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Development of Non-Destructive Testing for Hydraulic Metal Structures and the Application of Phased Array Ultrasonic Technology

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Abstract

Against the background of increasingly complex operating conditions and the aging of early equipment in hydraulic metal structures, conducting preventive non-destructive testing is of great significance for ensuring the safe operation of water conservancy and hydropower projects. Compared with traditional inspection methods, phased array ultrasonic technology effectively overcomes the limitations of conventional techniques, such as large inspection blind zones and radiation hazards. This technology has demonstrated high reliability and significant practical value in addressing engineering challenges including full-coverage scanning of complex welds, inspection of special materials in turbine runners, and detection of high-strength bolts. The widespread application of phased array ultrasonic technology not only effectively identifies defects in deep structural regions but also provides a more scientific and modern inspection approach for ensuring the safety of hydraulic metal structures.

Keywords
hydraulic metal structures, non-destructive testing, phased array ultrasonic technology, welds

1. Introduction

Driven by the “dual carbon” goals, China is actively promoting the development of new energy power systems, and water conservancy and hydropower hub projects such as pumped-storage power stations are developing rapidly. Hydraulic metal structures constitute a core component of water conservancy and hydropower hub projects, and their safe operation is directly related to the flood control and power generation functions of the entire project. Large-scale water conservancy hubs that have already been constructed, such as the Gezhouba Dam and the Three Gorges Dam, contain massive metal structural equipment operating under complex environmental conditions. However, hydraulic metal structures constructed during the early stages are now facing serious aging problems. Some equipment suffers from quality defects resulting from the design standards, manufacturing processes, and material levels available at the time of construction.

Meanwhile, hydraulic metal structures typically exhibit complex characteristics such as intricate spatial geometric configurations. During actual operation, when these structures remain under harsh conditions such as deep water and high pressure for extended periods and are influenced by complex hydrodynamic effects such as cavitation, they are highly susceptible to corrosion, fatigue, and other failure phenomena. Therefore, ensuring the safe operation of hydraulic engineering projects cannot rely solely on repairing damaged components after failure; preventive inspection of structural components is also essential [1].

To effectively detect such structural damage, non-destructive testing (NDT) technologies have been developed. In past engineering practice, the commonly used conventional NDT methods in the hydraulic engineering sector mainly include visual testing (VT), magnetic particle testing (MT), penetrant testing (PT), radiographic testing (RT), and conventional ultrasonic testing (UT) [2]. These technologies have made significant contributions to the safety of hydraulic engineering. However, with the development of hydraulic metal structures, traditional inspection methods have gradually exposed technical bottlenecks that are difficult to overcome in terms of probe accessibility, blind-zone coverage, defect imaging capability, and the efficiency of large-area on-site scanning.

In response to the limitations of conventional inspection methods, phased array ultrasonic inspection (Phased Array Ultrasonic Testing, PAUT) technology has emerged and become an important development direction in the field of non-destructive testing for hydraulic engineering. By precisely controlling the trigger delay of array elements through an electronic system, this technology enables beam steering and dynamic focusing, thereby effectively addressing inspection challenges associated with complex structures [3, 4]. In the field of hydraulic metal structures, PAUT technology has demonstrated significant application potential in solving complex engineering problems. This paper adopts a literature review approach to address the gaps in defect detection technologies for hydraulic metal structures, focusing on the application progress of phased array ultrasonic technology in complex structures, and providing references for improving the safety assessment level of hydraulic metal structures in China.

