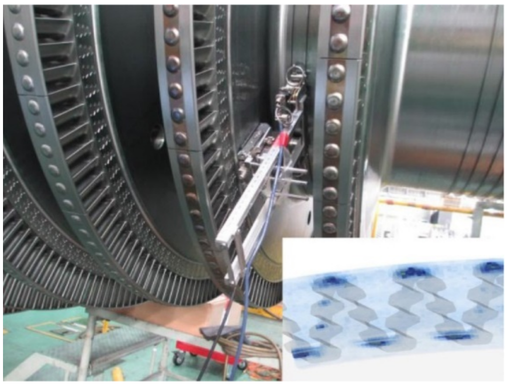
High-efficiency and High-precision Ultrasonic Testing Technologies for Complex Shaped Blade Grooves for Maintenance of Steam Turbine Rotor



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The low-pressure stage of a steam turbine rotor has the potential risk of blade scattering caused by stress corrosion cracking in the blade groove where the rotor blade is implanted due to long-term operation. Mitsubishi Heavy Industries (MHI) Group has developed ultrasonic testing technologies for axial entry blade grooves with a complicated processing shape that is used to detect and identify minute stress corrosion cracking occurring in the blade groove that can be used without removing the rotor blade. This report presents an overview and inspection examples of ultrasonic testing techniques that can handle special blade groove processing shapes and disk shapes.

1. Introduction

Over the years, MHI Group has manufactured and delivered a wide range of steam turbine equipment that can meet diverse needs, from small single casing turbines for private power generation to large turbines for nuclear power, as well as variable speed steam turbines for compressor drives for petrochemical plants. The number of steam turbine equipment units manufactured and delivered by our group has reached more than 2,500 in 70 countries for power generation and more than 1,400 in 60 countries for compressor drives.

Steam turbine rotors, which convert high-temperature and high-pressure steam into high-speed rotating motion, have a structure in which rotor blades for receiving the steam flow and generating rotation are implanted in the rotor shaft. Since stress corrosion cracking (SCC) occurs in the blade grooves of the low-pressure stage of a rotor due to long-term operation, it is important to carry out maintenance and management through regular non-destructive inspection in order to prevent accidents such as blade scattering. So far, we have developed blade groove inspection techniques that utilize phased array UT (ultrasonic testing) technique and do not require the removal of the rotor blade. However, in the case of some axial entry blade grooves that are processed in the rotor axial direction, the groove shape and disk shape may be special, so UT cannot be applied and inspection with the rotor blade removed is required. As a result, large-scale incidental work may be required for the removal and reinstallation of the blade.

Our blade groove UT techniques have been applied to a lot of actual equipment so far, but we developed inspection techniques that can handle curved blade grooves and complicated disk shapes in large turbines to expand the application further. These techniques eliminate the need for incidental work to remove and reinstall the rotor blade and can shorten the inspection schedule.

2. Disk shape and blade groove shape of steam turbine of low-pressure stage

The shape of the disk that forms the blade groove into which rotor blades are implanted is

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optimized according to the customer's plant operation specifications and the rotor blade specifications, so there are various disk shapes such as a straight type disk, a tapered disk, a disk with a curvature and a flanged disk as shown in **Figure 1**. In the case of general UT, it is necessary to place a sensor on the smooth surface of the disk to detect the blade groove. Therefore, this cannot be applied to these various disk shapes.

As shown in **Figure 2**, there are three types of axial entry blade groove shapes, namely straight type, skewed type and curved type. In order to detect SCC generated in the stress concentration area of each groove shape, an optimal flaw detection approach that appropriately controls the ultrasonic beam direction is required.

We have developed ultrasonic testing techniques to handle these various disk cross-sectional shapes and blade groove processing shapes and the details are described below.

