Development of Long Blades with Continuous Cover Blade Structure for Steam Turbines

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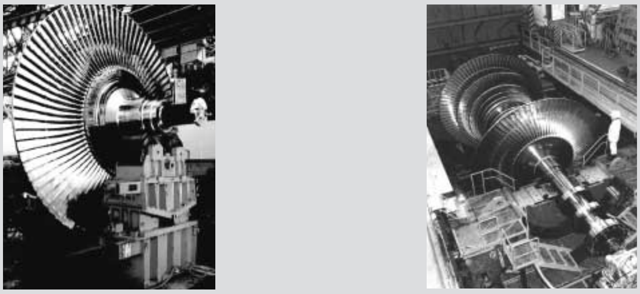
OVERVIEW: In today's power market, the importance of thermal and nuclear generated power as the stable core foundation of our basic energy needs remains unchanged. Yet the energy industry is facing growing pressure on the cost front as the unit price of energy is driven down by the relaxation of industry regulations and at the same time on the environmental front as the industry struggles to satisfy COP3 (Third Conference of the Parties, Kyoto, Dec. 1-10, 1997) recommended guidelines for the reduction of greenhouse gases. This translates into a demand for more efficient and more reliable steam turbines for thermal and nuclear power plants, not only for new plant installations but also for retrofitting steam turbines that have long been in service. In its commitment to meet these demands, Hitachi has developed a new turbine blade design featuring a CCB (continuous cover blade) structure based on the state-of-the-art analytical technologies and an enormous amount of test data on performance, vibration, and strength from the outset of the development. The blades, from 26 inches (66 cm) for rotation speed of 3,000 rpm to 46 inches (117 cm) for 3,600 rpm, are the basis of a full line-up of CCB long blades for low-pressure last stage blades corresponding to the range of plant outputs. The new blades are now operating smoothly in numerous turbines in Japan and in various other countries.

INTRODUCTION

LONG last stage blades bear the burden for approximately 10% of the output of large steam turbines, and since they are under the largest centrifugal force, they are a critically important component affecting the performance and reliability of the turbine as a



33.5-inch (85-cm) CCB long blade test rotor

Last stage 43-inch (109-cm) CCB long blade rotor

Last stage 40-inch (102-cm) CCB long blade rotor

46-inch (117-cm) CCB long blade test rotor

Fig. 1—Steam Turbine Rotors Featuring Various CCB Blading Configurations.
Hitachi is in the last stages of developing a full lineup of CCB long blades for different output plants, and has installed the new blades in numerous turbines that are now in service.

TABLE 1. CCB Long Blade Lineup
Lineup of CCB long blades developed so far.

Speed (rpm)	Cover alone	Cover + Tie-boss*
3,600	26 inch (66 cm)	33.5 inch (85 cm), 40 inch (102 cm), 46 inch (117 cm)
3,000	26 inch (66 cm)	33.5 inch (85 cm), 43 inch (109 cm)
1,800	—	48 inch (122 cm)

*: See Fig. 5

whole. Furthermore, as last stage blades have become longer, this has resulted in faster stream flows, larger centrifugal force, and reduced natural frequency, thus requiring more advanced design technologies to optimize the performance, strength, and vibration characteristics of blades.

Based on a number of cutting-edge design technologies, Hitachi has now developed a new long blade technology featuring a CCB structure that offers better overall performance and superior strength and vibration characteristics. This design approach has been the basis of a full lineup of CCB blades covering a range of power plant outputs (see Table 1), and the new blades are already in service and running smoothly in Japan, the U.S., Canada, Mexico, Korea, Pakistan, Peru, and other countries around the world.

This article gives an overview of the CCB long blades, and describes some of the latest design technologies contributing to the blade's superior performance.

PERFORMANCE DESIGN TECHNOLOGY

Performance Analysis Technology

Steam flows at the tip of last stage blades in turbines is generally transonic, so the longer the blade, the higher the exit Mach number tends to be. It is therefore important that the blade profile of each type of blade be optimized for a particular transonic stream flow and designed to minimize losses from shock waves. An enormous amount of test data has been collected based on experimental and actual blades over the years for this purpose. However, in the last few years we have seen remarkable improvement in flow analysis technologies that now make it possible to evaluate blade profiles much faster and much more accurately than in the past.

In the last stage of a turbine the stream path abruptly broadens and takes on a pronounced 3D (three-dimensional) aspect, so the ability to optimize 3D flow patterns is essential. Traditional experimental turbine flow measurements remain an important method for obtaining this information, but more recently 3D stage flow analysis has come into widespread use and is now recognized as an valuable design tool. Fig. 2 shows typical computational results derived by this analysis method.

