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The promise of ultrasonic phased arrays and the role of modeling in specifying systems

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ABSTRACT

This article illustrates the advantages of phased-array systems and the value of modeling through several examples taken from phased-array training classes and aerospace problems. 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. The general strategy for specifying hardware and designing phased-array NDT procedures is described. For example, using phased-array modeling, it is possible to determine resolution limits and the minimum size of a detectable defect. The ways in which parametric studies can be used to evaluate tradeoffs between detectability and industrial constraints are also discussed.

INTRODUCTION

Unlike conventional ultrasonic systems that use a single piezoelectric crystal, phased-array probes are composed of multiple elements that can be designed either as a general purpose transducer, or optimized for a specific application. The advantages of phased-array systems include improved resolution and flexibility derived from the ability to perform electronic focusing, beam steering and scanning. 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 determine their probe and controller requirements. Modeling stands to be an increasingly important tool for both specifying hardware and for determining optimal inspection strategies.

Phased-array principles

Phased-array probes are composed of several piezoelectric crystals that can transmit/receive independently at different times. To focus the ultrasonic beam, time delays are applied to the elements to create constructive interference of the wavefronts, allowing the energy to be focused at any depth in the test specimen undergoing inspection. This principle is illustrated in Figure 1, where delay laws have been computed to focus the acoustic beam at a specified depth and angle. As shown in the figure, each element radiates a spherical wave at a specified time. The superposition of these wavelets results in an almost planar wavefront at the specified location.

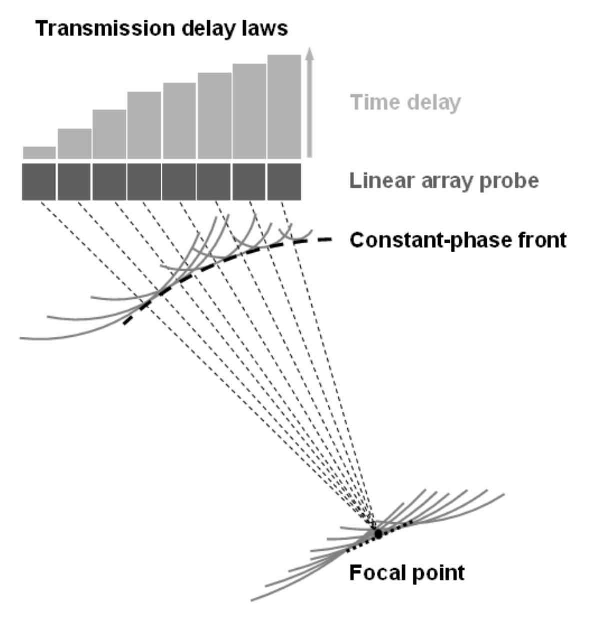
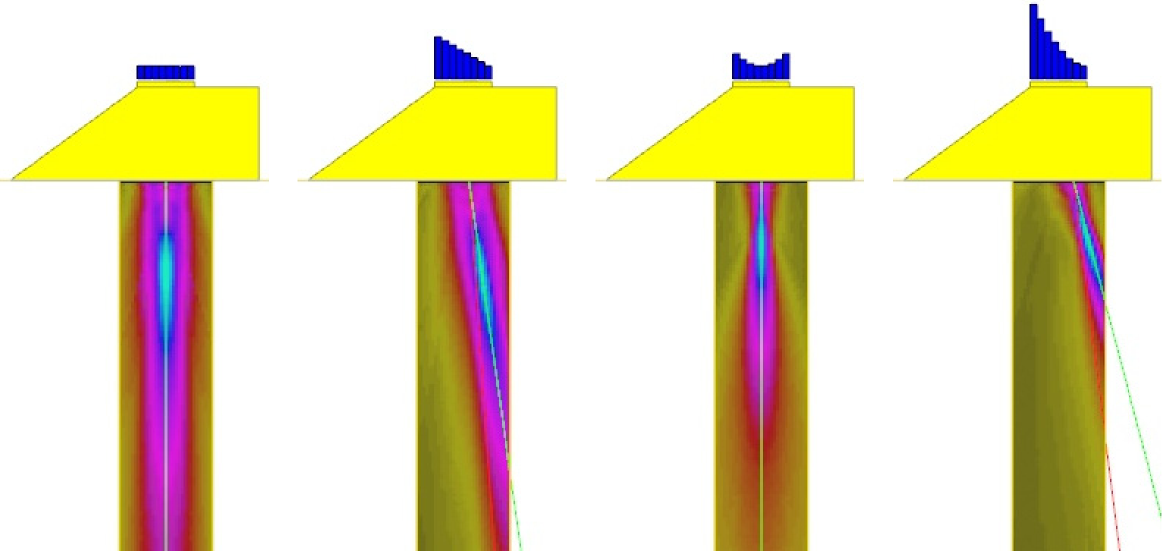


