Development of 3,600-rpm 50-inch/3,000-rpm 60-inch Ultra-long Exhaust End Blades

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Mitsubishi Heavy Industries, Ltd. (MHI) has developed a series of integrated shroud blade (ISB: Integral Shrouded Blade) low-pressure (LP) end blades and promoted its application on actual turbines designed for high efficiency, high reliability, and rational cost reduction in turbines used in thermal power generation plants. In 2003, MHI developed a new high-performance turbine\(^1\) that used next-generation high-performance blades (e.g., reaction blades, impulse blades, and LP end blades), and tested a full-scale model turbine to confirm the internal efficiency and flow patterns. MHI has now completed the development of the next generation of 3,600-rpm 50-inch and 3,000-rpm 60-inch ultra-long steel LP end blades, integrating high-strength blade materials with other advanced technologies to achieve higher performance. MHI has also carried out rotating vibration tests as the verification test. This paper describes the design summary of the LP end blades and the results of the rotating vibration tests.

1. Introduction

The demand for high-efficiency, low-cost steam turbines for thermal power generation accompanied by lower construction and operational costs for power generating plants is increasing due to the rise of environmental issues such as energy resource problems and CO\(_2\) emissions.

The LP end blades of steam turbines have a large output distribution, so their performance has a large effect on the overall efficiency of the turbines. Because the size of an end blade determines the number of low-pressure turbine casings, the overall turbine size, and thus the size of the plant building, the end blade is a very important component that has a great impact on the efficiency and construction costs of power generation plants.

Extending the end blade is the most promising way of improving the efficiency to reduce the exhaust loss, which accounts for a large portion of the total loss in steam turbines. However, the flow field aspects at the base and tip of a blade are completely different, involving supersonic flow fields under wet steam conditions. State-of-the-art knowledge, advanced analytical techniques and the accumulation of adequate test data are essential to maintaining high performance. In addition to corrosive environments and repeated high-centrifugal loading conditions due to daily start and stop (DSS) operations, the end blade is activated under a synchronously excited force coupled with rotational frequencies. Therefore, highly advanced technologies and accumulated test data related to material, structural, and vibrational strength are also required.

Starting in the 1990s, MHI formalized the development process and adopted the ISB structure, changing the end blade concept to achieve high performance. As well as enhancing blade strength applicable to high loading regions, we promoted the development of high-efficiency and high-reliability steam turbine ISB end blades to improve the overall performance of power generation plants.

MHI led the world in the development of the 3,600-rpm 40-inch/3,000-rpm 48-inch series of end blades, and designed 15 other types of blades including titanium 3600-rpm 45-inch end blades and 1,500/1,800-rpm 54-inch end blades. These have been used in new power plants and upgrades, and have demonstrated excellent operational results over the past ten years.
Figure 1 shows the verification process and Figure 2 shows examples of the ISB end blades. MHI completed the verification of a new high-performance steam turbine in 2003 that combined analytical techniques based on developmental experience, accumulated test data and knowledge. Along with testing the performance and the reliability of the 3600-rpm 36-inch blades, validated the design technologies and completed the advance verification for the development of the next generation of end blades.

Based on the verification results obtained from the technical innovations described above, the latest technology into the next generation of ultra-long end blades has been integrated, and the development design and rotating vibration tests for 3600-rpm 50-inch/3000-rpm 60-inch end blades have been completed, which perform better and are more reliable than conventional end blades.

Figure 3 shows the basic configuration of the 3,600-rpm 50-inch/3,000-rpm 60-inch blades. Figure 4 shows their applicable scope. The ultra-long end blades substantially enhance the performance of and reduce the number of casings for low-pressure turbines compared to conventional ones. In particular, for bottoming steam turbines used in gas-turbine combined-cycle (GTCC) applications, single-casing reheat steam turbines with axial-flow exhaust can be applied to all the one-on-one and two-on-one types of MHI’s F and G models, achieving a drastic reduction in construction costs for power generation plants.
<table>
<thead>
<tr>
<th>Blade height (mm)</th>
<th>3,600rpm-50IN</th>
<th>3,000rpm-60IN</th>
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<td>1,270</td>
<td>1,524</td>
</tr>
<tr>
<td>Blade material</td>
<td>13Cr steel</td>
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<tr>
<td>Blade root type</td>
<td>Straight</td>
<td>Side-entry</td>
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**Figure 3** Basic configuration of 3,600-rpm 50-inch/3,000-rpm 60-inch blades

**Figure 4** Applicable scope of 3,600-rpm 50-inch/3,000-rpm 60-inch ultra-long end blades

**Figure 5** shows the outline of a single-casing steam turbine with axial-flow exhaust and ultra-long end blades, buildings and frames, for a conventional low-pressure two-diversion bottoming turbine.