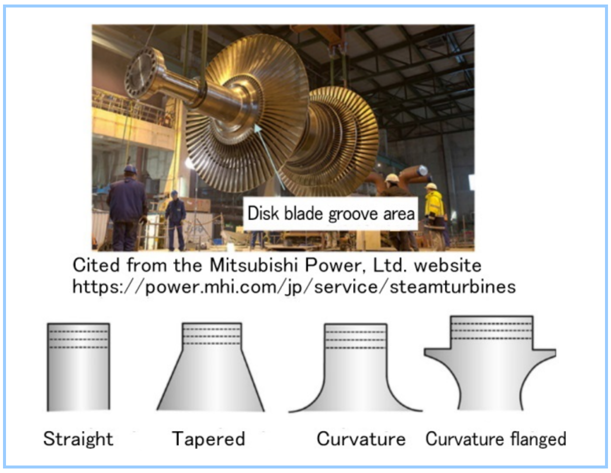

Figure 1 Example of disk cross-sectional shape of steam turbine rotor

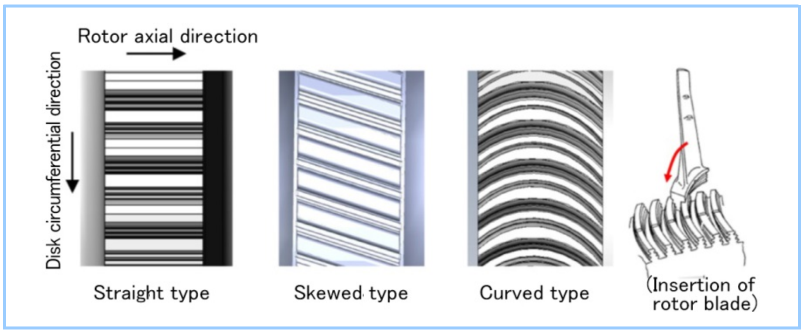

Figure 2 Processing shape of axial entry blade groove

3. UT technique for axial entry blade grooves

The ultrasonic testing technique for straight- or skewed-shape axial entry blade grooves is the most proven inspection technique to date(1). As shown in **Figure 3**, this is a technique of detecting SCC by arranging an array probe on the side surface of the disk and performing a beam scan in the direction of the disk thickness. In order to detect SCC inclined with respect to the ultrasonic beam direction with high sensitivity, we designed an array element that optimized the beam focusing range according to the disk thickness by utilizing ultrasonic simulation, and developed a compact, high-performance sensor that can be placed in the narrow space between disks. Disks have approximately 100 blade grooves or more machined in the axial direction over the entire circumference, so it is necessary to efficiently inspect all blade grooves. We also developed a manual scanner that can record data of the entire circumference of a disk in just a few minutes to tens of minutes with its sensor fixed in the narrow space between disks, and dedicated flaw detection software that can differentiate SCC with a depth of 1 mm or less from a shape echo with high accuracy using software that combines inspection data and 3D-CAD, thereby realizing highly-efficient inspection.

In blade grooves, depending on the steam environment, deposit adherence and corrosion pits that may initiate SCC, as well as fatigue cracking due to operation and steam conditions may occur. Over the past 10 years or more, we have accumulated verification data using SCC generated in an acceleration test conducted by heating a blade groove sample in a high-temperature furnace and from an actual rotor in which SCC echoes were detected due to long-term operation as shown in **Figure 4**. We are working on the identification of harmful SCC by evaluating the correlation of reflected echoes with reflection sources based on the gained empirical data and by superimposing inspection data and 3D-CAD.