Figure 1: Principle of phased-arrays; delay laws calculated to focus at a given depth and angle.



(a) (b) (c) (d)

Figure 2: Examples of delay-laws and visualization of the radiated acoustic beam (displacement field). Calculations made using CIVA simulation software: (a) no delay-laws applied, (b) steering only, (c) depth focusing and (d) combined steering and depth focusing.

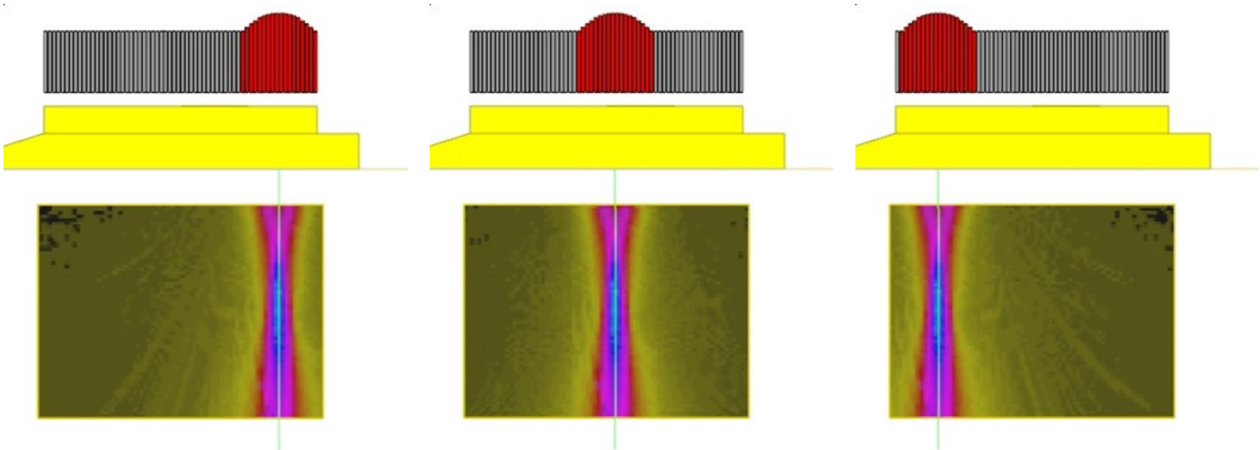


Figure 3: Example of electronic scanning. A subset of the elements in the array are used to generate a focused beam at normal incidence; this beam is then translated across the test specimen by firing subsequent groups of elements without moving the probe.

Before and after the targeted focal spot, wavefronts are spherically converging and diverging, respectively. A few examples of delay-law computation are displayed in Figure 2. When no delay laws are applied (Figure 2a), the resulting ultrasonic beam is unfocused and is equivalent to the beam generated by a conventional flat transducer. The natural “pseudo focalization” evident in the image corresponds to the near-field distance of the probe. The configuration illustrated in Figure 2b results in the same ultrasonic beam that would be generated by a conventional flat transducer used in conjunction with a wedge. In this case, there is no focusing of the ultrasonic energy; the applied delay laws result in steering of the ultrasonic beam. Figures 2c and 2d are the same configurations as illustrated in 2a and 2b, respectively, except that the delay laws have been modified to focus the acoustic energy at a specified depth. In both images (2c and 2d), it is evident that the focal spot is narrower and more localized. To obtain the same results with a conventional probe would require using a specially designed crystal shaped to obtain the desired focal point.