**Figure 5** GTCC bottoming turbine with ultra-long end blades
2. Development design

In the development design of the end blades, we used developmental design technologies for the next-generation ultra-long blades proven in the development of the new high-performance turbine described above. In addition, high-strength blade materials developed through ten years of research and testing has been adopted. The outlines of the high-strength blade materials, aerodynamic design, and strength design shows as follows.

2.1 High-strength blade materials

We used the newly developed PH13-8Mo (ASTM A705-XM13) as the material for the ultra-long blades. It is a steel with a very high tensile strength among precipitation-hardening stainless steels, similar to the time-tested 17-4PH (SUS630). With 13Cr-8Ni-2.5Mo-Al as the main component, this material utilizes aluminum-supplemented nanosized fine precipitate (NiAl) to increase its strength. If it is heat treated appropriately, it is possible to adjust its strength most suitable for ultra-long blades.

We conducted long-term verification tests in addition to various tests to confirm the material's applicability for ultra-long blades. These included the evaluation of its tensile strength, toughness, delayed fracture, high-cycle fatigue strength, low-cycle fatigue strength, corrosion fatigue strength under various environments, fretting fatigue strength, and erosion resistance. We confirmed that the steel met the requirements for ultra-long blades. In addition, we verified its long-term reliability in actual working environments at the demonstration power generation facility (T spot) at the MHI Takasago Machinery Works.

2.2 Aerodynamic design

The three-dimensional nature of the flow is intensified in the flow fields of end blades due to the small hub/tip ratio and the rapidly expanding canted wall of the blade. In addition, the flow field is highly complicated by the generation of shock waves due to the high Mach number, interaction with boundary layers, and thermal energy loss due to steam or condensation in wet steam environments.

For the aerodynamic design of the next-generation ultra-long blades in this complicated flow, computational fluid dynamics (CFD) verified by measurement data was applied. Using a three-dimensional multistage-viscosity unsteady flow analysis that considered non-equilibrium steam characteristics, a loading control (flow pattern design) for each stage and each row was conducted, taking into account all the body forces affected by the wall and blade geometry of the multi-stage turbine.

At the same time, the behavior of the wakes of stationary blades injected in the rotating blades, the behavior of the wakes of rotating blades injected in the stationary blades, the interaction between wakes and secondary flows, and the interaction between shock waves and boundary layers or secondary flows were considered. In addition, by including cavities in the analytical model, the flow of the entire flow path including the interaction between leakage flows from stationary and rotating blades, and the main flow on a time-history basis were considered. As a result, the optimized design was obtained to obtain the maximum efficiency in the time average of unsteady flow fields while controlling the load distribution on the blade surface.

Bowed and skewed blades, an end-wall contour for the stationary blades, and a new negative contoured profile to minimize the shock-wave loss for the profile of stationary and rotating blades were applied. The loss of the whole multistage turbine were dramatically reduced by optimizing the gap between the stationary and rotating blades, the relative position of the stationary blades, the connection of stationary and rotating blade walls, and the cavity geometry. For the reduction of moisture loss due to water-droplets peculiar to the end blades, a more accurate prediction of the water-droplet trajectories using flow analysis technology was applied as described above, and the moisture removal efficiency was greatly improved by optimizing the position and geometry of a moisture drainage suction slit on the blade surface.

Figure 6 shows an example of the three-dimensional multi-viscosity unsteady flow analysis that considered non-equilibrium steam characteristics, indicating the analysis results of a meridian surface in last three stages. Figure 7 gives an example of the analysis results around the blade surface.
The diffuser plays an important role in recovering kinetic energy disposed of at the end-blade exit. It has a significant effect on the pressure distribution at the turbine exit and determines the magnitude of the exhaust loss. Using a three-dimensional viscosity flow analysis that considered steam characteristics, similar to the blade analysis, the flow fields from the end-blade exit to the diffuser or condenser by examining coupling with the blades were optimized. In addition, the recovery efficiency of the kinetic energy was drastically improved by lowering the mixing loss. Based on this, a three-dimensional asymmetrical diffuser and a new axial diffuser that reduced the axial length were developed.

