the test specimen

For the example presented in Figure 4, simulation was used to evaluate two different sectorial scanning strategies. The simulation images shown in the left-hand column of Figure 4 are the acoustic beams resulting from firing 7 elements (of a 64-element linear array) with focusing at a distance of 35 mm. The images correspond to the case where the probe is used with a wedge angled at 45° on a steel specimen. The acoustic beam shown in the upper-left image of the figure is from the first shot in the sectorial scan. For subsequent shots, the beam is steered in increments of one degree up to 70 degrees, while maintaining the focal point at a distance of 35 mm (the middle and final shots of the sequence are displayed in the center and lower-left images of Figure 4). The simulations (left-hand column) show that the beam is not well focused, meaning that resolution and the ability to size defects will not be optimal with this configuration. In addition, a side lobe is evident that becomes more and more significant for angles greater than 62 degrees. The creation of side lobes results in signals that are more complicated and generally more difficult to interpret. To improve the inspection, simulations were run using different numbers of elements to optimize the beam in the sample. The right-hand column of Figure 4 shows the ultrasonic beam obtained using 16 elements focused at a fixed distance of 35 mm for each angle in the sectorial scan. By comparing the left- and right-hand columns, it is easy to see that the beam in the second case (left-hand column) is much better focused, which allows detection of smaller defects and improved sizing.

Although the previous example is a relatively simple case, the challenge increases with the complex geometries encountered in practice, along with physical constraints that limit access, making modelling an extremely valuable tool that is often necessary for determining optimal inspection strategies. For example, in those cases were access to the part is limited, it is very useful to be able to determine the minimum size and number of elements necessary to perform the required measurements. For the case presented here (Figure 4), it is possible to compare the 7- and 16-element configurations to determine the optimal tradeoff between size and detection capability.

![Images showing radiated beams at different angles.](image)

**Figure 4.** Radiated beams (shear waves) at 45, 58 and 70 degrees (first to third rows, respectively) for focused beams formed with 7 and 16 elements (left- and right-hand columns, respectively). The orange dots on the images indicate the targeted focal points.
7. Optimization of fastener-hole inspection in pitch-catch mode

In the aerospace industry, detecting the cracks that sometimes develop around fastener holes is a major issue for aircraft maintenance and life extension. Parts undergoing inspection are usually made of an aluminum alloy and typically have a complex geometry. Cracks of concern can be as small as 1.0 mm (0.04 inches) and can be located anywhere throughout the spar thickness (Figure 5). The conventional inspection technique requires the fastener to be removed. The challenge in developing an easier and less expensive inspection strategy were to design a technique that can be used from the skin side, that does not require removal of the fastener, and that provides the same or better resolution than the conventional method. The phased-array concept designed and implemented uses a large linear array in a pseudo-tandem configuration, in which different elements of the same probe are used for transmission and reception (Figures 5 and 6). In subsequent experiments, consistent resolution was achieved throughout the entire thickness [5].

![Figure 5. Schematic diagram of aircraft fastener joining the skin and spar (left-hand image) and resolved focal points obtained using separate transmission and reception delay laws (right-hand image).](image)

![Figure 6. Visualization of the focused beam after reflection off the bottom surface using 54 elements for transmission (left-hand image) and 54 elements for reception (middle image). The convolution of the transmitted and received beams gives the effective focal-spot size for defect detection (right-hand image).](image)

8. Optimization of T-section stiffener inspection

Crack detection in T-section stiffeners is a recurrent problem for aircraft manufacturers [5]. In most cases, there is a corner piece that cannot be removed for the inspection that prevents the NDT inspector from using a relatively simple procedure (see Figure 7). Without the corner part, the inspection could be performed using normal-incidence pressure waves with good accuracy. In this configuration, however, pressure waves at normal incidence do not reach every zone of the stiffener, resulting in an unacceptable shadow zone (or silent zone).
Figure 7. T-section stiffener (left-hand drawing) indicating the likely location of defects. The corner piece prevents the inspection from being performed at normal incidence only. The right-hand picture shows a sectorial scan superimposed on the stiffener geometry. Using a sectorial scan allows cracks lying underneath the corner piece to be detected.