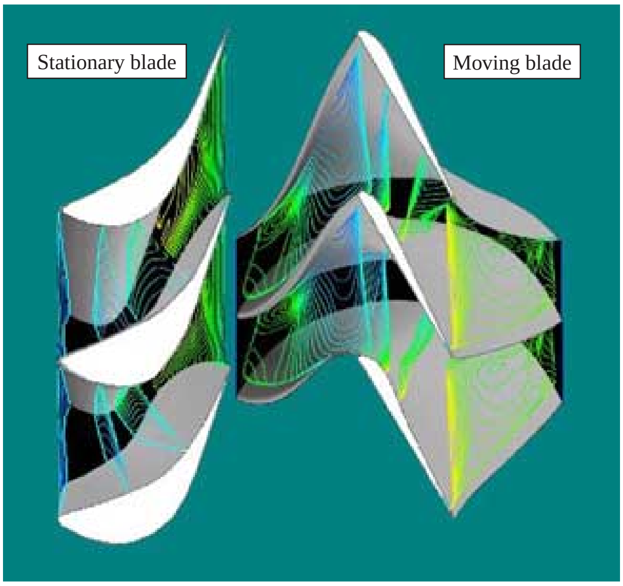


Fig. 2—3D Stage Flow Analysis Example.
Changes in Mach number distribution for stationary and moving blades obtained by 3D stage flow analysis. This leads to the understanding of the optimum flow for stationary and moving blades conforming to actual conditions.

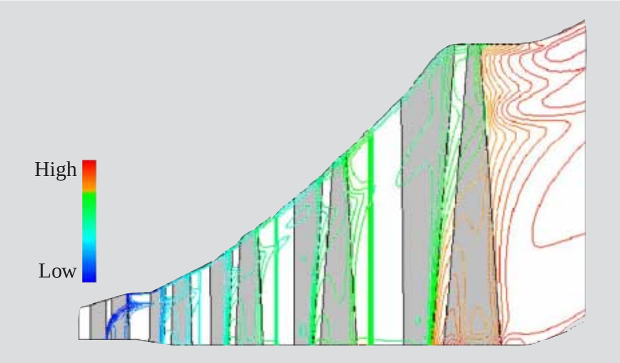


Fig. 3—Wetness Distribution Derived by Nonequilibrium Condensation Flow Analysis.
Estimation accuracy of flow rates, and stage loads and losses are enhanced by considering the wetness accompanying phase changes in high-velocity flows.

In contrast to the old flow analysis that could only deal with ideal gases, we can now analyze nonequilibrium condensation flows considering different wetness conditions of the steam and phase variations, so we can estimate the flow rate, loads and losses of individual low pressure turbine stages much more accurately (see Fig. 3). This type of flow analysis

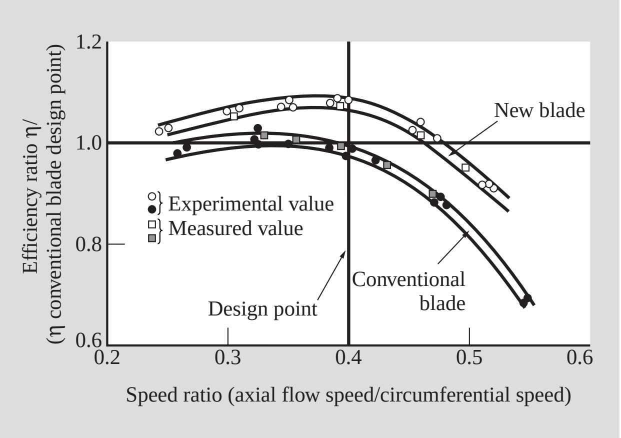


Fig. 4—Comparison of Stage Efficiency for 26-Inch (66-cm) Blade.
By designing the blade profile most suitable for the exit Mach number, stage efficiency shows significant improvement over conventional blades.

can therefore be used to evaluate performance with a high degree of accuracy and as a way to identify profile design changes that can enhance blade performance even more.

Performance Evaluation Testing

When considering the retrofitting of an old turbine with new blades, it is important to verify both experimentally and analytically just how much improvement might be gained by the refurbished blading. As an example, let us here consider the case of a last stage blade with the length of 26 inches (66 cm) for the rotation speed of 3,600 rpm.