Figure 8 shows the results of the flow analysis for the new axial diffuser. Figure 9 gives an example of the flow analysis results for the three-dimensional asymmetrical diffuser.

2.3 Strength design

Detailed structural and dynamic analyses were carried out using the verified latest three-dimensional finite element method (FEM).

The ISB rotating end blades form a 360 degree continuously coupled structure by the contact between the shroud and the stub utilizing torsional deformation of blades in centrifugal fields. For ultra-long end-blades, the accuracy of the deformation analyses is crucial for the structural analysis. For this reason, we conducted detailed nonlinear elasto-plastic stress analyses considering stiffness change corresponding to the deformation and contact friction. The static stress distribution at the blade profile, base and steeple was balanced, and the deformation from the blade base to the blade tip was optimized. Then, the optimized blade design was achieved based on the aerodynamic performance.

To increase resilience of stress corrosion cracking (SCC) for blade bases and steeples along with the corrosion fatigue (CF) and DSS, large base and steeple which was possible due to the ISB structure, the local static stress was decreased to 60% of that of conventional blades, resulting in highly enhanced reliability.
Figure 10 shows the nonlinear elasto-plasticity FEM analytic model and the results of the static analysis.

Vibration analyses were also carried out using cyclic-symmetry finite element analysis and nonlinear forced response analysis, which were verified by rotating vibration tests and actual loading test. The geometries and positions of the shrouds and stubs were decided based on the analysis results, and the contact rotational speed and reaction forces at the contact surfaces were controlled. The structural dumping was also optimized. In addition, low-order mode resonances were de-tuned from rated operational speed with stable 360 degree continuous blade characteristics, an adequate dynamic strength to withstand high-order mode vibration stress and random vibration stress.

Figure 11 shows examples of the vibration analysis results.

3. Verification tests

Rotating vibration tests and total verification tests of the newly developed blades based on the verification process described above using actual loading conditions were carried out. Comprehensive verification in terms of performance and reliability was performed. The blades were fabricated completely in house, from the forging to the machining. At the same time, the manufacturing feasibility by fabricating full-scale experimental blades was verified.

After completing the development design, one-stage full-scale next-generation experimental ultra-long 3,600-rpm 50-inch/3,000-rpm 60-inch steel end blades was fabricated. Rotating tests for
the test rotor was conducted and the vibration characteristics were confirmed after confirming the fabrication feasibility. The test rotor was connected to a motor in a vacuum chamber, the rotation speed was increased, and the static stress was measured simultaneously during the rotation. After reaching a 110% overspeed, air excitation was provided while decreasing the rotation speed, and the stress amplitude and displacement amplitude generated at resonance were measured using a dynamic strain gage and a blade vibration monitor (non-contact blade vibration measurement) respectively. The vibration characteristics were verified by confirming the Campbell diagram and the vibration mode.

Figure 12 shows an overview of the rotor used for the rotating vibration tests, and Figure 13 gives the Campbell diagram obtained from the test. These results demonstrated that the actual vibration characteristics were the same as the design values. The 360 degree continuous vibration mode under seven harmonic excitation frequencies was found, and it was confirmed that the blade frequency cleared the resonance in the 57–62-Hz high- and low-cycle operational range with an adequate margin.

4. Conclusion

We completed the development of 3600-rpm 50-inch/3000 rpm 60-inch next-generation ultra-long steel ISB end blades, and achieved even higher performance, larger capacity, and lower costs than the previous series of blades. We conducted rotating vibration tests for the 3600-rpm 50-inch blades as the verification test, confirmed the manufacturing feasibility, and determined that the actual vibration characteristics were the same as the design values.

We plan to conduct actual-loading total verification tests of the 3600-rpm 50-inch exhaust blades, including over-loading conditions, and use these blades in actual power plants after confirming their performance and reliability. Based on our ample experience in the development and verification testing of long blades, we believe that these state-of-the-art next-generation ultra-long steel end blades will make a valuable contribution to the power generation plants by increasing their reliability, lowering their cost, and improving their efficiency.

References


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