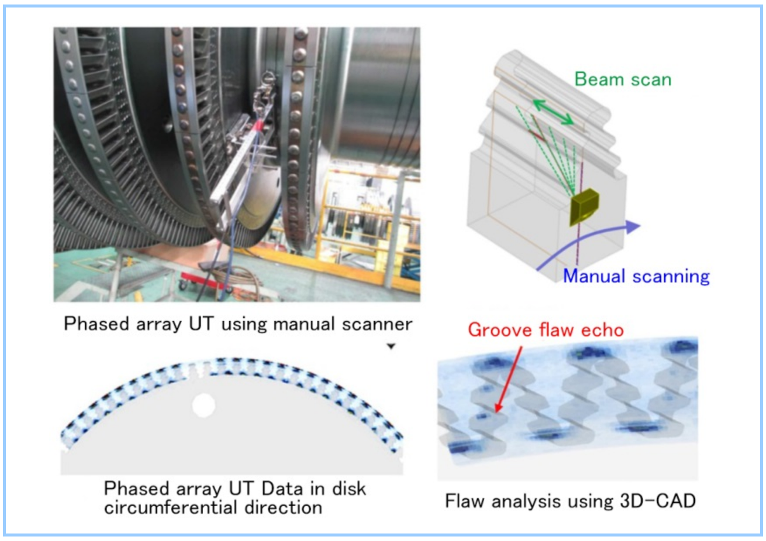

Figure 3 Phased array UT of axial entry blade groove

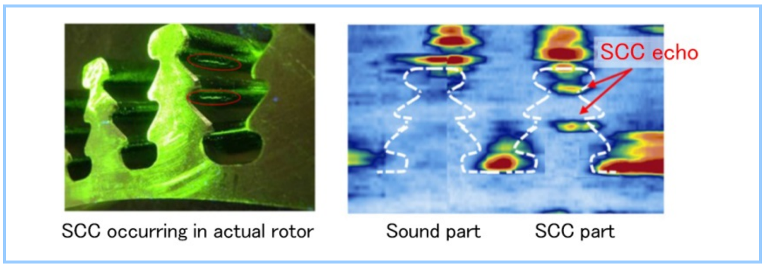

Figure 4 Inspection example of axial entry blade groove

4. UT technique for curved axial entry blade grooves

A curved blade groove is processed with a curvature in order to alleviate the centrifugal stress on the rotor blade due to the high-speed rotation of the turbine rotor. For this blade groove shape, we developed a flaw detection technique that electronically scans the ultrasonic beam in the disk circumferential direction with the array divided in the sensor width direction as shown in **Figure 5**, unlike the conventional method that scans the beam with the array divided in the sensor in front and rear direction in order to properly emit ultrasonic waves to detect SCC.

This method can efficiently detect SCC throughout the curved blade groove by recording the flaw detection data of the entire disk thickness for the entire curved blade groove area by performing mechanical sensor-scanning in the disk radial direction with a dedicated scanner simultaneously with electronic scanning in the disk circumferential direction. The detection performance of this technique has been verified with SCC occurring in the long-term operation of actual equipment and SCC generated by accelerated testing in a high-temperature furnace. This technique can also efficiently inspect the entire area of various blade grooves with different disk thicknesses and evaluate them with high accuracy, by combining sensors optimized for shallow region and deep region according to the thickness of the disk to be inspected.

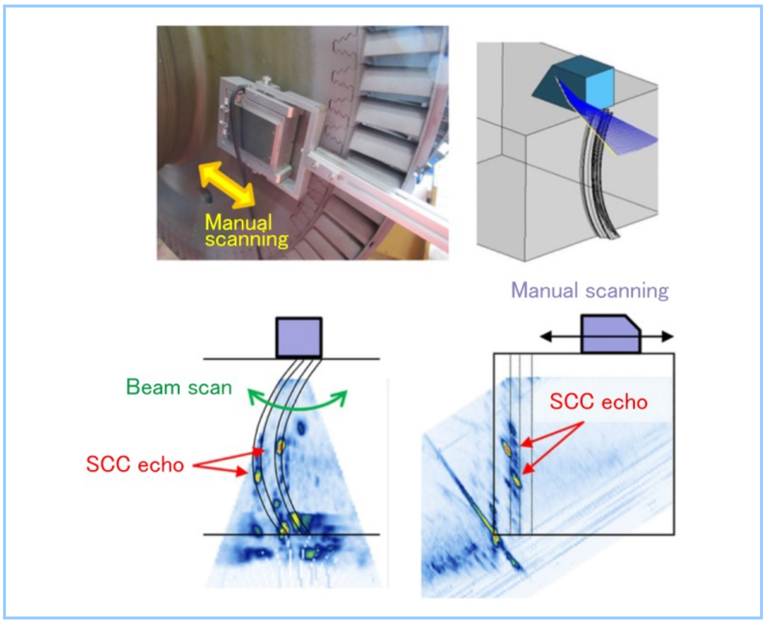

Figure 5 UT technique for curved axial entry blade groove

5. UT technique for disks with complicated shapes

In many cases, disks in the low-pressure stage of large turbines have a tapered, curvature, or curvature flanged shape as shown in Figure 1, so a general flat-shape ultrasonic sensor cannot be attached to them. Therefore, we have developed an inspection technique that can visualize internal defects with high accuracy even from a disk surface with an arbitrary curvature or with a tapered shape by utilizing the adaptive ultrasonic testing technique(2) developed by our company. This technique applies an ultrasonic acoustic gel between the ultrasonic sensor and the surface of the disk so that the ultrasonic sensor can adhere to the arbitrarily curved surface or tapered shape and efficiently transmit and receive ultrasonic waves, as shown in **Figure 6**. In order to make an image of internal flaws, this technique first utilizes signal processing called FMC/TFM (Full Matrix Capture/Total Focusing Method) to obtain the spatial coordinates of the surface shape by visualizing the surface shape with transmitted and received signal data of all elements in the sensor. It then calculates a propagation path that passes through the surface coordinates and satisfies Snell's law to divide the predetermined blade groove area into grids, integrates the peak value of the waveform time corresponding to each coordinate and performs imaging. This technique implements calculation processing using a GPGPU (General-Purpose Computing on Graphics Processing Units) and enables real-time flaw detection.