ADVANTAGES OF PHASED ARRAYS

Less movement, faster inspection, better reliability

The advantages of phased-array systems include the ability to perform electronic scanning of the ultrasonic beam, which can reduce inspection times by eliminating or reducing the need move the probe. As illustrated in Figure 3, electronic scanning is accomplished by firing successive groups of elements in the array. A complete C-Scan image can be obtained with a matrix phased array with the probe in a fixed position. The reliability of inspections can also be improved by reducing the need to move the probe. As is well known, good coupling between ultrasonic probes and the part undergoing inspection is crucial for good acoustic measurements. Each time the probe is moved, there is a risk of losing or degrading coupling. Thus, minimizing the number of times the probe is moved helps to maintain uniform conditions for multiple measurements.

Real-time imaging, easier interpretation

Phased arrays allow a broad spectrum of inspection strategies that improve performance, for example, sectorial scanning and focalization after reflection off the back surface of the test specimen. The most advanced phased-array systems include tools such as dynamic-depth focusing. With real-time imaging, inspections are easier to perform and the reliability of the measurements is also greatly improved. Because thousands of signals are captured and displayed at once, the struggle that operators often have in locating and visualizing defects on the screen is greatly reduced. In addition, the number of false alarms is diminished because of reduced operator dependence, and data recording and traceability are improved. Experimental results obtained using a sectorial scan are shown in Figure 4. Measurements were performed using 32 elements of a 64-element linear array with a frequency of 5 MHz. The test specimen was an aluminum reference block containing planar defects.

Applying delay laws to improve performance and simplify procedures

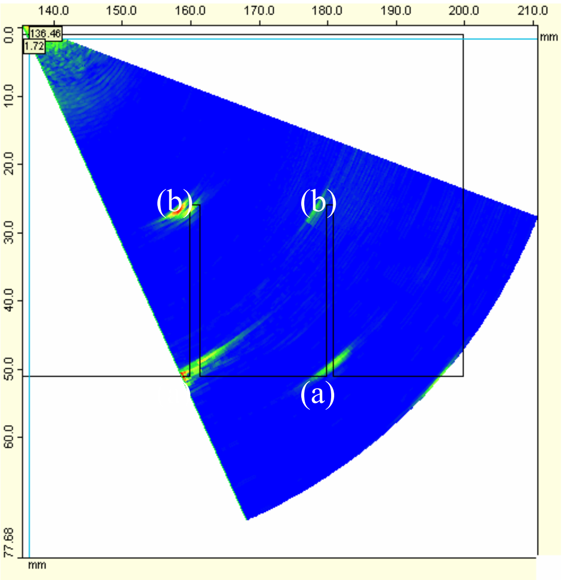


Figure 4: Example of sectorial scanning used for crack sizing. The solid rectangular line indicates the geometry of the test specimen under examination, including two parallel saw cuts. The corner echoes (labeled "a") resulting from the cuts were easily detected using 32 elements of a linear array with a central frequency of 5 MHz. Diffraction from the crack tips (labeled "b") is only observed when the beam is appropriately focused and directed.

Phased arrays can also replace an entire tool kit of conventional transducers. A single phased array used in conjunction with appropriate delay laws can reproduce the same acoustic beams achieved with numerous conventional probes, while also providing greater functionality. Using a phased-array controller that allows several types of delay laws per inspection, the results of several different sets of measurements that comprise a complete NDT procedure can be visualized simultaneously in real time.

THE IMPORTANCE OF MODELING

Modeling results obtained using CIVA (developed by the Commissariat à l'Energie Atomique in France) are used here to illustrate some of the unique features of phased array systems, and to demonstrate how modeling can be used to determine the optimal inspection strategy, which, in turn, can be used to specify the appropriate probe and to determine hardware needs.

Understanding and visualizing the beam radiated in the test specimen

The example discussed in detail here is the use of the same linear-array probe with two different sectorial scanning strategies. In this case, simulation is used to understand and visualize the beam shape, to help the engineer find the optimal inspection procedure. The simulation image shown in Figure 5a is the acoustic beam 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 Figure 5 is from the first shot in a 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 5). What the simulation shows is 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 (shear wave at 45 degrees), 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. Recall that the right-hand column of Figure 5 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. Using the -6dB sizing technique, the focal spots can be determined and compared for both cases.

