1. Introduction

The blades and blade attachments in a steam turbine belong to the most-highly stressed components in a turbine/generator. The high turbine speed (3000 rpm) and the dead weight of the blades means that the last-stage blades in a steam turbine are subjected to enormous centrifugal forces during plant operation. The roots on such blades are designed and calculated using the most up-to-date methods to allow them to accommodate these high loads. Particularly during transient loading conditions (startup and shutdown processes) certain areas of the blade roots and blade attachment grooves are subjected to high stressing.

Under unfavourable conditions unusual events occurring during operation of a turbine (e.g. loss of vacuum, overspeed) can result in damage to blading, with possible crack initiation in the
highly-stressed areas of the blade root and subsequent service-induced crack propagation. In addition steam purity is also an important criterion regarding the susceptibility of a turbine blade to corrosion. If the steam is polluted with chlorides this is one of the basic prerequisites for the occurrence of corrosion fatigue in turbine blades, blade roots and blade attachment areas.

In addition to the operational stress situation, steam purity and the corrosion susceptibility of the used material play an important role regarding the occurrence of corrosion fatigue or stress corrosion cracking in turbine blades, blade roots and blade attachment areas. Due to these facts, advanced non-destructive examination methods are required to ensure the safety and availability of the unit.

2. In-Service Inspection of Steam Turbine Blade Roots

The task faced here was to develop an ultrasonic testing technique for special types of blade roots to allow inspection of the most stressed blade roots in the rotor of a low-pressure steam turbine. When installed in the rotor the most highly-stressed areas of the blade root are not accessible for standard crack testing techniques. The objective was therefore to develop a technique which allowed these highly-stressed areas of the blade root to be inspected in situ, i.e. without removing the blade. The examination system had to provide reliable and reproducible results while remaining cost effective.

2.1 Inspection of L-0 blade roots (fir tree design)

Extensive theoretical investigations had to be performed before any decisions could be made regarding selection of the ultrasonic examination technique. The blade under investigation was a last-stage blade from an LP turbine rotor.

Performance of the inspection on the blade roots of the dual-flow turbine rotor required that a test block be fabricated for the right and left side.

2.1.1 Qualification of Inspection Technique

Reference reflectors (grooves, 6 mm long, 2 mm deep) were introduced into these test blocks at the most-highly-stressed areas. These areas can be found on the pressure side in the vicinity of the leading/trailing edge of the blade root in the first serration of the fir-tree root as well as in the middle of the first serration on the suction side of the blade root.
The theoretical investigations showed that it is indeed practicable to select scanning positions at the blade root which allow reliable detection of the reference reflectors. Along the complex geometry of this blade root these scanning positions were also situated in radii and on other curved surfaces which required a customized inspection solution for the component in question. For this reason, it was decided to fabricate specially-fitted pieces for each area to be scanned, which would allow exact positioning of the ultrasonic search units. This inspection technique seemed to be the right solution for the inspection problem, providing a suitable tool for power plant inspection services.

Once various suitable scanning parameters had been determined, practical tests were able to begin on the test blocks. The results of investigations with phased-array search units at various frequencies (3, 7, and 11 MHz) indicated only limited reliability. For the customized solution (using contoured probe holders with integrated search units) it was decided to use 5 MHz longitudinal wave search units with a transducer diameter of 6.3 mm as well as 60° shear wave search units. These search units were equipped with Plexiglas wedges. It was then possible to contour the Plexiglas wedges so that they could be coupled to the surface at the determined scanning positions.

On the basis of the theoretical investigations, at least two scanning positions were determined for each reference reflector which seemed suitable for detecting the reflector. All the scanning positions calculated during the theoretical investigations were checked during the practical tests on the test block. This confirmed that all reference reflectors could be reliably detected, in all cases.