Figure 7 compares the flaw detection waveform of conventional phased array UT and the flaw detection waveform of adaptive UT (FMC/TFM) for SCC occurring in a blade groove of actual equipment and artificial defects. It is shown that adaptive UT can receive, with all array elements, ultrasonic echoes scattered on the irregular surface of SCC due to long-term corrosion and synthesize them, so the resolution of echoes reflected from groove shapes and artificial defects is improved, resulting in higher differentiability between those echoes and shape echoes.

Figure 8 shows the actual inspection of a large low-pressure turbine. Even in the narrow space between disks with a flanged shape near the blade groove, the scanner that records continuous inspection data in the circumferential direction can perform high-efficiency UT inspection of all the blade grooves using a large ultrasonic sensor incorporating acoustic gel. In addition, for T-slot type blade grooves machined in the tangential direction, we have also developed a scanner that automatically records inspection data with its ultrasonic sensor automatically travelling in the circumferential direction with reference to the shoulder area where the blade is implanted as shown in **Figure 9**. In this way, we have built an inspection system that improves not only the inspection efficiency, but also the traceability.

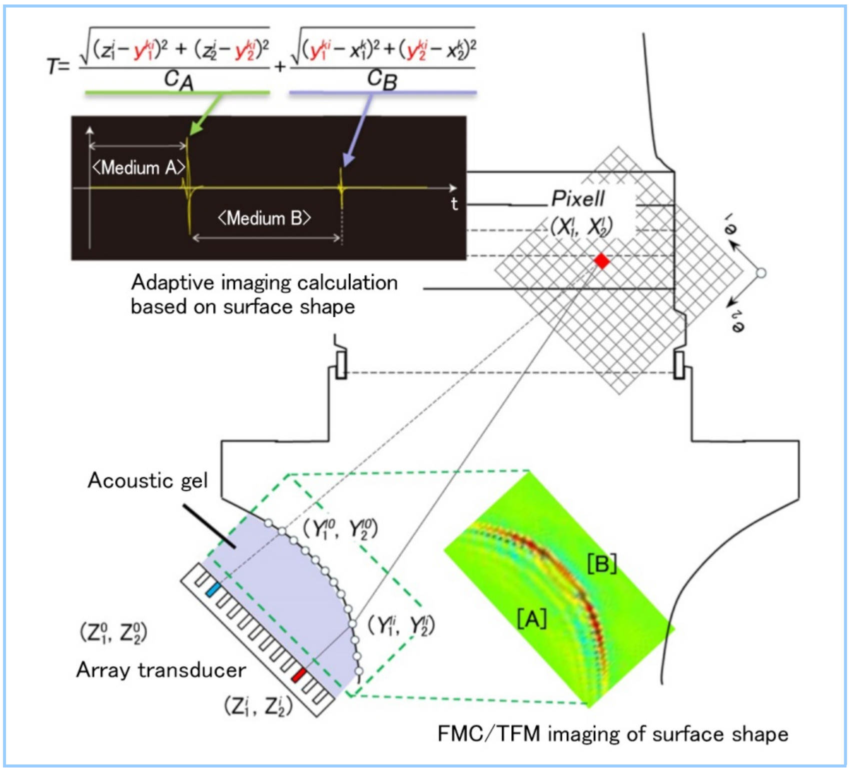

Figure 6　Principle of adaptive ultrasonic testing for disks with complicated shapes in large turbines

