

Adaptive ultrasonic inspection of complex-shaped structures: From data acquisition to imaging algorithms

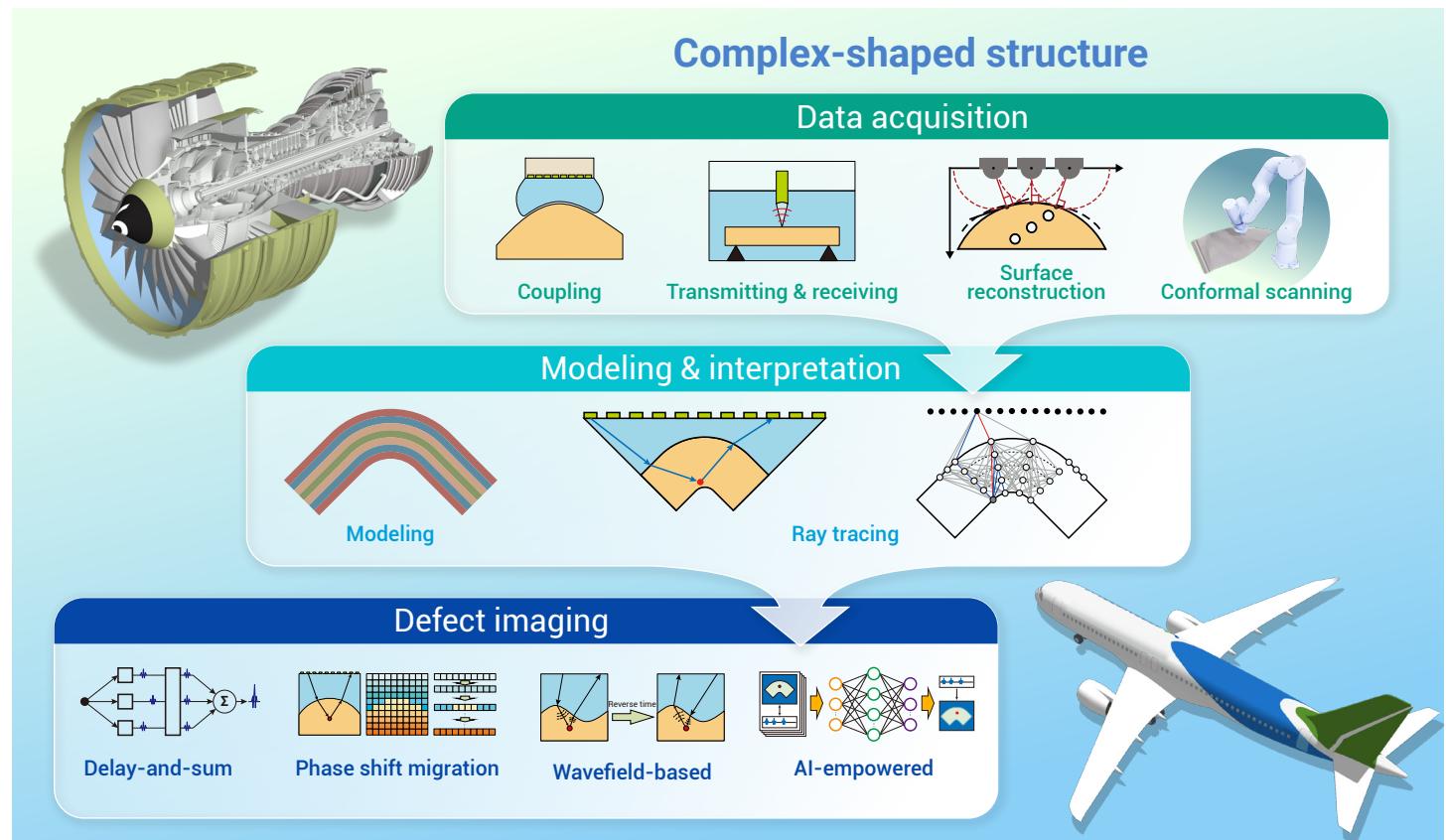
Zhijun Yao,^{1,2,7} Qimin Zhu,^{1,7} Huanqing Cao,^{1,3,4,*} Fan Shi,⁵ Chao Lu,⁶ Jian Yang,² and Shifeng Guo^{1,3,4,*}

*Correspondence: hq.cao@siat.ac.cn (H.C.); sf.guo@siat.ac.cn (S.G.)

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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Shape complexity poses significant challenges for ultrasonic inspection.
- Challenges lie in ultrasonic coupling, scanning control, and wave propagation.
- Various methods have been developed for data acquisition, modeling and imaging.

Adaptive ultrasonic inspection of complex-shaped structures: From data acquisition to imaging algorithms

Zhijun Yao,^{1,2,7} Qimin Zhu,^{1,7} Huanqing Cao,^{1,3,4,*} Fan Shi,⁵ Chao Lu,⁶ Jian Yang,² and Shifeng Guo^{1,3,4,*}

¹Shenzhen Key Laboratory of Smart Sensing and Intelligent Systems, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China

²Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham Ningbo China, Ningbo 315100, China

³University of Chinese Academy of Sciences, Beijing 100049, China

⁴Guangdong Provincial Key Laboratory of Robotics and Intelligent System, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China

⁵Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Hong Kong SAR 999077, China

⁶Key Laboratory of Nondestructive Testing, Ministry of Education, Nanchang Hangkong University, Nanchang 330063, China

⁷These authors contributed equally

*Correspondence: hq.cao@siat.ac.cn (H.C.); sf.guo@siat.ac.cn (S.G.)

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Complex-shaped structures are common in engineering components and prone to internal defect formation or even failure during manufacturing and service. Non-destructive ultrasonic inspection is an effective method for evaluation of manufacturing quality and in-service safety but faces challenges in ultrasonic coupling, ultrasound transmission and detection, surface conformal scanning control, and complex ultrasound propagation behavior brought by shape complexity of the tested structure. This review summarizes and addresses the challenges in adaptive ultrasonic inspection of complex-shaped structures, and discusses current developments in methodologies for solving such problems from the aspects of ultrasonic data acquisition, structure modeling, and defect imaging. Finally, future prospects for ultrasonic imaging of complex-shaped structures are proposed, including methods for inspecting ultra-complex and irregular surfaces, the development of highly flexible two-dimensional arrayed ultrasonic transducers, and the enhancement of imaging algorithms by simultaneously accounting for the influence of both macro/micro morphology and acoustic properties of the tested structure.

INTRODUCTION

Complex-shaped structures including curved surfaces, corners, and inclined surfaces are widely used in industrial scenarios such as airplanes, spacecrafts, pressure containers and pipelines, and rail traffic to meet specific in-service performance. Compared to simple structures like planar or small-curvature surfaces, complex-shaped structures require more complicated manufacturing processes and are prone to form defects such as cracks, delamination, and holes during manufacturing, thus reducing mechanical performance and structural integrity. Moreover, due to harsh service environments of alternative stress, extreme temperature and pressure, moisture, and radiation in application scenarios, material aging and internal defect expansion are more likely to occur in complex-shaped structures, leading to the overall failure of the structure. Therefore, non-destructive testing techniques for complex-shaped structures are highly demanded to timely and accurately detect internal defects and quantitatively evaluate the in-service performance, providing support for clarifying failure mechanism, improving manufacturing processes, and forecasting safety accidents.

Due to the advantages of wide applicability, high detection sensitivity, accurate defect localization, low cost, and convenient on-site use, ultrasonic testing has become the most used technique for non-destructive internal defect detection of complex-shaped structures. At present, automated ultrasonic testing techniques and equipment for relatively simple structures have been widely developed and become mature, while adaptive defect detection of complex-shaped structures still faces many challenges, as one of the major research topics in the field of ultrasonic non-destructive testing.

This review aims to provide a comprehensive overview of current challenges and solutions in adaptive ultrasonic inspection of complex-shaped structures and to provide reference for further research and applications. The challenges of ultrasonic inspection of complex-shaped structures are first addressed, including stable ultrasonic coupling, efficient ultrasonic trans-

mission and detection, surface conformal scanning control, and complex ultrasound propagation behavior. Then, current developments for overcoming such challenges are reviewed from the aspects of different inspection stages including ultrasonic data acquisition, structure modeling, and defect imaging. Ultrasonic coupling strategies, ultrasonic transmitting and receiving techniques, surface profile reconstruction methods, and surface conformal scanning control methods for ultrasonic data acquisition are introduced. Ultrasonic models of different types of structures, including the ultrasonic ray tracing model are overviewed, with the coupling effect between shape complexity and material elasticity being addressed. Conventional ultrasonic defect imaging methods as well as novel algorithms based on the delay-and-sum principle, phase shift migration, ultrasound wavefield, and machine learning methods are discussed. Finally, the challenges being faced are summarized to forecast future research in ultrasonic inspection of ultra-complex irregular surfaces, development of highly flexible two-dimensional (2D) arrayed ultrasonic transducers, and improvement of internal defect imaging algorithms.

