CLOUD ULTRASOUND SYSTEM WITH FLEXIBLE ULTRASONIC PHASED-ARRAY TRANSDUCER FOR CRITICAL COMPONENT MONITORING

Xuanrong Ji1,2*, Maodan Yuan1, Yan Chen1

1Guangdong University of Technology, No. 100, WaihuanXi Road, Guangzhou Higher Education Mega Center, Panyu District, Guangzhou, China
2Guangzhou Doppler Electronic Technologies Co., Ltd., No.1501 Kaichuang Avenue, Huangpu District, Guangzhou, China

*Corresponding Author: xr.ji@gdut.edu.cn

ABSTRACT

With the rapid development of high-end equipment manufacturing industries, the safety guarantee of the critical equipments including high-speed railway, wind power, and petrochemistry, etc need a rapid, full-coverage, and real-time monitoring system. To address such applications, the concept of a cloud ultrasound server wirelessly connected to multiple ultrasonic transducers is proposed. Firstly, flexible ultrasonic phased array technology based on piezoelectric composites and piezoelectric film is developed. The flexible phased array transducer enables large-area inspection with high-resolution and high-conformability for components with complex shapes and varying geometries, and is designed to satisfy the requirements of the inspection for high temperature and high-pressure components. Secondly, a miniaturized, low-power, and wireless data-transmission technology is developed. Controlled by a lightweight device, the real-time on board ultrasonic signals are wirelessly transmitted to a cloud. Finally, an open software platform is developed for the cloud ultrasound processing service. The cloud server is able to accept a large amount of the ultrasonic data wirelessly transmitted from multiple transducers simultaneously. The cloud ultrasound system will offer a great opportunity for the real-time on-board monitoring of the critical components with complex geometries, even under extreme environmental conditions.

KEYWORDS: Flexible Phased Array, Wireless Data Transmission, Big Data, Artificial Intelligence, Complex Structure, Structural Health Monitoring

1. INTRODUCTION

The equipment manufacturing industry has been developing rapidly, especially the high-end equipment manufacturing industries, such as high-speed railway, wind power, and petrochemistry. First and foremost, the safety quality of the critical equipment or components in these industries should be guaranteed. For instance, as the second source of electric power in China, there are around five-hundred major hydroelectric power stations (HPS) and bolts are the safety-critical components in large and medium HPS. It is estimated that there are 360-660 bolts for each major HPS. During the manufacturing, installation, and operating of HPS, cracks will be initiated due to improper process control and grow into fatigue fracture after long-term operation under high preload within the bolts. Such failure of these bolts may cause unexpected malfunction or shut down in HPS. Therefore, it is of great importance to build a rapid, full-coverage, and real-time monitoring system to enhance the safety management of the bolts at key positions and secure the safety operation of HPS [1]. In order to provide structural information within all depth, high-quality three-dimensional displays are desired. Ultrasonic imaging system is one of the common nondestructive testing (NDT) solutions to detect, identify, and size defects in different critical components. Phased array offers the capability to steer and focus the ultrasonic beam into the inspected objects and generate volumetric images of the internal structure [2]. Especially the flexible ultrasonic phased array based on piezoelectric composites and piezoelectric film enables large-area inspection with high-resolution and high-conformability for various components with complex shapes and varying geometries. Moreover, the application of total focusing method (TFM) as the post-processing approach will gain improved spatial resolution and ratio of signal to noise. Compared to other imaging algorithms, TFM enables the focus at every point inside the inspected objects to generate the ultrasonic images [3]. Therefore, it is able to perform the real-time adaptive inspection of the safety-critical components with various geometries by TFM with the combination of flexible phased array ultrasonic transducers.
Image reconstructed by TFM usually requires the Full Matrix Capture (FMC) acquisition, which requires very expensive multi-channel acquisition units and large amount of computation [4]. To extend the industrial application of TFM, a single-channel acquisition unit wirelessly connected with a cloud ultrasound system is proposed. The application of time division multiplexing method in a single-channel system is able to reduce the amount of data and the system cost [5]. And massive graphical processing units (GPU) based computing in the cloud ultrasound system will be considered to accelerate the computation of TFM.

In this paper, the concept of a cloud ultrasound system, including adaptive and flexible ultrasonic transducer manufacturing, the principle of ultrasonic total focusing method, and cloud ultrasound processing will be firstly explained in part 2. A case study of such a system for bolt monitoring will be shown in part 3. In the end, conclusion remarks will be drawn in part 4.