The inspection strategy has, therefore, to be modified to be able to detect defects that lie beneath the corner part. Using sectorial scanning delay laws with a linear phased-array probe is one solution to this problem. Using the capability of phased arrays to steer the beam in several directions, the formerly silent zone becomes insonified. The cracks lying underneath the corner part can be detected using this procedure, as displayed in Figure 7. In this figure, the inspector can observe the multiple reflections coming from the thin upper section (occurring at normal incidence and appearing on the left side of the sectorial scan), as well as other structural reflections (at high steering angles, visible on the right side of the sectorial scan). Most importantly, the inspector is also able to detect cracks (reflection visible on the lower-right side of the scan).

9. Weld inspection

In the automotive industry, steel body parts are spot welded together. In general, the quality of ultrasonic measurements depends in large part on the surface conditions of the parts including the depth, shape and roughness of the surface indentations caused by the welding electrodes [6]. A tremendous advantage of phased arrays compared to conventional ultrasonics is that the focal laws applied to the probe elements can be modified to account for changes in surface geometry. CIVA simulation software was used to illustrate the effect of the indentation on the ultrasonic beam, and to demonstrate how changing the focal laws applied to the probe elements can be used to correct for the indentation [7].

All simulations were performed for a 17-MHz phased-array probe with a pitch (center-to-center distance between elements) of 0.25 mm. Ten elements at a time were used to form the ultrasonic beam transmitted into the part. The distance between the probe and test specimen was held constant at 7 mm. The test specimen was modeled as a 2-mm-thick steel sheet. For the relatively simple case of an equal-depth indentation and a beam focused at the interface between the welded sheets, the effect of the indentation is that the beam is focused lower in the sample, as a result of the longer water path between the probe and the test specimen. The
beam is focused at the desired point at the middle of the test specimen by increasing the time delays to account for the reduced thickness of the sample. An additional challenge occurs when relatively deep indentations also have a spherical shape, as occurs when the welding electrodes have a spherical tip. In this case, the shape of the indentation affects the travel paths of both the transmitted and reflected waves making it more difficult to transmit energy into the weld, and resulting in signals returning to the inspection surface at wide angles that may be outside the area of the probe, and thus not measured. If the shape of the indentation is known, based for example on the shape of the welding electrode, then it is possible to adjust the focal laws used to form the ultrasonic beam to direct the energy into the weld. The principle is illustrated in Figure 8, where CIVA simulation results indicate how the focal laws would be modified to optimize the ultrasonic beam for relatively deep spherical indentations.

The top image in each column of Figure 8 shows the delay laws applied to the active elements of the probe (blue bars), and the images below the probe show the ultrasonic beam for different measurement positions. The images of the beams shown in the left-hand column in Figure 8 are for delay laws that would focus the beam at the midpoint if there was no surface indentation. In this case, the simulations show that beam splitting occurs at the edges of the indentations, and the focal point is below the midpoint. The images in the right-hand column show the beam at different measurement locations when the focal laws have been modified to account for the spherical indentation. In this case, a different set of focal laws is used at each measurement position to account for the change in curvature of the surface. The simulated beams show that the focal spot is now maintained at the interface and the beam splitting at the edges of the indentation has been eliminated.

Figure 8. Beam simulations for an indented surface when the focal laws do not (left-hand column) and do account (right-hand column) for the surface indentation caused by the welding electrodes.
10. Conclusions

Complex shapes, joints, attenuative and heterogeneous materials, and the need for high-speed in-line solutions are just some of the conditions that create challenges in industrial applications. While the tremendous versatility of phased arrays greatly helps in overcoming many inspection challenges, the extensive options for probes and controllers makes it much more difficult for users to optimize designs and specify hardware requirements. The large number of parameters that must be examined to evaluate competing designs makes laboratory testing cost prohibitive. Parametric studies using CIVA simulation software have proven to be an essential tool in determining optimal probe and inspection configurations. CIVA simulation allows characterization of the beam radiated into structures undergoing inspection, as well as the response of the radiated field to defects. This allows resolution limits and the minimum size of a detectable defect to be determined, as well as the coverage zone. Although modelling does not eliminate the need for experimental validation, it can greatly reduce the number of required experiments. Moreover, both qualitative and quantitative characteristics of an NDT procedure can be evaluated. These modelling and parametric studies are often a necessary step in ensuring that inspection requirements are met and in evaluating the optimal tradeoffs between performance and cost.

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