CHALLENGES IN ULTRASONIC INSPECTION OF COMPLEX-SHAPED STRUCTURES

The challenges in ultrasonic inspection of complex-shaped structures exist in inspection procedures including ultrasound incidence, propagation, detection, scanning, and imaging that are affected by the shape complexity. The main challenges are discussed in the following paragraphs.

Stable ultrasonic coupling

Due to the significant acoustic impedance mismatch between air and solid materials, and the high attenuation of high-frequency ultrasound propagating in air, achieving stable ultrasonic coupling, thus ensuring efficient ultrasound transmission between the transducer and tested structure, is the first major challenge to be addressed in ultrasonic inspection. However, current commercial ultrasonic transducers are generally made of rigid piezoelectric ceramics and metal casings, as shown in Figure 1A, which makes them difficult to perfectly fit complex-shaped surfaces. And the air gap remained in the interface greatly impedes the transmission of high-frequency ultrasound. Consequently, it is necessary to fill a layer of acoustic transmission medium between the two solid surfaces to eliminate the air gap. In addition, since the space near large-curvature corners are generally narrow, which makes it difficult for transducers to reach directly, additional fixtures or waveguides are often needed to achieve stable acoustic coupling.¹

Efficient ultrasonic transmission and detection

As discussed previously, coupling layer is needed between the transducer and tested structure when inspecting complex-shaped structures. Due to the significant difference in acoustic characteristics between the coupling medium and tested material, acoustic impedance mismatch exists at the interface between the coupling layer and tested structure. When ultrasound is transmitted through such interface, part of its energy is lost due to interfacial reflection. Normally, when the ultrasonic wave is incident perpendicular to the

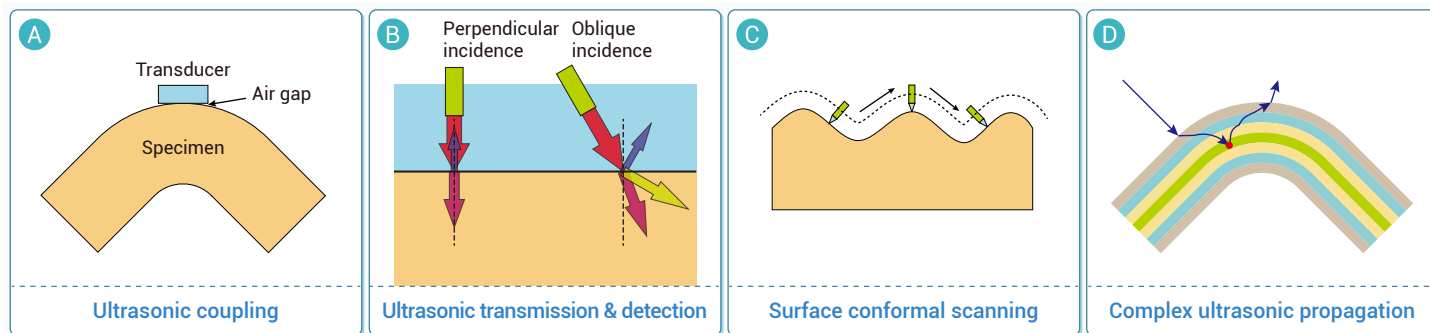


Figure 1. Challenges in ultrasonic inspection of complex-shaped structures (A) Ultrasonic coupling for rigid transducer. (B) Ultrasonic interfacial reflection and refraction at oblique incidence. (C) Surface conformal scanning. (D) Complex ultrasound propagation behavior in CFRP corner.

surface or interface, the transmission coefficient is the highest,² which is beneficial for enhancing the detection sensitivity. In addition, interfacial reflection and refraction occurred at oblique incidence will lead to the deflection of ultrasound propagation path (Figure 1B). In this case, when detecting planar defects with orientation parallel to the surface using reflection mode, the ultrasonic wave cannot return along the original path after being specularly reflected by the defect. Transmitted ultrasound detection is also challenging when using transmission mode for cardiac detection.

Surface conformal scanning control

The sound beams excited by ultrasonic transducers are highly directional, with maximum excitation intensity and detection sensitivity along the transducer surface normal and rapid reduction when propagation direction deviates. As a result, to acquire optimal ultrasonic inspection results, the pose of the transducer needs to be adjusted adaptively in real time during scanning process to maintain collinearity between the central axis of the sound beam and the surface normal of the tested structure. For planar structures, after adjusting the transducer orientation to ensure perpendicular incidence, full-coverage ultrasonic detection can be simply achieved by performing linear grid scanning without the need for adjustment of transducer pose. On the other hand, conformal scanning path planning according to surface contour of tested structure is necessary for inspection of complex-shaped structures to improve scanning efficiency while avoiding omission of inspection (Figure 1C). In addition, to ensure consistent sensitivity at all sampling positions, both the orientation and lift-off distance of the transducer need to be adaptively adjusted in real time to ensure perpendicular incidence and consistent amplitude throughout the scanning process. Consequently, the scanning control for complex-shaped structures is more complicated than that for conventional planar structures.

Complex ultrasound propagation behavior

A primary difficulty in inspecting complex-shaped structures lies in the coupling of material-related challenges with geometric complexity, which significantly complicates the ultrasound propagation behavior. For example, when the tested structure is a corner part of carbon fiber reinforced plastic (CFRP) with fiber orientation bending continuously along the curved surface, the anisotropic wave velocity distribution also varies with the fiber orientation at different positions. This results in continuously bending ultrasonic propagation paths, which increases the difficulty for ultrasonic focusing regulation and target signal decoupling (Figure 1D). In addition to these material complexities, the physics of wave interaction at the curved interface presents critical challenges, particularly regarding mode conversion and energy partitioning. Unlike planar structures where normal incidence is easily maintained, scanning complex curvatures inevitably introduces varying oblique incidence angles relative to the local surface normal. The oblique incidence induces mode conversion at the interface, resulting in longitudinal and shear waves with distinct refraction angles.³ And the acoustic impedance mismatch leads to energy partitioning between these modes. This phenomenon impairs imaging accuracy in two major ways. First, the energy partitioning significantly attenuates the amplitude of the primary detection mode, degrading the signal-to-noise ratio (SNR). Second, the mode-converted waves propagating at different velocities may generate artifacts if misinterpreted as the primary

mode. For these reasons, longitudinal waves are typically established as the primary modality for volumetric inspection of thick complex components to ensure signal stability, while shear waves are generally employed to enhance sensitivity to defects oriented perpendicular to the surface. Furthermore, guided waves are typically employed for thin-walled complex structures to achieve large-area detection, but the wave physics becomes more complicated because the curvature of the structures alters the dispersion relations. In flat plates, the frequency dependency of phase and group velocities can be described by dispersion curves that can be calculated with thicknesses and elastic parameters. However, in complex-shaped components, the radius of curvature fundamentally alters these boundary conditions. The dispersion characteristics evolve as the wave propagates from flat to curved regions, inducing mode coupling and velocity shifts.^{4,5} Crucially, the uncompensated application of standard dispersion curves to curved geometries introduces significant deviations in defect localization and sizing.^{6,7} Therefore, curvature-induced dispersion needs to be explicitly incorporated into the forward modeling and compensated in the imaging process to mitigate these effects.

To address the above challenges, current research mainly focused on several aspects, including ultrasonic coupling strategies, ultrasonic transmitting and receiving techniques, surface profile reconstruction methods, surface conformal scanning control methods, ultrasonic modeling techniques, and defect imaging algorithms. These aspects are classified based on different ultrasonic inspection stages in the following sections, and corresponding research progress will be introduced.

ULTRASONIC DATA ACQUISITION

Ultrasonic data acquisition is the first stage of ultrasonic inspection that provides data support for subsequent data processing and visualization procedures. High quality ultrasonic data with optimal and consistent SNR is the key to high-resolution defect visualization. In this section, three main procedures at the data acquisition stage including ultrasonic coupling, ultrasonic transmitting and receiving, and surface conformal scanning will be introduced.

Ultrasonic coupling strategies

Stable ultrasonic coupling is the fundamental of ultrasonic data acquisition. Typical ultrasonic coupling strategies can be divided into contact and non-contact methods.