Once the investigations on the test block had confirmed the suitability of the selected inspection technique for the problem in hand, the contoured probe holders mentioned above were fabricated. The probe holders are matched to the blade root contour to guarantee exact positioning of the ultrasonic search units. Three contoured probe holders were fabricated, each containing several ultrasonic search units.
Their use in conjunction with a 4-channel ultrasonic instrument (µTomoscan) guarantees an effective inspection. Once the corresponding probe holder has been brought into position, this instrument allows the results from all the integrated search units to be evaluated at a glance. Three contoured probe holders were made for the blade root under investigation.

![Probe holder](image)

Fig. 3: Probe holder # 1 for inspecting zone # 1 in the blade root.

When testing the inspection system, investigations were performed using several different blades of the same type, to verify that existing manufacturing tolerances for these large LP blades do not have any influence on the results of the examination. It was shown that the dimensional differences existing between the blades inspected were able to be compensated for using a gel-type couplant and can therefore be neglected. The couplant bridges the gap between the contoured probe holder and the blade root. Manufacturing tolerances were not found to have any effect on test sensitivity/defect detectability.

### 2.1.2 Practical Experiences

The first Inspection of Blade Roots by using this inspection technique was performed in May 2005 in a Nuclear Power Plant in Spain. The Inspection was performed in place, in other words, there was no demand to open the turbine for the inspection. The Inspection was carried out with 2 teams in parallel. So the blade roots of 3 big nuclear LP turbine rotors was performed only within 2 shifts. The experience of this inspection shows, that the developed inspection technique is suitable to inspect the most critical areas of fir tree blade roots in place without opening the turbine using a reliable advanced inspection method.
Fig. 4: In-place Inspection of Steam Turbine Blades of an Nuclear LP Turbine rotor

2.2 Inspection of Finger Forked blade roots

Finger forked blade roots are a common design of several turbine manufacturer. Fig. 5 shows an example of this type of blade roots. The blade roots will be stacked in the invers contour of the rotor and locked by pins.

Fig. 5: LP Turbine rotor with finger forked blade roots

During operation of the turbine the area around the pin holes is loaded by very high stresses. Depending of the used pin design the pin holes of the blade roots prefer to crack at the upper pin hole. If such cracking will not detected during scheduled inspection, a blade failure with heavy damages at the complete turbine can not be excluded. Because this it is important to have
a reliable and sensitive inspection method available for the inspection of finger forked blade roots.

2.2 Qualification of the inspection technique

To develop an advanced UT inspection technique for finger forked blade roots, all conditions has to be into consideration. So the following facts has to be taken into account:

- Accessibility for UT inspection
- Orientation of the cracks
- Location of the cracks

After theoretical investigation it was decided, that a Phased Array Ultrasonic Inspection should be used for this application. The good accessibility allow the use of linear Phased Array probes. The main reason for this decision was the fact, that the cracks to be detected occurring in different orientations. So a number of various beam angles will be required to detect all relevant cracks.

Fig. 6 shows an example of an cracked finger forked blade root of an 900 MW LP turbine rotor (ALSTOM design).

![Fig. 6: Typical cracked finger forked blade root](image)

To ensure the detection of flaws with different orientation several test blocks were manufactured. These test blocks include artificial flaws with angles of ± 30° from the ideal horizontal orientation. To cover a wide range of the area near to the pin holes, a linear Phased Array Probe was developed. This Phased Array probe is able to cover the complete area, where the cracks will be expected.

The Inspection of the blade roots will be performed by using 3 inspection sequences on time.
The elements of the used linear Phased Array probes are divided in 3 sequences. All the three sequences working in parallel and cover a special defined area.

Fig. 7: Linear Phased Array Probe operating in 3 sequences in parallel

The investigation at the test blocks and especially at real cracked blades confirm accurate, that this inspection technique is suitable to detect smallest cracks in the area of the upper pin holes of finger forked blade roots. A procedure for crack-sizing was developed to allow an evaluation of the results of the Phased Array Inspection and if necessary the control of cracked blade roots for a limited time period.