2. METHODOLOGY

2.1 ADAPTIVE AND FLEXIBLE ULTRASONIC TRANSDUCER

To achieve good contact condition with the complex-geometry components, adaptive ultrasonic transducers are desired. However, adaptive transducers with complex-geometry piezoelectric ceramics (such as arched frame and spherical array) are difficult to be fabricated directly due to the great brittleness of ceramics. Usually, the water wedge or curved wedge is designed to match the irregular surface. But the water wedge is limited by the small acoustic impedance of water and not suitable for some complex structures, whereas curved wedge should be machined to match each specific surface. In this research, complex-shaped piezoelectric ceramics are manufactured by stereolithography-based 3D printing approach [6-7]. For the flexible arrayed transducers, the piezoelectric polymers and the ceramic/epoxy composites are selected as the active materials. And the soft epoxy resin is used for the matching layer and the backing layer to achieve good flexibility. Integrated by a flexible circuit board, each element in the arrayed transducer can be moving or rotating to be self-aligned with the curved or complex surface of the inspected structures. With specific fixtures, the flexible arrays can be applied as variable curvature transducers. Therefore, such flexible ultrasonic transducer offers a cost-effective way to achieve good acoustic matching with different materials and structures. Moreover, the new flexible array could be designed to satisfy the requirements of the inspection for high temperature and high-pressure components. A commercialized flexible arrayed ultrasonic transducer is shown in Fig. 1.

Fig. 1 The flexible arrayed ultrasonic transducer.

Besides, 3D printing technology is a rapid prototyping process that plays an effective role in geometrical flexibility without module [7]. The complex-shaped piezoelectric ceramics, backing layer and matching layer with high accuracy can be designed by computer and directly printed based on the stereolithography. The overall manufacturing process of ultrasonic transducers is explained in Fig. 2. Fig. 3 shows the microstructure, the ferroelectric properties of the printed ceramic and pulse-echo fabricated by the 3D printing technology. And the results indicate that the 3D-printed PZT ceramic has a good potential application for complex-shape ultrasound array.

Fig. 2 The manufacturing process of adaptive ultrasonic transducer.
2.2 ULTRASONIC TOTAL FOCUSING METHOD WITH A SINGLE-CHANNEL SYSTEM

Ultrasonic phased array has been increasingly applied for defect detection and material characterization in engineering components. Phased array is based on the focal law to steer and focus the ultrasonic beam, leading to improved image quality by maximizing the data acquisition. To reduce the amount of data, a single channel system with time division multiplexing method can be applied to perform FMC [5]. A pulse generator sends a pulse signal to each element and collect all the individual signals, respectively. Compared to multi-channel acquisition system, which is limited by large and expensive hardware and cross-talk between multiple channels, the single-channel system is able to implement the FMC based on equalizing the phase of the signals from each receiver.

Each element in the array can be act as both a transmitter and a receiver to form a transmitter-receiver pair. Therefore, there are totally $N^2$ data can be obtained for an N-element array. In TFM, the first step is to discretized the inspection area into a grid, as shown in Fig. 4. To focus on every point in the grid, the ultrasonic signals from all elements in the array are then summed based on the time-of-flight of ultrasound. The final intensity of the image, $I(x,z)$ at any position $(x,z)$ in the image is given by [2]

$$I(x,z) = \sum_{i=1}^{N} \sum_{j=1}^{N} S_{ij}(t_{ij}(x,z))$$  \hspace{1cm} (1)

where $S_{ij}$ is the received time-domain signal for each transmitter-receiver pair; the double summation is the all combination of ultrasonic transmitter-receiver pair; and $t_{ij}$ is the associated time delay. With TFM, we are able to focus the array at every point naturally and form an image of the internal structure, revealing the defect information, including its position, orientation, and specularity [2-4].

2.3 CLOUD ULTRASOUND PROCESSING

To perform on-board structural health monitoring (SHM) for critical components, the ultrasonic transducer module should be small sized and low power consumption. Therefore, a low-power and wireless data-transmission technology is required for the transducer module and the data processing module. Both transmitted and received signals for each element from the single-channel ultrasonic system are transmitted wirelessly to a cloud for further data processing. In the cloud, data organization, TFM implementation, ultrasonic image display, and defect evaluation based on intelligence augmentation (IA) or artificial intelligence (AI) are performed. The cloud ultrasound system enables to process the on-line data transmitted from the transducer module and assess the safety quality of the in-service components. In the future, an open software platform will be developed for the cloud ultrasound processing service. And this cloud server is able to accept a large amount of the ultrasonic data wirelessly transmitted from multiple transducers simultaneously.
To release the burden of the large amount of post-processing of TFM, GPU’s streaming multiprocessors will be adopted to perform parallel computation tasks [8]. To perform TFM with GPU, each GPU block will be assigned to a single pixel of the image. In a block, threads will calculate the time-of-flight from a transmitter to the focal point corresponding to the pixel and the time-of-flight from the same focal point back to the receiver. The total time delay is obtained with the sum of these two time-of-flights, and the intensity of focal point will be retrieved and superimposed by each thread from the FMC data stored in global memory.