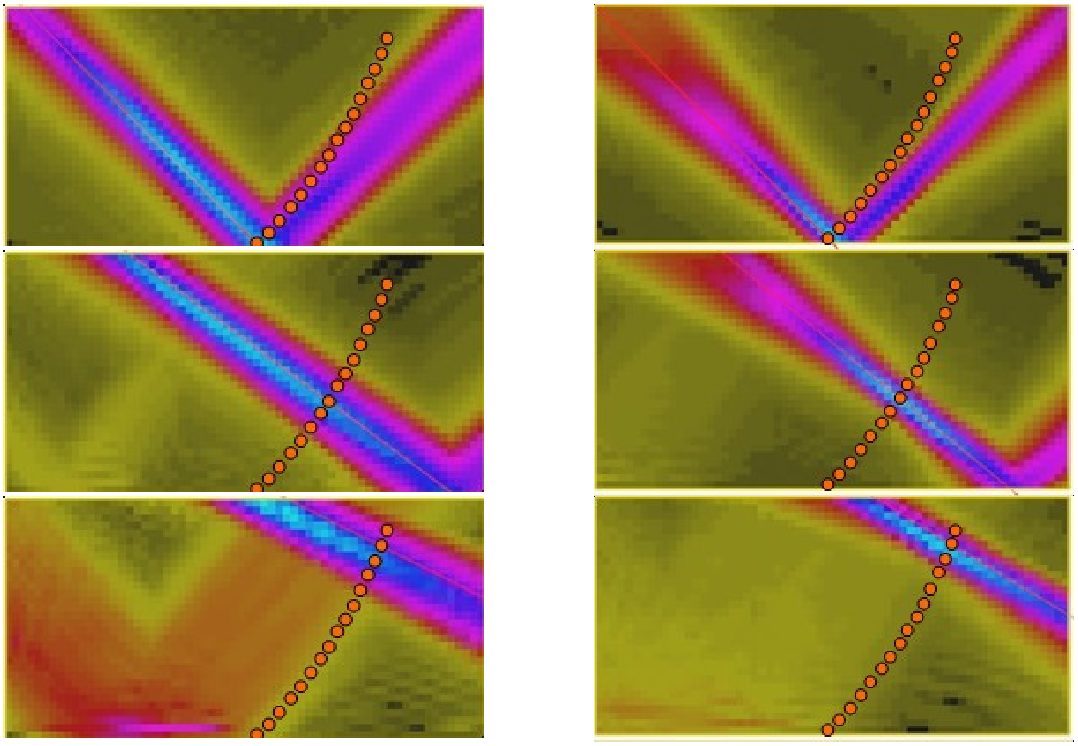
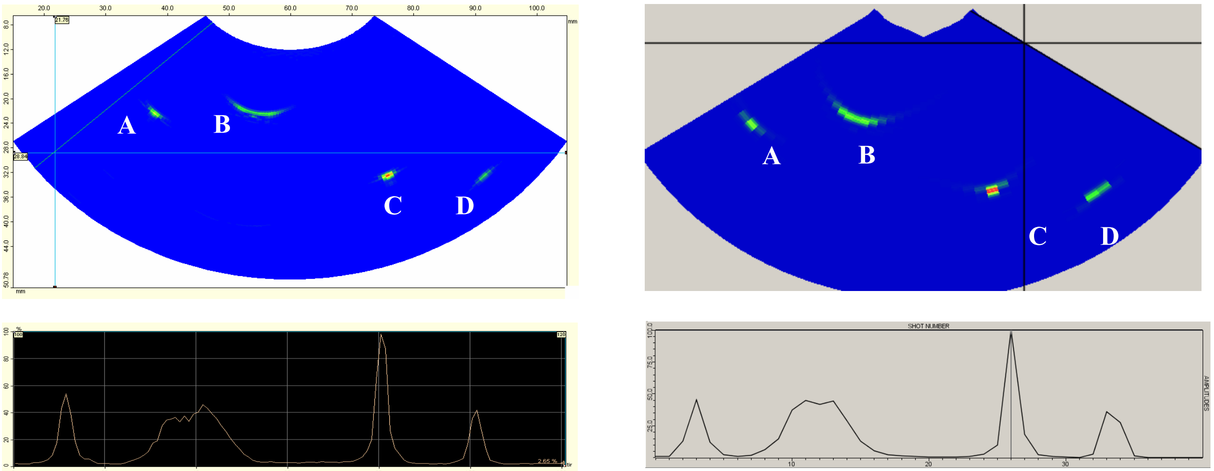