Contact ultrasonic testing is one of the major ultrasonic testing methods in the engineering field since it can avoid the influence of transmitted energy loss and propagation path deflection caused by the reflection and refraction at the interface between the coupling layer and the tested structure, which is beneficial for enhancing detection sensitivity and reducing complexity of signal interpretation. The surfaces of the most frequently used single element or phase arrayed ultrasonic transducers are usually flat. They can fit the planar structure surface by simple direct contact, with the addition of a thin layer of liquid coupling layer to eliminate the air gap between the transducer and sample surface. For complex-shaped structures, stable contact can be ensured only when the transducer size is smaller than the radius of curvature of the tested surface. To solve this problem, delay lines or wedges that match the tested surface are usually installed on the transducer surface (Figure 2A). For example, pen-shaped transducers installed with small-tip-sized

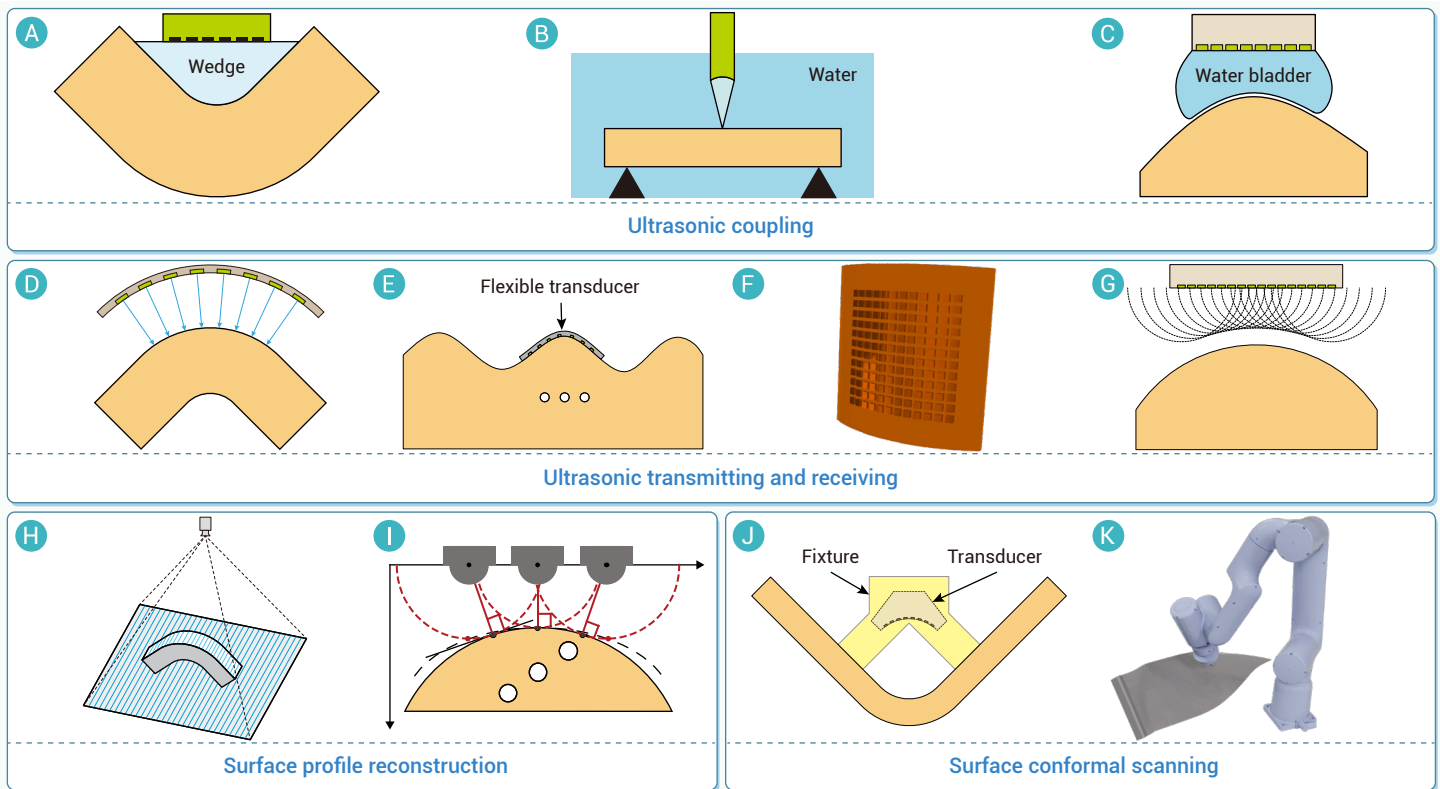


Figure 2. Procedures at the data acquisition stage (A) Ultrasonic coupling using wedges. (B) Ultrasonic coupling using liquid immersion. (C) Ultrasonic coupling using water bladder. (D) Arc-shaped linear-arrayed transducer for corner inspection. (E) Flexible ultrasonic transducer directed fabricated onto the tested structure. (F) Flexible array transducer with elements embedded into rubber matrix. (G) Surface-adaptive ultrasonic technique. (H) Surface profile reconstruction using optical devices. (I) Surface profile reconstruction using wavefronts of the surface reflection echoes. (J) Water immersion corner wedge for corner inspection using curved array transducers. (K) Surface conformal scanning using multi-degree-of-freedom robotic arms.

delay lines can be used for large-curvature regions.⁸ In addition to providing acoustic coupling, such solutions can also introduce extra time delay to the ultrasonic waves, which can avoid the surface detection blind zone caused by the overlapping of initial ultrasonic pulse signal in direct-contact tests. On the other hand, since such delay lines or wedges are typically made from rigid epoxy material, a single component can only suit a specific geometric profile, resulting in poor versatility. When testing different types of structures, or structures with varying surface profiles, such as aero-engine blades and aircraft wing spars, a series of wedges matching the surfaces at different positions need to be manufactured, which results in relatively high manufacturing costs. At the same time, frequent replacement of wedges is not convenient for continuous automatic scanning.⁹ In addition, pressing is generally needed to ensure tight fit of rigid wedges. However, during scanning of complex-shaped structures, it is difficult to maintain constant pressing force throughout the scanning process, resulting in fluctuation in signal amplitude and challenge in the interpretation of defect signal.

Liquid immersion is another type of contact method where the tested structure is fully immersed in liquid media such as water or oil, and the transducer is moved over the sample surface for ultrasonic transmitting and receiving (Figure 2B).¹⁰ This method enables stable acoustic coupling of any type of complex surface and is widely used in ultrasonic C-scan equipment. For scenarios where the tested structure is too large for full immersion, a water spraying device can be installed in front of the transducer to create local immersion condition where the ultrasonic wave is transmitted to the sample through the water column. This method is widely used in large gantry-type or robot arm-based ultrasonic testing equipment for inspection of large structures. However, due to the large difference in acoustic impedance between water (with a wave velocity of 1480 m/s) and metal (steel, with longitudinal wave velocity of 5920 m/s), the ultrasonic transmission coefficient at the water-metal interface is only a fraction of that when using rigid epoxy wedges (Rexolite, with longitudinal wave velocity of 2340 m/s). Given that the difference in wave velocity between ice (with a longitudinal wave velocity of around 4000 m/s) and metal is much smaller than that of water,

Simonetti and Fox proposed a novel acoustic coupling strategy by immersing the complex-shaped metal structure into water and then freezing it into a bubble-free ice block with tightly bonded interface.^{11,12} For scenarios where liquid contact is not applicable, such as when the tested material is hygroscopic (woods) or prone to water filling (porous materials), or when testing under some in field environments, water bladders coated with sound-transmitting films or rubbers (Figure 2C),^{13,14} or soft wedges made from polymers^{15,16} can be applied. With their flexible and deformable characteristics, assisted by clamping fixtures, they can adapt to changes in surface profiles and ensure close contact with the surface throughout the scanning process.

When testing in harsh environments such as high temperature, high pressure, and radioactive, the above contact methods are highly limited. For these cases, non-contact methods without coupling medium are more advantageous. Common non-contact ultrasonic testing methods include electromagnetic acoustic transducers (EMAT), air coupled transducers (ACT), and laser ultrasonics (LU). EMAT generates ultrasonic waves based on the electromagnetic induction effect and interaction between the eddy current and the magnetic field. The advantages of this non-contact technique are suitable for high temperature environments, sensitive to surface defects, low surface roughness requirement of sample. On the other hand, this method is limited to electrically conductive materials, and the sensitivity is much lower than piezoelectric transducers. In addition, since the lift-off distance significantly affects the signal amplitude, and the transducer works typically in contact or at a small distance from the surface, this method is not suitable for complex-shaped structures. ACT uses low-frequency ultrasound (in kHz range) to acquire relatively strong penetration ability in air to achieve fully non-contact testing and has been widely used for testing large-thickness CFRP structures with high ultrasonic attenuation.^{17,18} However, the huge acoustic impedance mismatch between air and solids and the high ultrasonic attenuation in air make the excitation efficiency and detection accuracy of this method much lower than the contact-based setups. Fully non-contact LU technology uses pulsed laser beam to generate ultrasonic waves on the

Table 1. Comparison of different coupling methods.

Coupling Method	Advantage	Limitation	Application
Contact Testing	Avoids energy loss	Poor versatility; sensitive to curvature radius of the tested surface	Planar structure
Rigid Wedges	Eliminates surface detection blind zones by introducing time delay	Poor versatility; inconvenient for continuous automatic scanning	Large-curvature components with special surface profiles
Liquid Immersion	Enables stable acoustic coupling for any type of complex surface	Low ultrasonic transmission coefficient	Large-curvature components
Flexible Coupling (bladder/soft wedge)	Adapts to changes in surface profiles	Requires clamping fixtures to assist the contact	Large-curvature components
Non-contact Methods	No coupling medium required; suitable for harsh environment	Lower sensitivity compared to piezoelectric transducers	Small structures

Table 2. Comparison of different transducer types.