Fig. 4 shows a comparison of stage efficiency characteristics where the efficiency of the conventional blade is 1.0 at the measurement point (speed ratio = 0.4). One can see that the average stage efficiency is markedly improved using the new blade. The efficiency gains are especially pronounced in the partial load region where the speed ratio is the greatest. The basic soundness of the flow analysis is also apparent from the fact that the measured values and the calculated values are in close agreement.

FEATURES OF CCB STRUCTURE

Adjacent blades in steam turbines are generally linked together to provide greater rigidity and to reduce or dampen vibrations. The old blade assemblies held together by tenons, caulked shrouds, and tie wires had a number of drawbacks:

(1) stress concentrations tended to occur in the area where the connecting members and blade met, and
(2) poor workability in putting the assemblies together.

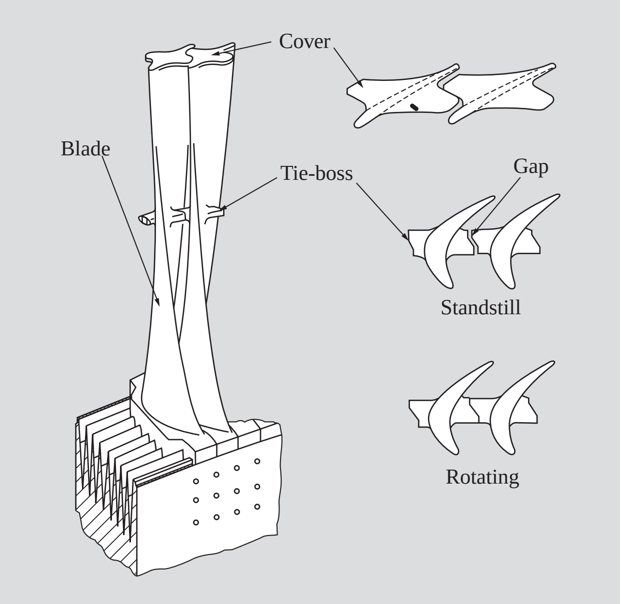


Fig. 5—Schematic Diagram of CCB Structure.
Blades are interconnected by shroud covers and tie-bosses. Covers interlock as blades begin to rotate, and tie-bosses interlock once rotation is under way.

In the CCB structure we have significantly relieved the stress concentrations by integrally forming the connecting members—the shroud covers and tie-bosses—with the blades (see Fig. 5).

By integrating the connecting members with the blades, the untwisting of the blades which is caused by centrifugal force when the blades rotate is restrained by the contact surfaces of adjacent covers and tie-bosses between blades. As a result, all the blades are held together to form a continuous ring of blades. One of the chief advantages of this continuous ring blade structure over the conventional grouped blade configuration (made up of several units of several blades each) is that the continuous ring blade structure has fewer resonance points during rotation.

Compared to conventional blading configurations, the CCB structure has much more stable vibration characteristics thanks to the contact interlocking between the blades, and this reduces resonance stress, reduces random vibration stress, and suppresses flutter.

RELIABILITY DESIGN TECHNOLOGY

Strength Characteristics Analysis Technology

Last stage long blades are subject to steady deformation and stress as a result of the centrifugal force under which they operate. Traditionally, the deformation and stress have been addressed by analysis based on the finite element method that takes steam

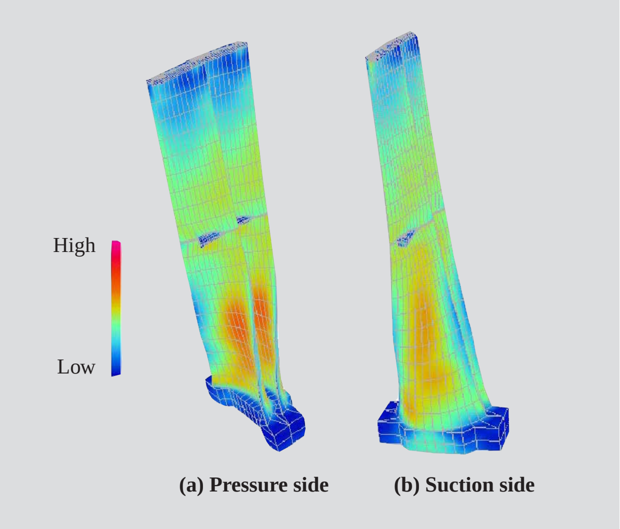


Fig. 6—CCB Long Blade Analysis Examples (Stress Distribution).
Stress distribution and amount of blade deformation can be accurately predicted through contact large deformation analysis.