2. Development of Non-Destructive Testing Technologies, Method Comparison, and Advantages of Phased Array Technology

2.1 Development of Non-Destructive Testing Technologies for Hydraulic Metal Structures

With the rapid development of water conservancy and hydropower projects in China, the scale and complexity of hydraulic metal structures have continuously increased in order to meet more complex and demanding operating conditions. These metal structures are primarily assembled through welding, and the quality of welds directly determines the overall structural strength and safety of hydraulic products. Consequently, construction standards and safety assessment requirements have also been continuously improved [2, 5]. To better maintain the stable operation of engineering equipment, non-destructive testing (NDT) technologies have continuously evolved in the field of hydraulic metal structures, undergoing a development process from single techniques to integrated approaches and from analog methods to digital technologies [1, 2]. In the early stages of water conservancy construction, quality control of metal structures mainly relied on surface NDT techniques such as visual testing (VT), magnetic particle testing (MT), and penetrant testing (PT) [2, 5]. To evaluate the integrity of the internal structure of welds, radiographic testing (RT) and conventional ultrasonic testing (UT) subsequently became the primary methods for internal quality control in the hydraulic engineering sector [2]. However, as the service life of a large number of water conservancy and hydropower projects in China continues to increase, metal structural equipment has gradually entered the aging stage. Accordingly, the safety assessment approach is shifting from traditional post-failure maintenance toward full life-cycle management [1]. This transition requires inspection technologies not only to detect surface cracks but also to accurately locate hidden internal defects. In practical engineering applications, the limitations of traditional inspection methods have gradually become evident, prompting the development of NDT technologies in hydraulic engineering toward more efficient, intuitive, and environmentally friendly advanced ultrasonic imaging technologies [1, 6].

2.2 Application Limitations of Conventional Non-Destructive Testing Methods

When applied to high-standard inspections of hydraulic metal structures, conventional non-destructive testing methods exhibit certain limitations.

For surface defect detection, magnetic particle testing (MT) and penetrant testing (PT) are relatively simple to operate and can effectively detect open defects on material surfaces and near-surface regions [2]. However, their limitation lies in their shallow detection depth, which prevents effective identification of volumetric or planar defects hidden inside welds—such as lack of fusion, incomplete penetration, and deep slag inclusions—that pose serious threats to structural safety [7].

For internal defect detection, radiographic testing (RT) utilizes the penetration and attenuation characteristics of radiation to visually record internal weld defects, such as pores and slag inclusions, in the form of radiographic films, which can also be preserved for long-term documentation. However, the detection sensitivity of RT for planar defects such as micro-cracks and lack of fusion is relatively low [2]. Moreover, RT involves significant radiation hazards. During on-site operations, extensive safety isolation measures must be implemented, which seriously interfere with other construction activities. In addition, the RT inspection process is complex, time-consuming, and costly, making it difficult to meet the requirements for rapid equipment inspection [5, 6].

In comparison, conventional ultrasonic testing (UT) offers advantages such as strong penetration capability, high sensitivity, and the absence of radiation hazards [3]. However, conventional UT probes typically contain only a single piezoelectric element, which results in a fixed beam emission angle. When inspecting T-joints or fillet welds commonly found in hydraulic structures, the fixed-angle beam is often unable to fully cover the root region of the weld due to the complex geometry of the workpiece, thereby easily creating inspection blind zones [2, 8]. Furthermore, the results of conventional UT are mainly displayed in the form of one-dimensional A-scan pulse waveforms, lacking intuitive imaging support. Inspectors must infer the characteristics and size of defects based on the dynamic features of the waveform, and this non-intuitive evaluation approach relies heavily on the personal experience of the operator [2, 3].

3. Phased Array Ultrasonic Testing Technology and Its Advantages

3.1 Principle of Phased Array Ultrasonic Testing Technology

In response to the limitations revealed by conventional non-destructive testing methods, phased array ultrasonic testing (Phased Array Ultrasonic Testing, PAUT), as a cutting-edge technology in the field of ultrasonic inspection, has been introduced into the hydraulic engineering sector. Although the core physical basis of PAUT remains the reflection principle of ultrasonic waves at interfaces between media with different acoustic impedances, the internal structure of its probe and the electronic control of the acoustic beam are fundamentally different from those of conventional ultrasonic testing [4, 6].

A phased array probe consists of multiple independent miniature piezoelectric elements arranged in a specific array pattern. The core of PAUT technology lies in the precise control of the time delay for the excitation and reception of ultrasonic waves by each array element through a complex electronic control system within the instrument, combined with specific focusing laws [6, 7].

Therefore, the core advantages of PAUT are mainly reflected in the following two key functions:

(1) Beam steering, which allows the propagation angle of the ultrasonic beam to be changed electronically while keeping the probe position fixed, thereby enabling sectorial scanning within a certain angular range [6, 7].

(2) Dynamic focusing, whereby the system automatically adjusts the focal distribution of the acoustic beam according to the preset inspection depth, concentrating acoustic energy in a specific depth region and significantly improving the resolution of local imaging and the signal-to-noise ratio of echoes [3, 4].

3.2 Engineering Application Advantages of Phased Array Technology

Based on the principles of beam steering and dynamic focusing described above, PAUT demonstrates several significant advantages over traditional methods when addressing inspection challenges in hydraulic metal structures.