Transducer Type	Advantage	Limitation	Application
Rigid Special-shaped Transducer	Ensures perpendicular incidence	Poor versatility	Specific types of surfaces and geometric specifications
Direct-write Transducer	Good adhesion; couplant-free; conformability to complex surface	Fixed position; no scanning capability	Structural health monitoring
Flexible Phased Array Transducer	Surface adaptability; dynamic focusing	Dimensional constraints; high manufacturing cost	Complex curved surfaces

tested structure remotely based on the thermoelastic or ablation effect and is often combined with laser interferometers to detect ultrasonic signals.¹⁹ With the combination of fiber optical phased array technology, the focusing characteristics of the generated ultrasonic beam can be controlled.²⁰ Since the ultrasonic wave is excited and detection remotely using laser, this method can be used for testing in harsh environments and for fine scanning on small structures. The current limitations of this technology are relatively low sensitivity compared to piezoelectric transducers under fully non-destructive conditions, and high sample surface requirements. To provide a clear overview, the advantages, limitations, and typical applications of these different coupling strategies are summarized and compared in Table 1.

Ultrasonic transmitting and receiving techniques

Ultrasonic transducers are the basis for ultrasonic transmitting and receiving. Currently, planar rigid single element transducers or phased array transducers are still widely used by the industry. To meet the requirement of ultrasonic perpendicular incidence when testing complex-shaped structures, special-shaped transducers designed for specific surfaces have emerged, such as cylindrical transducers for small-diameter pipe detection, and arc-shaped linear-arrayed transducers (Figure 2D) for corner inspection.²¹⁻²³ Since such rigid special-shaped transducers can only be applicable to specific types of surfaces and geometric specifications, they have poor versatility and not suitable for automated scanning of structures with varying shapes.

In recent years, flexible ultrasonic transducers have become an effective solution for overcoming the challenges in testing complex-shaped structures.²⁴ Direct-write transducers are fabricated on the tested structure as standalone or arrayed transducers by dispersing piezoelectric ceramic or polymer powder into a solution, and then through thin-film forming processes such as tape casting, solution casting, spin coating, dip coating, and direct-write printing. Since flexible ultrasonic transducers are fabricated directly onto the tested structure (Figure 2E), they have the advantages of simplicity for sensing network fabrication, light weight, good adhesion and conformability to complex surfaces, and no need for coupling agent, greatly improving the stability and repeatability of ultrasonic signals, and are favorable for structural health monitoring applications.²⁵⁻²⁷ However, since such transducers are fixed on the tested structures, they are only suitable for monitoring at fixed positions and cannot cover a larger detection range through scanning.²⁸ To achieve conformal scanning of arrayed transducers, the initial solution was to connect a series of piezoelectric elements with hinges to form a one-dimensional (1D) linear array where the relative position between the elements could be changed freely to obtain flexible fitting to different curved surfaces, overcoming the challenge of acoustic coupling for rigid transducers.²⁹ To further improve the flexibility of transducers, designs

of embedding the transducer elements into a flexible rubber matrix have been proposed for adapting to surfaces with larger curvatures (Figure 2F).³⁰ To overcome the problem that 1D flexible linear array transducers cannot be used for three-dimensional (3D) curved surfaces, Toullelan et al.³¹ developed a 2D flexible phased array transducer with displacement sensors integrated on the back of the array elements. This design can achieve real-time adjustment of the focal law according to the change of element positions during scanning, ensuring stable imaging quality throughout scanning. Such transducer has been applied for inspecting boss head welding seams and pipe elbows in nuclear power plants. In addition, leading NDT manufactures have also commercialized flexible phased array technologies to meet real industrial demands. For instance, Evident and Eddyfi Technologies offer commercial flexible phased array transducers designed for defect detection on curved metallic and composite components. Although these transducers are promising for solving the acoustic coupling problem on complex-shaped structures, current flexible phased array transducers still have limited bending curvature and cannot adapt to structures with arbitrarily large curvatures. Moreover, due to the relatively thin damping layer, the frequency bandwidth of flexible transducers is very narrow, resulting in a large surface blind zone. Coupled with the high manufacturing cost, flexible array transducers have not been widely used yet. To provide a systematic overview, the advantages, limitations and applications of the different transducer types discussed above are summarized in Table 2.

Leveraging on the capability of phased array ultrasound to electronically control beam focusing and steering via the adjustment of element excitation and reception delays, the French Atomic Energy Commission (CEA) proposed the Surface-Adaptive Ultrasound (SAUL) technique. This method utilizes a standard planar linear array transducer to determine the surface profile of complex-shaped structures from the time-of-flight differences among the surface reflection echoes received by individual elements.³²⁻³⁴ Based on the reconstructed surface profile, the system calculates and corrects the element excitation delay times in real time, resulting in the synthesis of a wavefront which is precisely conformal to the surface (Figure 2G). Crucially, this approach does not require a priori knowledge of the geometric outline and eliminates the need for multi-degree robotic arm to maintain transducer perpendicular to the inspection surface.³⁵⁻³⁸ However, the substantial computational burden of the iterative and real-time process poses a limitation on the applicability of the technique, particularly in high-speed scanning scenarios or on systems with constrained computational resources.

Surface profile reconstruction methods

Knowing the surface profile of the tested structure in advance is the requirement of conformal scanning control and ultrasonic imaging. In

general, there are three strategies to obtain the surface profile of the tested structure.

The first strategy is to directly acquire the surface profile using the computer-aided design (CAD) drawings of the tested structure. However, in many situations, CAD drawings are often unavailable. Moreover, integrally formed large structures, especially CFRP parts, are prone to geometric errors due to various manufacturing factors.

The second strategy is to reconstruct the surface profile using optical devices such as high-precision laser profilers and binocular cameras (Figure 2H).³⁹ These technologies have been very mature in the field of machine vision, and many commercial devices and software have been available. However, since such devices are typically independent from the ultrasonic systems, the reconstructed profiles must go through the coordinate conversion process to perform ultrasonic scanning path planning. Consequently, ultrasonic scanning systems using this strategy typically need to perform two scans: the first scan is to reconstruct the surface profile with optical devices, and the second scan is to perform conformal ultrasonic scanning based on the reconstructed profile. The limitation of this strategy is the low inspection efficiency due to the need for two scans, especially for large structures. In addition, for structures that are classified, surface profile scanning is typically prohibited, which also limits the application scene of this strategy.

The third strategy is to perform surface profile reconstruction and defect detection of complex-shaped structures completely rely on the ultrasonic testing system itself. For example, when using 1D linear array transducers or 2D matrix array transducers to collect ultrasonic signals propagating at various directions using the full matrix capture (FMC) method, the recorded ultrasonic signals contain reflection echoes of both sample surface and internal defects.⁴⁰ With the assistance of ultrasonic post-processing algorithms such as synthetic aperture focusing technique (SAFT) or total focusing method (TFM), ultrasonic imaging of the coupling layer above the complex surface can be achieved. The contour profile of the interface between the coupling layer and the tested structure can be extracted from the imaging result and further used for ultrasonic visualization of internal defects.^{41,42} Alternatively, full-waveform inversion (FWI) can reconstruct surface profile during imaging by treating the couplant-solid interface geometry as part of the unknowns and fitting the measured waveforms with a coupled medium model.⁴³

Another method is to perform quick surface profile reconstruction using the wavefronts of the surface reflection echoes (Figure 2I).³⁷ Limited by the narrow angular wave field coverage range of the transducer, ultrasonic waves cannot cover the entire large-curvature arc surface or large-inclination inclined surface with perpendicular incidence. The oblique incident wave cannot return along the original path and be received by the same transducer element, and it is difficult to be captured by other elements of the array transducer. Thus, it is challenging to reconstruct the entire complex surface using ultrasonic methods.⁴⁴

Surface conformal scanning control methods

The strong directivity characteristic of ultrasonic wave determines that the transducer pose must be adjusted in real time during scanning to ensure that the direction of wave beam with strongest transmission and reception sensitivities is always perpendicular to the inspected structure surface. In current engineering applications, manual inspection using handheld single element ultrasonic transducers are still widely used. However, manual adjustment of transducer orientation lacks accuracy and stability, resulting in unstable signal intensity throughout scanning, affecting the sensitivity of defect detection and the quantitative accuracy. When the oblique incident angle is too large, the defect signal may become weak and unrecognizable. Moreover, since the ultrasonic beam of a single element transducer is relatively narrow, the detection range is restricted, and the efficiency of manual point-by-point scanning is extremely low. For the surface with a fixed geometric specification, constant relative position between the transducer and the tested structure can be ensured by using specific clamping and scanning fixtures that match the sample surface. For example, stable scanning of convex structures can be achieved by supporting the transducer with three adjustable bolts. The Olympus corporation designed a water immersion corner wedge that can be closely attached to the two right-angled sides of the corner to

provide stable support for the inspection of corners using curved array transducers (Figure 2J). With this wedge, the relative distance between the transducer and the corner can be adjusted to adapt to corners with different curvatures, ensuring that the transducer is always centered with the corner surface.