Figure 5: Radiated beams (shear waves) at 45, 58 and 70 degrees (first to third rows, respectively) for 7- and 16-element probe configurations (left- and right-hand columns, respectively). The dots on the images indicate the targeted focal points.

Although this relatively simple case might not warrant a modeling study, the complex geometries encountered in practice, along with physical constraints that limit access, make modeling an extremely valuable tool 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 5), it is possible to compare the 7- and 32-element configurations to determine the optimal tradeoff between size and detection capability.

Wave-defect interaction: evaluating the sensitivity of an NDT procedure

Using CIVA simulation software, it is not only possible to characterize the acoustic field for any phased-array configuration, but it is also possible to determine the sensitivity of the proposed inspection procedure. Even with sophisticated modeling tools there is still a need for calibration experiments, but they can usually be reduced to validation experiments performed on reference specimens (for example, a block with side-drilled holes). The reference test specimens are modeled and the results are compared to experimental measurements.



Gain A/C = -5.5 dB
Gain B/C = -6.8 dB
Gain C/C = 0 dB
Gain D/C = -7.6 dB

Gain A/C = -6.5 dB
Gain B/C =-7 dB
Gain C/C = 0dB
Gain D/C = -8.6 dB

Figure 6: Sectorial scans (top images) and dynamic echo curves (graphs below scans). Laboratory measurements are displayed on the left, and the results of the corresponding simulations are shown on the right. Experimental and simulation results are within 1 dB agreement.

The CEA is continually validating CIVA with experimental data [1], and the results displayed in Figure 6 are an example of how modeling results are validated. In this case, experimental and simulation results are shown for an aluminum block containing side drilled holes obtained from a focused, sectorial scan using 40 elements of a 64-element Imasonic probe. The sensitivity of proposed inspection protocols is determined by quantifying the defect response in terms of gain compared to the reference case (calibrated defects); i.e., if the gain required to identify the defect is within the dynamic range of the phased-array controller, then it will 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.

WORK UNDER DEVELOPMENT

Simulation studies are underway for relatively complex inspection problems [2]. For example, DASSAULT AVIATION (business jet and jetfighter manufacturer) is currently investigating a phased-array NDT procedure for fastener-hole inspection. The concept is to use a large linear array in a pseudo tandem configuration, in which different elements of the same probe are used for transmission and reception [3]. The transmission elements are used to perform a focused sectorial scan. The receiving elements are phased to perform focused sectorial reception after reflection off the bottom surface. The convolution between transmitted and received signals defines the active focal spot for the measurements.

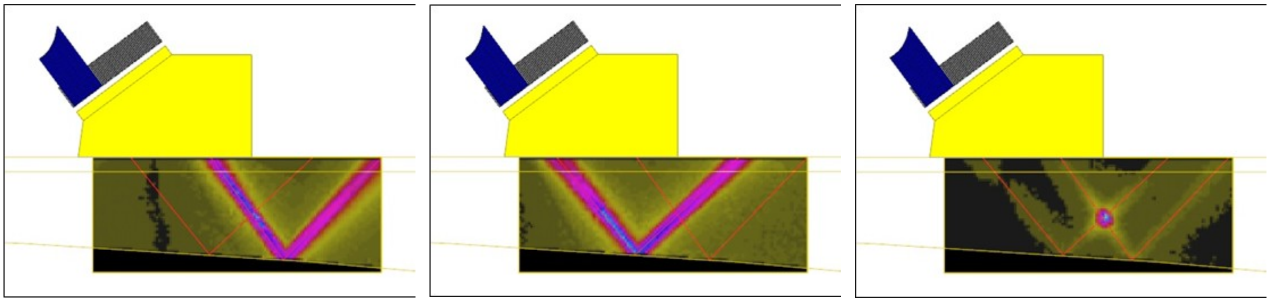

(a) (b) (c)