With the ultrasonic image data, the cloud ultrasound server is able to perform the real-time diagnosis of the monitored structures. To acquire the defect size, a digital discretization processing is carried out for every point in the ultrasonic image. Each grid is labeled with or without defect, forming some dependent defects in the space. Then, the number and the size of dependent defects are calculated. Based on the shape and the volume of each defect, the type of each defect is analyzed by fuzzy matching. For different shapes of defects, such as cylindrical, spherical, bar, and planar, different criteria are applied to evaluate their severities. Finally, the defect level of the structure will be normalized by weighting of all the defects. Fig. 5 explains the detailed procedures for AI-based monitoring.

3. CASE STUDY FOR BOLT MONITORING

3.1 BOLT MONITORING SYSTEM

To validate the cloud ultrasound monitoring system, a case study is performed to realize the real-time, online monitoring of the HPS bolts. This bolt monitoring system is consist of GPU-based computation module, data acquisition module, and adaptive phased array transducer module, as shown in Fig. 6. The phased array transducer module is consisted of one holographic transducer and multiple 2D matrix transducers. The data acquisition module controls the signal transmitting and data receiving for each element, which will be quickly and wirelessly transmitted to the GPU-based computation module. The FMC data are collected by the data acquisition module and stored in the GPU supercomputer. Then TFM algorithm is quickly performed in the supercomputer based on GPU parallel computing. The ultrasonic volumetric imaging of bolts will be obtained and the defect information will be analyzed and summarized by an artificial intelligent program.
Practically, there are different types of bolts that are required for different positions, such as head cover, spiral case mandoor, and cone bottom in HPS. The difference in shape and size of the bolts brings in difficulties in the applications of standard and uniform ultrasonic transducers. Therefore, different kinds of phased array ultrasonic transducers are customized to ensure the good acoustic penetrating through the bolt. A lock sleeve is designed to fasten the bolt head via strong magnet and fix the transducer with screw thread. The high-density 2D-matrix transducers are fabricated to obtain high sensitivity, large angle of spread, and broadband, resulting high-quality image and high ratio of signal to noise. Fig. 7 shows two customized phased array ultrasonic transducer which is adaptive for two kinds of bolts.

3.2 ULTRASONIC VOLUMETRIC IMAGING FOR BOLTS

With the full matrix captured data and TFM algorithm, the ultrasonic volumetric image can be obtained quickly by GPU-based computation module. Fig. 8 shows the volumetric images for bolts with and without defect. Fig. 8 (b) also demonstrated that defects with different sizes can be differentiated and evaluated quantitatively. Fig. 9 shows the images of TFM for a stud with a crack, demonstrating the feasibility for monitoring other types of bolts.
3.3 DEFECT EVALUATION FOR BOLT MONITORING

With the full matrix capture data, the ultrasonic volumetric image of the bolt is obtained based on TFM. To realize the online monitoring and diagnosis of HPS bolts, an artificial intelligence program is developed and trained here to evaluate the defect level.

After long-term comparative analysis, the AI program can category the defect into different levels and a synthetical score can be obtained by fixing the weight for particular defects. The bolt should be replaced once the score is larger than the failure criteria of bolt. Table 1 shows an example of summary sheet from AI program.
<table>
<thead>
<tr>
<th>Defect Type</th>
<th>Number</th>
<th>Weight</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 1 defect</td>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Level 2 defect</td>
<td>3</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Level 3 defect</td>
<td>2</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Level 4 defect</td>
<td>1</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Level 5 defect</td>
<td>0</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>Level 6 defect</td>
<td>0</td>
<td>32</td>
<td>0</td>
</tr>
<tr>
<td>Level 7 defect</td>
<td>0</td>
<td>64</td>
<td>0</td>
</tr>
<tr>
<td>Level 8 defect</td>
<td>0</td>
<td>132</td>
<td>0</td>
</tr>
<tr>
<td>Synthetical score</td>
<td></td>
<td></td>
<td>27</td>
</tr>
</tbody>
</table>

**Table 1** Summary sheet for bolt monitoring.

### 4. CONCLUSIONS

This paper presented a cloud ultrasound system for the real-time on-board monitoring of the critical components with complex geometries. Adaptive and flexible ultrasonic transducers are manufactured to achieve good contact condition with the complex-geometry components. Full matrix capture is achieved with a single-channel system by time division multiplexing to maximize the data acquisition with reduced hardware cost. The ultrasonic total focusing method is able to reveal the internal structural information of structures, with an accelerated GPU-based computation module. Based on the ultrasonic volumetric images of bolts, an artificial intelligence program can be developed in the cloud ultrasound server and trained to identify the dependent defect, evaluate the defect size, and estimate the defect level of the in-service structures. Case studies are performed to validate this cloud ultrasound system and a bolt monitoring system is built. Such bolt monitoring system is able to provide visualized information of the bolt and the severity level. The further application and promotion of such a monitoring system will ensure the safe operation of hydro power stations and other high-end equipment.

### ACKNOWLEDGMENT

This work was performed with support from Guangdong Innovative and Entrepreneurial Research Team Program (Grant No. 2016ZT06G375).

### REFERENCES