To overcome the limitations of manual scanning and improve the efficiency of ultrasonic inspection, multi-degree-of-freedom robotic arms are being increasingly used for automated scanning of complex-shaped structures (Figure 2K).⁴⁵ At present, the conventional solution is to perform automatic conformal scanning path planning through computer programming based on the surface profile of the tested structure. At the same time, the transducer pose is adjusted in real time during scanning to ensure perpendicular ultrasonic incidence at each scanning point distributed over the entire complex surface. In the field of robotics, conformal scanning path planning and controlling of multi-degree-of-freedom robotic arms have been relatively mature, and these technologies can be simply integrated with ultrasonic testing systems. For example, TPAC phased-array instrumentation has been integrated into automated inspection machines developed by USL, which combines advanced acquisition units with multi-axis motion control. By employing water jets and immersion coupling methods, these systems have been adopted in aerospace for inspecting complex-shaped components. However, the equipment cost for such fully automated system is relatively high.

ULTRASONIC MODELING

An accurate ultrasonic model is a fundamental prerequisite for developing high-resolution imaging algorithms and ensuring the precise characterization of defects within complex-shaped components. The modeling approaches can be broadly categorized based on the acoustic properties of the materials and the geometry of the structure, as shown in Figure 3.

Ultrasonic modeling of different types of structures

Homogeneous isotropic structures. Most metallic components and common ultrasonic couplants are modeled as homogeneous and isotropic with constant bulk wave velocities which do not vary with direction. In this scenario, ultrasonic wave propagates in straight lines within each homogeneous region, and wave refraction occurs only at interfaces between two media with different acoustic impedances such as the couplant-component boundary. Consequently, the calculation of the ultrasonic propagation path for these cases is considered relatively straightforward.

Homogeneous anisotropic structures. A more complex modeling case is presented by homogeneous anisotropic materials, such as single-crystal silicon and unidirectional fiber-reinforced composites with ply thicknesses smaller than the wavelength. The acoustic properties of these materials are spatially uniform, but their wave velocities are highly dependent on the propagation direction relative to the principal structural axes. This directional velocity dependence imposes a significant computational demand on the associated modeling. Specifically, while the ray path remains rectilinear, its accurate calculation requires that the full stiffness tensor of the material can be utilized in advanced formulations such as the Christoffel's equation.

Multilayered anisotropic structures. The most complex modeling category involves multilayered anisotropic structures. These composite structures are manufactured by stacking multiple unidirectional plies, each constituting a homogeneous anisotropic medium at a specified angular orientation. This material class is exemplified by carbon fiber-reinforced plastic (CFRP), a material critical to primary load-bearing aerospace structures, and glass fiber-reinforced plastic (GFRP), prevalent in wind turbine blades.¹⁶ When these fiber-reinforced plastic (FRP) materials are formed into components with complex geometries such as corners or variable-thickness sections, the geometric factors interact with the material's intrinsic multilayered and anisotropic nature to alter the acoustic properties of the structure. This interaction manifests as a complex change in fiber orientation, which not only varies within the layers but also changes continuously in through-thickness direction, tangentially following the surface contour. As a result, the anisotropic velocity distribution of a curved ply varies continuously with spatial position, causing the ply itself to exhibit acoustic inhomogeneity. For an obliquely incident wave in such a region, the ray path within a single curved ply is no longer rectilin-

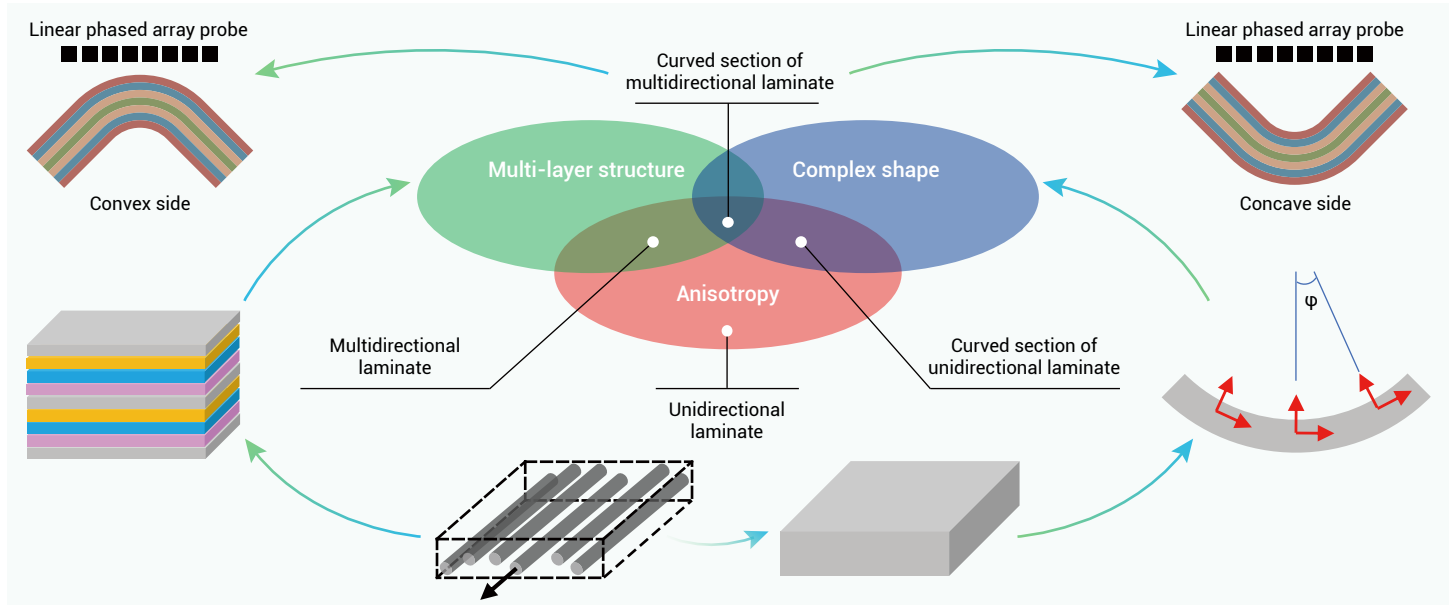


Figure 3. Ultrasonic modeling of complex structures.

ear and both its velocity and direction change continuously, making the wave propagation considerably more complex than in homogenous isotropic materials.⁴⁶⁻⁴⁸

Ultrasonic ray tracing method

The ultrasonic ray tracing method is an effective solution to calculate the ultrasonic propagation path and time in complex-shaped structures. The basic principle of ultrasonic ray tracing is that when the acoustic properties are uniform compared to the wavelength, the ultrasonic wave can be treated as a series of rays that propagate as straight lines in homogeneous media and divert at acoustic impedance mismatched interfaces due to reflection and refraction.

The ultrasonic ray tracing problems can be divided into two types, i.e., forward and inverse problems.⁴⁹ The forward ray tracing (Figure 4A) predicts the on-going ultrasonic propagation path with a specific initial direction, while the inverse ray tracing (Figure 4B) finds the propagation path with given start and end points.⁵⁰ For ultrasonic defect imaging using the delay-and-sum (DAS) principle, the inverse ray tracing problem needs to be solved. Conventionally, the solution is based on Snell's law which calculates the relationship between the incidence and reflection/refraction angles using the ratio of wave velocity of the two media on both sides of the interface. The initial propagation angle is iteratively changed until the end point of the path reaches the target point (Figure 4C).⁵¹ This method strictly follows the Snell's law and can predict acoustic energy evolution, but it is computationally inefficient when calculating massive amounts of ray paths in multilayered anisotropic structures.^{50,52-54} To improve computation efficiency, shortest path searching algorithms such as Dijkstra's or A* algorithms are promising solutions. The application of such algorithms comes from Fermat's principle that rays always travel along the path with minimum propagation time. When using such algorithms to perform ray tracing, the inspection region is first discretized as mesh grids where adjacent nodes within a local range are connected via straight paths according to the wave velocity distribution. Finally, a global search is performed in accordance with specified rules to determine which locally connected paths will be segmented and concatenated to form the propagation path (Figure 4D).⁵⁵ The major advantages of these methods are that they eliminate the need for iterative calculations to determine the reflection and refraction of the rays at interfaces, and that they can perform high-precision and fast computations. Therefore, they are highly suitable for rapid ray tracing in structures with complex geometry and acoustic properties.

To achieve high-resolution imaging based on the DAS principle, the formidable ray-tracing challenge in complex, multilayered and anisotropic FRP structures must be solved first. It should be noted that in engineering practice, this complexity is usually minimized by employing a normal-incidence inspection.