Figure 7: Simulation results for a linear array used in a pseudo tandem configuration: (a) transmission, (b) reception, (c) intersection of transmitted and received beams. A series of delay-laws is applied to make measurements throughout the thickness of the structure.

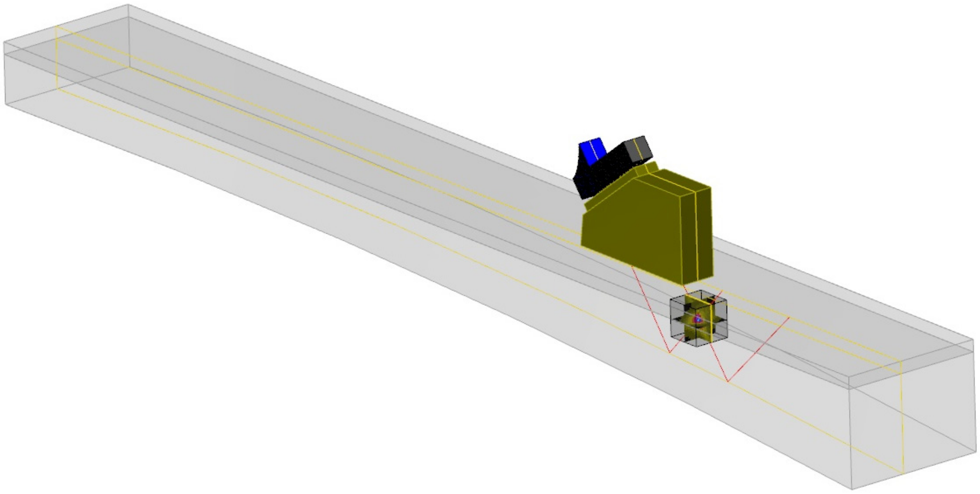


Figure 8: Simulation results from Figure 7c displayed in 3D in the CAD drawing of the test specimen. The solid lines indicate the ray paths of the shear waves, and the cube corresponds to the calculation zone.

A snapshot of the acoustic beams is shown in Figure 7. The objective is to obtain coverage over the entire thickness of the part while keeping the size of the focal spot the same. This is achieved by using different elements for transmission and reception and by applying different delay laws to each set of elements. The resulting focal zone is a sphere with a 5-mm radius that remains of constant size over the entire thickness of the structure under investigation. A 3D view of the convoluted beam is shown in Figure 8.

This first set of simulations has made it possible to optimize the number of elements used in the procedure. Based on this study, the number of elements used for transmission was found to be satisfactory. However, for reception, the number of elements had to be increased to be able to focus over the full thickness of the part. The travel path to the focal spot is much greater when focusing after reflection off the bottom surface, and therefore requires a wider aperture to increase the penetration depth. Once the probe design is finalized, sensitivity studies will be carried out to evaluate both the minimum detectable crack size and the coverage zone [4].

SUMMARY

The extensive capabilities of phased-array systems promise to improve inspectability and resolution for many nondestructive inspection applications. Basic studies as well as ongoing work at DASSAULT AVIATION demonstrate the advantages of phased arrays that include electronic focusing, scanning and beam steering, as well as real-time imaging. These features in turn enable inspection procedures that are faster, easier, and more reliable. Modeling stands to be an increasingly important tool for both specifying hardware and for determining optimal inspection strategies. Simulations performed with CIVA software [5] illustrate how modeling 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, as well as the coverage zone. Although phased-arrays and modeling 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 using modeling tools such as CIVA. These modeling and parametric studies are often a necessary step in designing green-light/red-light solutions used in the field. Modeling also helps to find the optimal tradeoffs between performance and cost, while also meeting field constraints.

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