First, PAUT can adapt to complex geometric structures and effectively eliminate inspection blind zones. Hydraulic structures contain numerous complex components, such as penstocks, whose joints often exhibit saddle-shaped spatial curves with significant variations in wall curvature [8]. Through beam steering, PAUT enables flexible multi-angle scanning of T-joints and fillet welds of branch pipes. By bypassing complex external geometries and directly inspecting difficult-to-access regions, it achieves full coverage inspection of critical weld cross-sections and significantly reduces the probability of missed detections [4, 6, 7].

Second, PAUT can effectively penetrate special materials. Key rotating components such as turbine runners are typically made of stainless steel, which is characterized by coarse grains and strong anisotropy. These characteristics often cause severe attenuation and scattering of ultrasonic waves during propagation [3]. By utilizing dynamic focusing, PAUT can concentrate acoustic energy to effectively penetrate coarse-grained microstructures and significantly improve the echo signal-to-noise ratio for deep defects [3]. In addition, the PAUT system converts the received signals into two-dimensional cross-sectional images. This “visualized” representation overcomes the limitations of conventional UT, which relies heavily on one-dimensional waveforms and operator experience, by directly presenting the morphology and spatial location of defects, thereby improving the accuracy of inspection results [3, 7].

Third, PAUT offers high inspection efficiency and environmental advantages while reducing interference with construction activities. When inspecting hydraulic welds, phased array systems commonly employ single-axis linear scanning combined with a position encoder for automatic data recording, enabling faster inspection speeds than the equivalent raster scanning used in conventional ultrasonic testing [4, 7]. Moreover, PAUT involves no radiation hazards and eliminates complex procedures such as film development. In practical applications, PAUT inspections can be conducted simultaneously with welding, installation, and other construction processes. While ensuring or even improving the detection rate of internal defects, phased array technology can significantly shorten maintenance and construction cycles and has increasingly replaced conventional radiographic testing in many hydraulic engineering scenarios [6].

4. Application of Phased Array Ultrasonic Technology in Hydraulic Metal Structures

4.1 Weld Inspection of Complex Structures

During the manufacturing process of hydraulic metal structures, a large number of welds with complex stress conditions and irregular geometries are involved. Owing to its flexible beam steering and focusing capabilities, phased array ultrasonic testing (PAUT) has achieved favorable engineering application results in the non-destructive inspection of such structures.

For the inspection of medium- and thick-plate butt welds, Wu Weiping and Wang Ningning et al. [4, 7] reported an application in the pressure penstock project of a hydropower station. The penstock was fabricated from WDB620-grade steel, with a plate thickness of 42 mm and an inner diameter of 4.7 m. During inspection, a sectorial scanning procedure with a shear-wave steering angle range of 40°–70° and an angular resolution of 0.5° was employed. This method not only successfully detected defects in the circumferential welds but also enabled the S-scan images to clearly provide precise information such as the maximum echo amplitude, defect depth, distance from the weld centerline, and the height of the defect itself.

For T-joint inspection, the geometric configuration at the intersection of the flange plate and the web plate is highly complex. Conventional ultrasonic probes can only perform direct-beam scanning from limited surface positions, making it difficult to fully cover the weld root region and thus easily leading to missed detections. Engineering practice by Huang Xunlei et al. [6] demonstrated that introducing ultrasonic simulation software such as CIVA prior to inspection can effectively simulate the propagation paths of acoustic beams within T-shaped components and optimize the scanning scheme. In the phased array inspection of actual hydraulic T-joints, sectorial scanning not only clearly presented the two-dimensional structure of the weld cross-section but also successfully detected hidden defects—such as internal flaws within the base material—that are easily missed by conventional methods. Furthermore, the size and location of these defects were quantitatively evaluated with high accuracy, verifying the reliability of PAUT in the inspection of complex structures.

For the inspection of branch pipe fillet welds, structures such as manholes and monitoring pipe seats installed on pressure penstocks form intersecting weld lines that exhibit complex saddle-shaped spatial curves with significant variations in pipe wall curvature. Conventional ultrasonic probes encounter considerable scanning blind zones when inspecting such curved surfaces. Research by Ai Wenbo et al. [8] indicated that using a 5 MHz phased array probe with 32 elements, combined with beam simulation software to optimize the inspection procedure, enables the ultrasonic beam to effectively adapt to the geometric variations of saddle-shaped curved surfaces. This approach achieved full cross-sectional coverage of branch pipe fillet welds and successfully detected subtle defects such as interlayer lack of fusion and cracks, thereby addressing a long-standing technical challenge in the comprehensive inspection of such hydraulic structures.