When the ultrasonic wave is perpendicular to the surface, its propagation direction and velocity remain stable, which is effective for detecting delamination that are typically aligned with the ply interfaces.^{56,57} However, a more rigorous approach is required for more advanced imaging. This requirement is typically met by a two-step numerical strategy. First, the inspection volume is discretized into a mesh of voxels, within which fiber orientation is assumed to be constant. It allows the ultrasonic wave to be modeled with a rectilinear path inside each element, approximating the global complex ray path as a polyline. Second, Fermat's principle-based ray tracing is employed to efficiently search this network of path segments for the optimal trajectory.⁵⁸ This combined numerical strategy has enabled the successful implementation of ray tracing and DAS imaging in scenarios, e.g., the inspection of large-curvature corners, wedge-shaped composite structures, and components with out-of-plane fiber wrinkles.^{49,59-64}

ULTRASONIC DEFECT IMAGING

Ultrasonic defect imaging is the final stage of ultrasonic inspection that utilizes the acquired ultrasonic data and structure model to visualize the internal defects in complex-shaped structures. Ultrasonic defect imaging methods for complex-shaped structures can be categorized into conventional real-time imaging methods, and post-processing imaging methods which include delay-and-sum (DAS), phase shift migration (PSM), and wavefield-based imaging algorithms. With the rapid development of machine learning (ML), this technology has begun to address the challenges in defect imaging in complex-shaped structures. To provide a clear overview, the principles, advantages, and limitations of these different imaging algorithms are systematically compared in Table 3.

Conventional real-time ultrasonic imaging methods

Conventional real-time ultrasonic imaging methods are mainly based on the reflection signals acquired by scanning on the tested structures. The acquired ultrasonic data is recorded and processed rapidly by the ultrasonic testing system and visualized via graphical user interface, enabling real-time defect identification.

The testing method commonly used in engineering is based on hand-held single element ultrasonic transducer, which often determines the presence and location of defects based on the change of waveform presented as A-scan, B-scan, and C-scan images. The visualization of this method is not intuitive enough and difficult to interpret, and the results are greatly affected by subjective factors such as personnel knowledge, experience, and working status. The conformal testing method using curved or flexible array transducers, or the surface-matching testing method using flat linear array transducers, is generally based on surface-matching wavefront. In such scenarios,

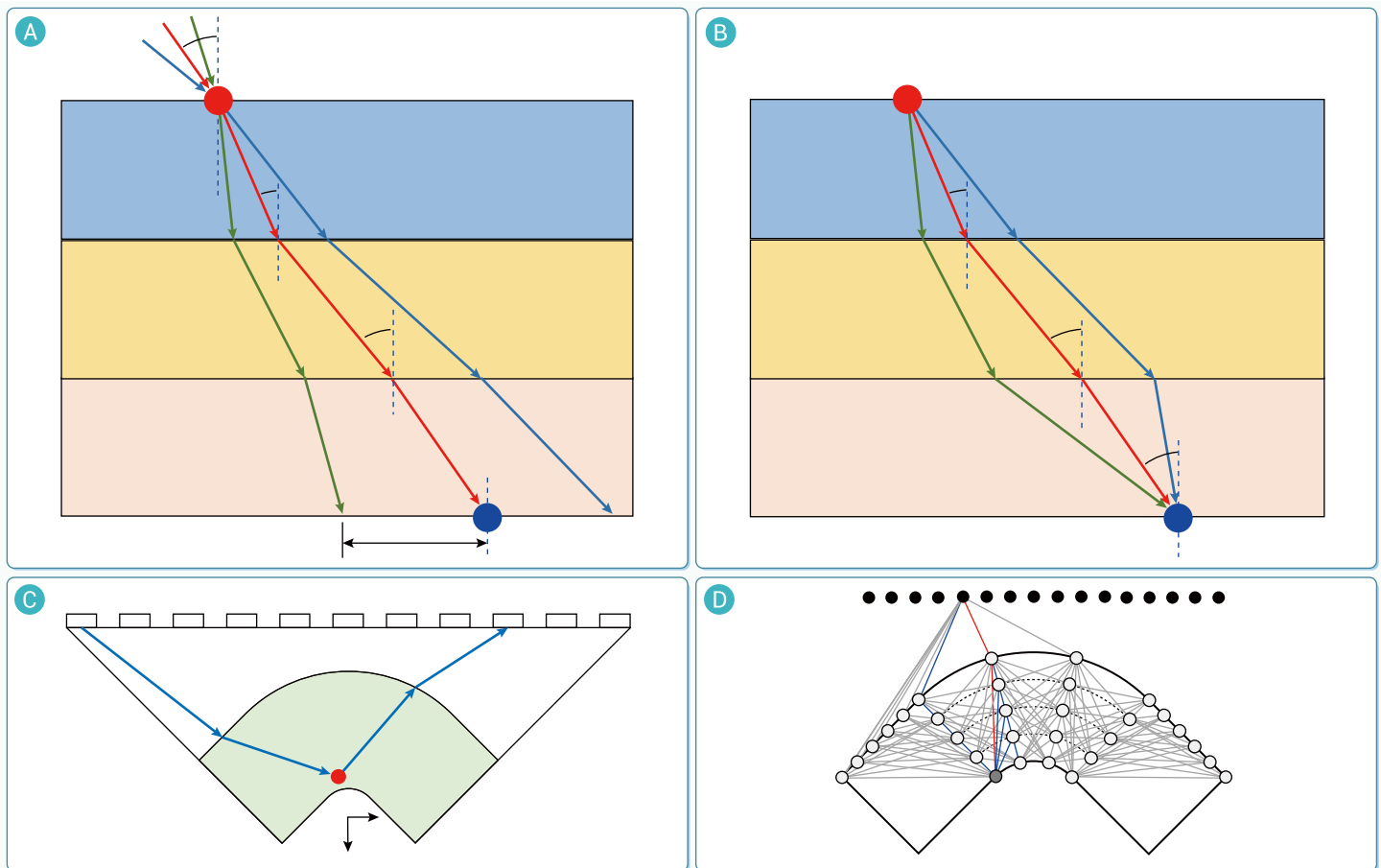


Figure 4. Ultrasonic ray tracing model (A) Forward ray tracing. (B) Inverse ray tracing. (C) Ray tracing based on Snell's law. (D) Ray tracing based on shortest path finding algorithm.

Table 3. Comparison of different imaging algorithms.

Imaging Algorithm	Principle	Advantage	Limitation
Conventional Real-time Imaging	Direct visualization of echo amplitude or flight times	Rapid processing and real-time defect identification	Low resolution
Delay-and-sum Imaging	Coherent summation of signals aligned by computed flight times to target point	High SNR and resolution	Computational burden
Phase Shift Migration Imaging	Recursive wavefield extrapolation	High efficiency	Requires pre-known velocity distribution
Reverse Time Migration	Time consistency theory	High-quality defect imaging	Requires high-precision velocity model
Full Waveform Inversion	Calculates wave velocity distribution	Not requires prior knowledge of surface profiles	Sensitive to distorted data
Artificial Intelligence-empowered Imaging	Data-driven mapping	Enhances imaging speed and accuracy; solves complex and non-linear inverse problems	Data dependency

only the ultrasonic wave propagating along the surface normal is used. In addition, since the wave beam is unfocused, the imaging resolution of these methods is low, and they are mainly used for the detection of 2D delamination defects parallel to the surface of composite structures. When used for the detection of holes and crack tips with omnidirectional scattering characteristics, the imaging characteristics appear as long arcs, resulting in errors for quantification and a high likelihood of misjudging the defect type.

Using focused ultrasonic beams for testing is an effective method to improve imaging resolution. Focusing of the ultrasonic beam in commonly used water-immersed focused ultrasonic transducers is accomplished via a spherical crown-shaped piezoelectric element or an acoustic lens. The accurate convergence of the ultrasonic beam at the geometric focal point is theoretically possible only when the beam remains wholly within a single material. Therefore, when geometrically focused ultrasonic beam is used for inspecting complex-shaped structures with coupling media, the refraction at complex interface causes differences in deflection angle of ultrasonic propa-

gation paths incident in different directions. As a result, the ultrasonic beam cannot focus accurately on the desired position, and the degree of focusing quality degradation depends on the complexity of the inspected surface profile. When using array ultrasonic transducers, steering and focusing of the ultrasonic beam at desired angles or depths can be achieved during excitation by adjusting the excitation delay time of each individual element. Real-time imaging can then be achieved by visualizing the reflection signals excited with different focal laws. Alternatively, the ultrasonic signals incident and reflected in different directions can be collected using the FMC method, then full-depth and high-resolution focused imaging can be achieved with post-processing imaging algorithms which can utilize multi-path and multi-reflection signals for more flexible and precise ultrasonic beam focusing.