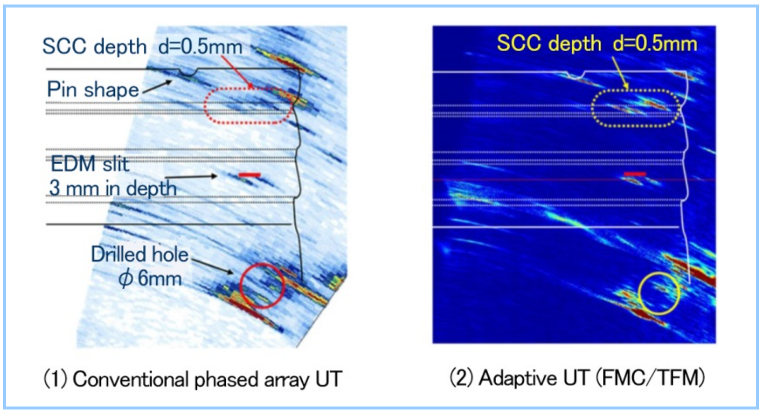

Figure 7　Inspection example of disk with complicated shape in large turbine

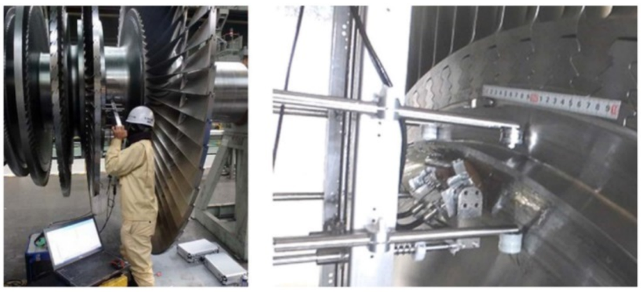

Figure 8　UT of disk with complicated shape in large turbine

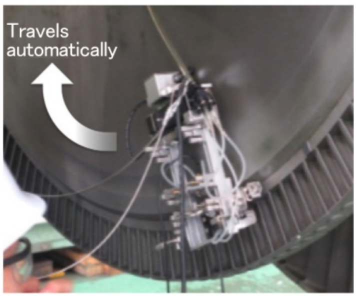

Figure 9　Self-propelled scanner for UT of steam turbine blade groove

Figure 10 shows a standard inspection schedule of axial entry blade grooves in a single disk stage. In contrast to conventional inspection involving blade removal, which requires six days for the entire process, the developed technique eliminates the need for removal work to remove and reinstall the blades, and can significantly shorten the inspection schedule with the rate of one stage per day. We will continue to strive to improve the discrimination and inspection accuracy of this technique.

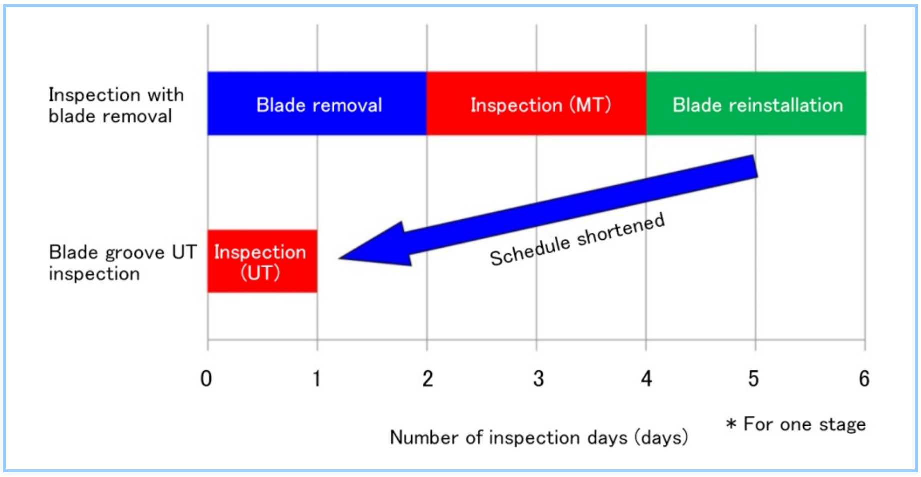

Figure 10 Inspection schedule example of turbine rotor blade groove

6. Conclusion

MHI Group has been working on the development of technologies to efficiently detect stress corrosion cracking that occurs in the blade grooves of the low-pressure stage of a turbine rotor due to long-term operation of the turbine equipment. This paper described ultrasonic testing technologies that can handle various groove shapes and disk shapes for axial entry type blade grooves with complicated machined shapes.

These inspection technologies are currently accumulating results in maintenance inspections of many steam turbines including small- and medium-sized units, and it is expected that their application will be expanded to the inspection of areas with complicated shapes in high-speed rotating machines other than steam turbines. We will continue to improve inspection and evaluation systems and contribute to the maintenance management of rotating machines during long-term operation.

References

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