4.2 Inspection of Turbine Runner Welds

The turbine runner is a core component of hydropower generation systems. Due to the long-term exposure to alternating hydraulic loads, runner blades are typically manufactured by casting and welding high-strength stainless steel materials. Such stainless steel materials exhibit coarse grain structures and strong anisotropy, which can cause significant energy attenuation and scattering noise during ultrasonic wave propagation, thereby resulting in a low signal-to-noise ratio in conventional ultrasonic testing [3].

To address the issue of ultrasonic attenuation in runner weld materials, Huang Zhiqiang et al. [3] investigated the specific application of PAUT technology in this context. Their study indicated that by appropriately selecting the frequency and the number of elements of the phased array probe and utilizing the dynamic focusing capability of the system, ultrasonic energy can effectively penetrate coarse-grained structures and be concentrated in depth regions where defects are likely to exist. Meanwhile, by employing the beam steering function, inspectors only need to move the probe within a limited area on the blade surface to obtain high-resolution two-dimensional images of internal weld defects such as pores and slag inclusions. This approach effectively overcomes the difficulties associated with scanning curved runner surfaces.

4.3 Inspection of High-Strength Bolts

High-strength bolts are widely used in hydraulic metal structures for structural connections. Under long-term cyclic loading conditions, fatigue cracks are highly likely to initiate at the thread roots of these fasteners. Conventional non-destructive testing methods usually require the bolts to be dismantled for surface magnetic particle or penetrant inspection. This process not only involves a large workload but may also disturb the original stress equilibrium of the structure during disassembly [9].

To overcome these challenges, Li Dongfeng et al. [9] conducted specialized research based on phased array technology. Artificial notches were machined at different depths of standard high-strength bolts—specifically at positions 41 mm, 81 mm, 114 mm, and 141 mm from the bolt end face—with notch depths of 1 mm and 1.5 mm to simulate early-stage fatigue cracks. The experiment employed both phased array linear array probes and matrix (rosette) array probes to perform vertical incidence inspections from the bolt end face. The comparative results indicated that both probes were capable of effectively identifying artificial internal defects in the bolts; however, the matrix array probe demonstrated more significant scanning advantages. During inspection, this probe required little or no rotation to achieve rapid scanning of the entire bolt cross-section. The application of this technology significantly improves the efficiency and safety of high-strength bolt inspections in hydraulic engineering.

5. Conclusion

Driven by the “dual carbon” goals and the rapid development of new energy power systems, the safe operation of water conservancy and hydropower hub projects has become increasingly important. Faced with the growing aging problems of early hydraulic metal structures and potential damage risks under complex operating conditions such as deep water and high pressure, the transition of safety assessment strategies from traditional post-failure maintenance to full life-cycle preventive inspection has become an inevitable trend in the industry. Through a review of the evolution of existing technologies, this study finds that conventional non-destructive testing methods have gradually revealed limitations when dealing with complex geometries and special materials in hydraulic structures, including large scanning blind zones, significant radiation hazards, and excessive dependence on operator experience. These limitations make it difficult for traditional methods to meet the high standards required by modern hydraulic engineering.

Phased array ultrasonic testing (PAUT), with its core advantages of beam steering and dynamic focusing, effectively compensates for many deficiencies of conventional inspection methods. Current research and engineering practice have demonstrated that PAUT exhibits high reliability and practical engineering value in achieving full-coverage inspection of T-joints and saddle-shaped branch pipe fillet welds, overcoming ultrasonic attenuation in coarse-grained stainless steel turbine runner materials, and enabling non-disassembly inspection of high-strength bolts. The comprehensive integration of efficient, environmentally friendly, and visualized PAUT technology into the maintenance and inspection processes of hydraulic metal structures can not only help identify hidden defects in deep structural regions and prevent structural fatigue, but also improve the accuracy and efficiency of non-destructive testing. Ultimately, this approach will contribute to ensuring the safe and stable operation of large-scale water conservancy and hydropower hubs in China, thereby supporting the steady advancement of the national new energy strategy.

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Conflicts of Interest

The authors declare no conflict of interest.

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