Delay-and-sum imaging algorithms

Delay-and-sum is one of the common categories of ultrasonic post-processing imaging algorithms, including SAFT, TFM, and phase coherence

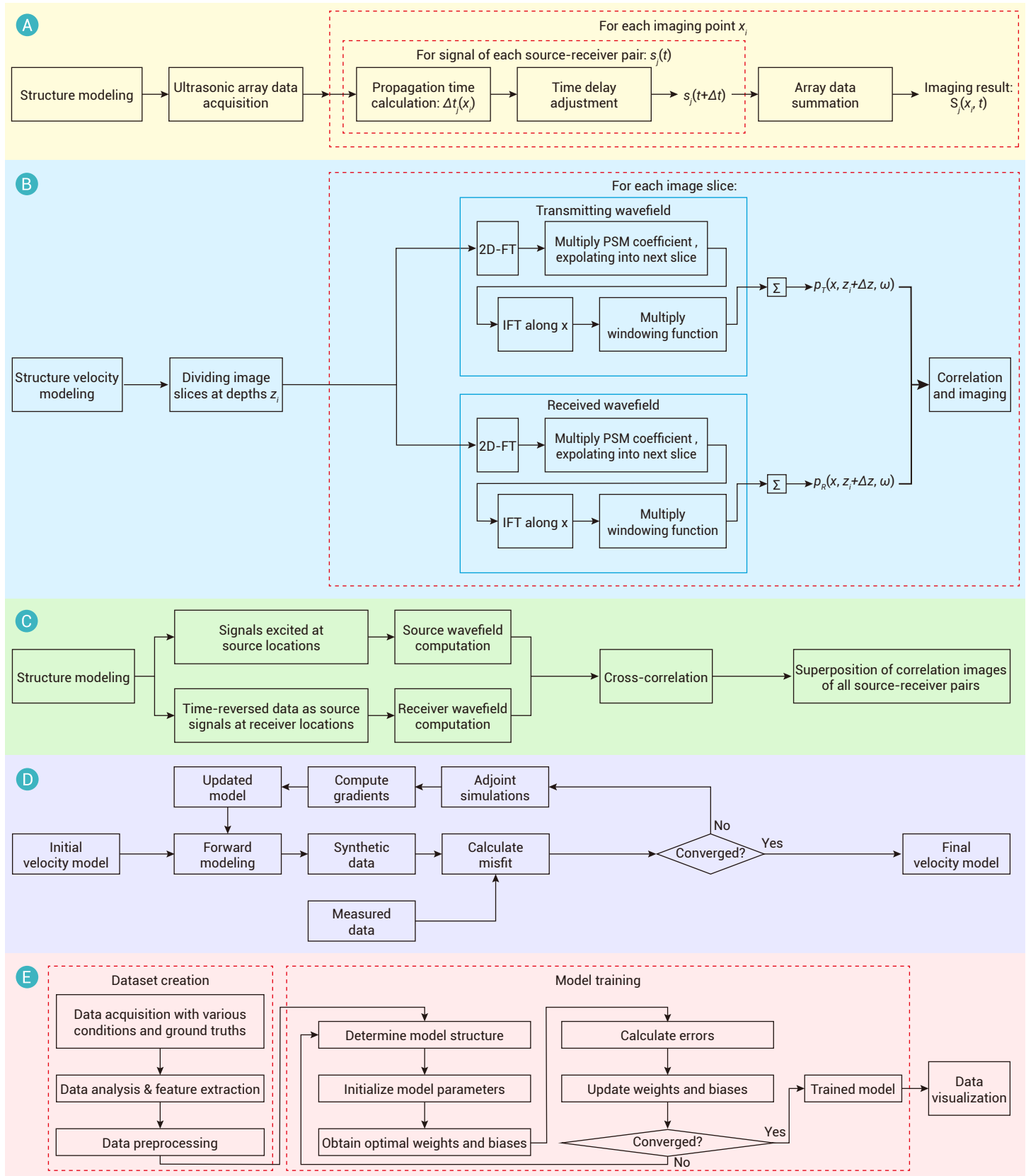


Figure 5. Principle of post-processing ultrasonic imaging methods (A) Delay-and-sum imaging. (B) Phase shift migration imaging. (C) Reverse time migration imaging. (D) Full waveform inversion imaging. (E) Artificial intelligence-empowered imaging.

imaging (PCI).⁶⁵ These imaging algorithms are based on the DAS principle which applies time or phase delay to each ultrasonic A-scan data whose propagation path starts at the excitation point, passes the target imaging point, and ends at the detection point according to its propagation time and

path, and then summing all A-scan data that pass through each corresponding imaging points to acquire improved resolution and SNR (Figure 5A).

The key prerequisite for DAS imaging algorithms is to accurately calculate the propagation path and time of the ultrasonic beam between the

excitation/detection array elements and the target imaging point. When using a flexible array transducer that is directly attached to the surface of a homogeneous structure, the ultrasonic beam propagates only within a single material without the need for obliquely crossing extra interface with acoustic impedance mismatch. In this case, the corresponding ultrasonic propagation path can be treated as simple straight lines. But since common flexible array transducers do not have sensors to monitor the element position, and the relative positions between elements may change with the shape of the attached surface. The element positions need to be calibrated using machine vision or other techniques. Another solution for this problem is to define the element positions as unknown polynomials and use optimization algorithms such as simulated annealing to iteratively update their coefficients until the DAS imaging contrast is converged to the highest value.^{14,66} After the iteration, the final imaging result is focused, and the corresponding element positions are the true values.

In the scenario with the presence of a layer of coupling medium, the ultrasonic beam propagates in the dual-layer structure composed of the coupling layer and the homogeneous tested structure, and the propagation path may be deflected due to refraction. The two major methods to calculate the deflected ultrasonic propagation path due to oblique incidence are presented below. One method is to define the surface profile of the tested structure as a polynomial,⁶⁷ then establish analytical equations of the position of the ultrasonic incident point with respect to the ultrasonic excitation point and the target imaging point using the Snell's law-based ray tracing method introduced in the previous section.^{68,69} The other method is to discretize the tested structure surface into a series of grid nodes, and then calculate the propagation paths and times of ultrasonic beam propagating through each node between the excitation points and the target imaging points inside this dual-layer structure using the Fermat's principle-based ray tracing method. Since ultrasonic imaging typically requires calculating the ultrasonic propagation paths and times between a large number of array element-imaging point combinations, finding the incident position with such traversal calculation method requires significant computation resources and is time-consuming. By combining the virtual source (VS) technology with the DAS principle, defining a virtual ultrasonic wave source on the tested surface, the complicated dual-layer imaging problem can be converted into two individual simple single-layer imaging problems including the ultrasonic propagation between the virtual source and the excitation point as well as the imaging point inside the tested structure, both involving only one layer of medium (either the coupling medium or the tested structure). In this case, time-consuming searching of incident position of the deflected propagation path across the sample surface is no longer needed, and the computation efficiency is significantly improved.⁷⁰⁻⁷²

When the tested structure is multi-layered, ultrasonic ray tracing computation inside the tested structure is also required. However, the bottleneck of high computational difficulty and low efficiency in the above methods for calculating ultrasonic propagation paths and times will become particularly prominent as the number of layer increases. One of the currently effective solutions is to borrow the root-mean-square (RMS) velocity model in the field of seismology which involves the equations of the RMS wave velocities of each layer of medium, and the propagation distances and times along the normal direction of each interface. In this model, the complicated functional expression of ultrasonic propagation time in terms of the position of the imaging point is given in the form of Taylor expansion with the high-order terms beyond the quadratic term ignored. The analytical expression of the RMS velocity is then established, enabling rapid computation of the approximate value of ultrasonic propagation time.⁷³ But it should be noted that as the angle of oblique ultrasonic incidence at each layer interface increases, the relative error of the calculated propagation time with respect to the actual value will gradually increase.^{74,75}

Phase shift migration imaging

Another type of ultrasonic imaging method is the phase shift migration (PSM) imaging algorithm that assumes the inspected region as a series of slices evenly distributed along the depth direction and extrapolate the wave field layer by layer using the wave equation (Figure 5B). This method addresses the influence of the refraction at the acoustic impedance

mismatch interface of the dual-layer structure without the need for calculating the complex ultrasonic propagation paths of individual combinations of excitation-imaging points.^{76,77} This method can achieve high-efficiency focused imaging of the entire inspection region in complex-shaped structures with pre-known influence of the complex surface profile on the wave velocity distribution at each depth during the wave field extrapolation process.⁷⁸

Wavefield-based imaging algorithms

Learned from the field of seismic imaging, wavefield-based imaging algorithms including the reverse time migration (RTM) and the full waveform inversion (FWI) methods have been adapted to ultrasonic post-processing imaging.