2.3 Inspection of blade attachment grooves of a 120 MW back pressure turbine rotor

The examination of selected blade attachment grooves in turbine shafts is an extremely important measure for guaranteeing turbine operational reliability, particularly in turbines, which have been operating for more than 100,000 hours. Stress corrosion cracking is the most frequent cause of crack formation in highly-stressed blade attachment grooves. Particularly at risk are those grooves which are subjected to the highest stresses based on the turbine design. The blade rows subjected to the highest stress vary considerably from turbine to turbine depending on the design and type of the turbine shaft.

In 2004, the shaft in a combined IP/LP cylinder of a 120 MW steam turbine in Warsaw was severely damaged. Cracks in the blade attachment grooves of Row 7 caused part of the blade attachment to become loose. This caused considerable damage to the turbine.

To prevent such damage to similar turbine shafts it became imperative to examine all turbine shafts of the same design to check for cracks in the blade attachment grooves.

2.3.1 Description of Task

The turbine shaft affected by the damage (supplier: ZAMECH ELBLOG / Poland) is shown in Figure 8. The turbine shaft has three different types of attachment groove.
The shaft has 12 blade stages with inverted tee roots, one stage with fir-tree roots and the blades of the last stage have pinned, radial-entry roots. The most highly-stressed grooves are the tee root design of Row 7, which were the source of the severe damage to the turbine in Warsaw.

### 2.3.2. Developing an Advanced Inspection Technique

Following the turbine damage in Warsaw in 2004, it became necessary to develop a reliable inspection technique within a short period which would be capable of reliably detecting the finest cracks in the highly-stressed areas of the blade attachment grooves which are particularly susceptible to crack formation. The NDT laboratory at Siemens Power Generation (PG) decided that the only way to develop such a technique would be to fabricate a full-scale model of the blade attachment grooves to be inspected for use as a test block. Reference reflectors were introduced artificially through electric-discharge machining (EDM) into those areas of the attachment grooves where defects are expected to be found. The artificial defects were introduced at various angles to ensure that all initial cracking at various orientations would be capable of being detected. To replicate realistic conditions to the greatest extent possible, reference reflectors with semi-elliptical form were introduced. The smallest reflectors had a representative reflector depth of 1 mm.
Eight weeks after receiving the task description we were able to present a qualified inspection technique with capabilities verified on calibration blocks. A mechanized phased array inspection technique was developed which covers several areas of the blade attachment grooves. When used in conjunction with a standard manipulator and a high-performance phased array ultrasonic instrument it can perform reproducible measurements which can be archived for comparison with the results of later periodic inspections.

2.3.3. Performing Inspections in the Power Plant

As explained earlier it became absolutely necessary to inspect all turbines having the same design as the damaged turbine to check for initial cracking in the blade attachment grooves. In 2005 the NDT laboratory of Siemens PG performed 3 inspections on such turbine shafts in Poland. At the time of the inspections the turbines had been operating between 110 000 and 135 000 hours.

In all three cases indications were found which were the results of initial cracking in the highly-stressed blade attachment grooves. In one case, the blades were removed after inspection to allow subsequent crack testing to be performed in the areas having indications. Crack tests showed that the indications detected with the phased-array technique were indeed due to discontinuities.

This therefore confirmed that the developed inspection technique is suitable for detecting cracks in the highly-stressed areas of the blade attachment grooves (tee design).

3 Summary

The manual ultrasonic inspection systems described above were developed to provide a reliable and cost-effective method of inspecting turbine blade roots and blade attachments. The main considerations during development work were:

- blades / blade attachments must be able to be inspected in situ
- simple handling and operation (no complex manipulators, etc.)
- reliable and meaningful test results
- fast test method

All these requirements are met by the used inspection systems. The configuration with the contoured probe holder and a systematic inspection procedure means that only a short introduction to the equipment is required before testing can begin.

In regard to the possible damages of a turbine due to a blade root / blade attachment cracking reliable inspection techniques are very important for a maintenance and operating concept of power plants.
References


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