The RTM imaging algorithm is based on the time consistency theory, that is, the reflecting interface is the position where the forward propagation field of wave source and the inverse propagation field of the received echo are consistent in time and space. Based on this theory, defect imaging can be achieved through the cross-correlation between the forward and inverse wave fields (Figure 5C).^{43,79} The imaging principle determines that RTM naturally has the ability to handle complex ultrasonic propagation behaviors such as multiple reflections and mode conversions, and the ability to illustrate the entire defect with full use of ultrasonic signals of different types and propagation paths, thus achieving better imaging results than the delay-and-sum algorithms. The key to high-quality RTM imaging is to obtain a high-precision wave velocity model. When the wave velocities of the coupling medium and the tested structure are known, the surface contour of the specimen becomes the key to accurate wave velocity modeling. Typically, the surface profile is reconstructed using machine vision or other techniques introduced previously in the section of surface profile reconstruction methods, or by performing separate RTM imaging first on the coupling layer.^{41,80-82}

The FWI algorithm achieves defect imaging by calculating the wave velocity distribution of the tested structure. During the inversion process, the initial model of wave velocity distribution of the tested structure is first established based on prior knowledge. The wave velocity distribution model is then updated iteratively by minimizing the objective function defined as the residual between the ultrasonic data generated by forward wavefield simulation and the experimentally acquired ultrasonic data (Figure 5D). Since the wave velocity distribution changes abruptly at the defect, the surface and internal reflection interfaces of the tested structure, as well as the defect morphology, can be identified from the wave velocity distribution map when the FWI converges.⁸³ The major advantages of FWI are that it does not require prior knowledge of the precise surface profile and wave velocity information of the tested structure, and that it can theoretically achieve fully automated high-resolution imaging. However, in practical applications, a more precise initial wave velocity distribution model can improve the imaging accuracy and convergence speed, while distorted ultrasonic data, which may result from various factors in actual situations, can easily lead to the non-convergence of the inversion process.

Artificial intelligence-empowered imaging approaches

With the advancement of the artificial intelligence (AI) technology, machine learning and deep learning are increasingly being employed to address long-standing challenges in ultrasonic inspection, moving beyond traditional physics-based models. Such methods utilize AI models such as the support vector machine (SVM) or variants of neural networks, instead of traditional numerical approaches, to solve the inversion problems for imaging with multiple parameters to be solved. For instance, to overcome the physical diffraction limit of the TFM, a back propagation neural network has been trained to decouple overlapping signals from subwavelength defects by predicting their arrival time, resulting in super-resolution imaging.⁸⁴ In another application, convolutional neural networks (CNN) are used to accelerate the computationally expensive FWI process.^{85,86} Models based on the U-net architecture can learn to transform a single, low-resolution image from an early FWI iteration directly into a high-resolution wave speed map, drastically reducing processing time. In these methods, a large dataset comprised of pre-processed ultrasonic data acquired with various conditions and corresponding ground truth models is required to train the selected AI model by iterative updating the model and minimizing the biases (or loss functions) until the

convergence criteria is reached (Figure 5E). These data-driven approaches show great promise for enhancing imaging speed and accuracy, and solving complex, non-linear inverse problems which are challenging for conventional methods. However, a significant challenge remains in applying these methods to component with complex-shaped geometries. The variability in surface curvature and its interaction with the acoustic properties of the materials make it difficult to generate sufficiently diverse training data, limiting the generalizability of current models for such applications.

LIMITATIONS AND FUTURE PERSPECTIVES

To solve the challenges in ultrasonic inspection of complex-shaped structures including stable ultrasonic coupling, efficient ultrasonic transmission and detection, surface conformal scanning control, and complex ultrasound propagation behavior, various effective methods have been proposed and studied in terms of ultrasonic coupling strategies, ultrasonic transmitting and receiving techniques, surface profile reconstruction methods, surface conformal scanning control methods, ultrasonic structure modeling methods, and defect imaging algorithms. In the future, further investigations are needed to address the limitations below.

First, current ultrasonic inspection methods still exhibit limited applicability to ultra-complex 3D irregular structures. Although the complex-shaped structures, including curved surfaces, corners, inclined surfaces, etc., are more complex than planar structures, they are still relatively regular structures. In actual engineering structures, there are many more complex 3D irregular structures that may simultaneously contain a variety of complex-shaped features such as lattices, cavities, and thin-walled structures that are commonly seen in additive manufactured structures. In these scenarios, the ultrasonic testing methods discussed above are basically ineffective. At present, the inspection of such ultra-complex irregular structures is mainly conducted with X-ray computed tomography (CT) imaging. Since additive manufactured structures are formed by stacking 2D layers, the layer-by-layer inspection during the manufacturing process is still the scenario of planar structure inspection. With the advantages of non-contact laser ultrasonic testing, the difficulties of ultrasonic excitation/detection, scanning, and imaging can be greatly reduced, and online continuous monitoring of manufacturing defects such as pores, lack of fusion, inclusions, and cracks during the manufacturing process can be achieved. For the direct inspection of the entire 3D irregular structure, the ultrasonic CT imaging technique originated from biomedical ultrasonic imaging is a promising solution.³⁷ This technique utilizes an ultrasonic transducer array arranged in a cylindrical or spherical surface to surround the tested structure immersed in water. Each transducer element is excited in sequence, and all elements receive the ultrasonic signal simultaneously. This ultrasonic transmission/detection strategy can achieve ultrasonic incidence from various directions and receive the full ultrasonic waves randomly scattered by the irregular-shaped structure in the 3D space. In this way, high-resolution 2D or 3D imaging can be achieved using ultrasonic tomography algorithms. One of the primary drawbacks of this technique lies in the significant computational cost necessitated by the large-scale data processing involved.

Second, the technological maturity and flexibility of industrial ultrasonic array transducers are still limited. The 2D flexible array ultrasonic transducer is one of the hotspots of research in the field of biomedical ultrasonic imaging. With the advantage of surface conformability, such transducers can greatly reduce the difficulty of inspecting complex-shaped structures and is very promising in the field of industrial ultrasonic inspection. At present, the mature commercial flexible array transducers in the field of industrial ultrasonic testing are still mainly 1D linear arrays with flexibility inferior to corresponding products for biomedical imaging and limited applicable surface types and complexity. To overcome such limitations, high-performance and highly flexible 2D array ultrasonic transducers can be developed for testing 3D irregular-shaped structures by learning from the advanced designs in the field of biomedical ultrasonic imaging.

Third, the oversimplified acoustic modeling in most of the existing imaging approaches can only handle the shape complexity instead of heterogeneity and anisotropy. However, for structures such as composites, chip packaging devices, and Lithium-ion batteries, the structural complexity lies in both surface profile, internal structure, and material acoustic properties. Conse-

quently, only considering the surface profile complexity while ignoring the other factors will inevitably lead to a deterioration in the SNR of imaging results as well as quantification errors. With the development of ultrasonic imaging towards multi-functional, multi-dimensional, high-precision, and micro-scale, it is necessary to equally emphasize the influence of macro/micro morphology and the material acoustic property distribution and improve the ultrasonic imaging algorithms in a targeted manner.

Finally, to develop a smart and truly autonomous inspection system for ultra-complex structures, the advancement in robotics, ultrasonic transmission and detection techniques, and AI-driven modeling need to be integrated. Signal acquisition modules comprised of high-performance flexible arrayed transducers or non-contact laser ultrasonic systems mounted on robotic platforms will ensure robust acoustic coupling, efficient signal transmission/detection, and conformal scanning on irregular surfaces. The scanning approach of robotic platforms will evolve from executing pre-defined paths to performing dynamic path planning and conformal scanning with the feedback of the signal acquisition modules or other measurement setups. The computation platform for ultrasonic modeling and defect imaging will be empowered by AI technologies such as physics-informed neural networks (PINN) to address not only the geometrical complexity but also the material-related complexities including anisotropy, inhomogeneity, and heterogeneity, achieving precise imaging of ultra-complex structures. This integration promises a paradigm shift towards high-fidelity, intelligent and adaptive inspection systems.

CONCLUSION

As the industrial structural surfaces become increasingly diverse and complex, complex-shaped structures remain hot and challenging issues in ultrasonic testing. This review has demonstrated the current challenges and solutions in adaptive ultrasonic inspection of complex-shaped structures. Current research in ultrasonic coupling strategies, ultrasonic transmitting and receiving techniques, surface profile reconstruction methods, surface conformal scanning control methods, ultrasonic structure modeling methods, and defect imaging algorithms have partly addressed the challenges in ultrasonic inspection of complex-shaped structures including stable ultrasonic coupling, efficient ultrasonic transmission and detection, surface conformal scanning control, and complex ultrasound propagation behavior. While challenges in inspecting irregular structures, flexible transducers, and the inhomogeneous material properties still exist, the continuous development of ultrasonic transducers and imaging algorithms gives a promising outlook for ultrasonic testing. With the addressing of current existing problems and ongoing advancements, the ultrasonic testing technology can be further expanded to ultra-complex irregular structures with inhomogeneous material properties.

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AUTHOR CONTRIBUTIONS

Z. Yao, Q. Zhu, and H. Cao were responsible for the conceptualization, visualization, and writing - original draft; F. Shi, C. Lu, and J. Yang contributed to validation, writing - review & editing and funding acquisition. S. Guo contributed supervision, validation, writing - review & editing and funding acquisition. All authors contributed to the article and approved the final version.

DECLARATION OF INTERESTS

Shifeng Guo is an Editorial Board member of The Innovation journals and was blinded from reviewing or making final decisions on the manuscript. Peer review was handled independently of this member and their research group. The other authors declare no conflicts of interest.

ETHICAL STATEMENT AND PATIENT CONSENT

Not applicable.