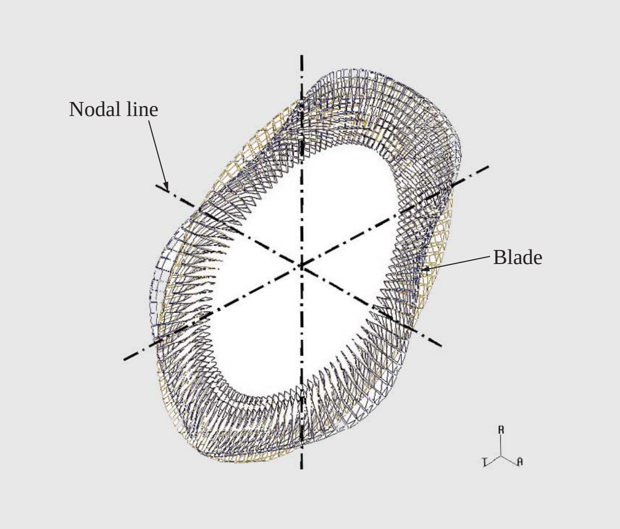


Fig. 7—Vibration Mode Analysis Example.
Vibration mode around the circumference can be analyzed quickly and accurately.

bending force and operating thermal condition into account. We observed earlier that adjacent blades in the CCB structure are bound together because the untwisting caused by centrifugal force is restrained by the contact interlocking of the covers and tie-bosses. To ensure high-strength design of this structure, we employed a non-linear contact large deformation analysis taking the cover and tie-boss contacts into account, and evaluated the strength of the CCB structure at its rated operating speed. Typical results of this structural analysis are shown in Fig. 6. This analysis enables us to identify the points of maximum stress on the surface of the blade, to check the stress distribution around the connecting members (cover and tie-boss), and to modify the blade profile as indicated. Of course, it is critically important when designing blade profiles for performance to consider the deformation blades are subject to when they are rotating. With this analysis we can accurately estimate blade deformation under rotating conditions, and this enables us to include this factor in our performance design1).

Vibration Characteristics Analysis Technology

The CCB structure is made up of single blade structures consisting of a blade and connecting members, that are periodically repeated. By applying an efficient vibration analysis using the periodicity of the structure, accuracy is enhanced even while the design time is reduced. Also, by dealing with contact elements between the blades, this has a major influence on the accuracy of natural frequency and other analysis, and thus enhances the modeling. Fig. 7 shows typical vibration mode calculations derived by this analysis.

Rotational Proof Test

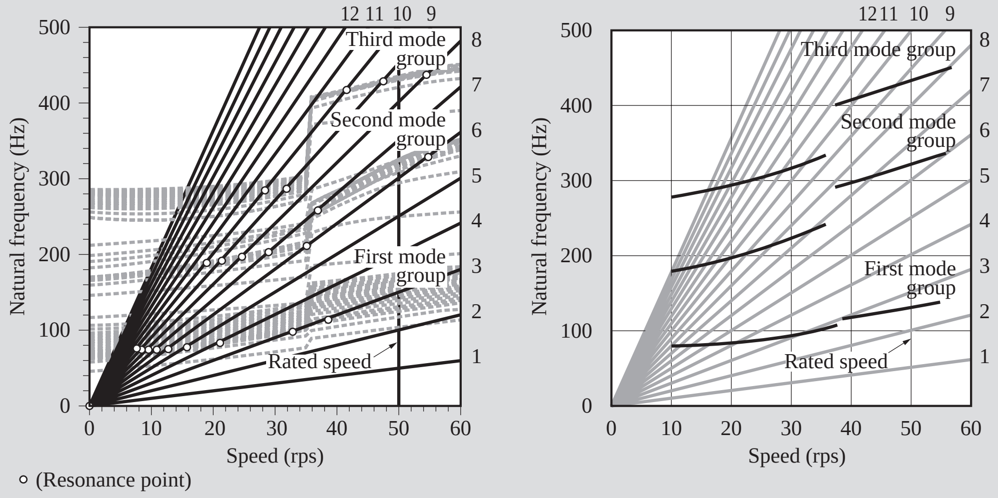
The vibration characteristics of actual full-scale last stage CCB long blades were measured and verified through rotational vibration tests. Fig. 8 shows an example of the vibration characteristics for a last stage blade with a length of 43 inches (109 cm) for a rotation speed of 3,000 rpm.

The actual measured results confirmed that the new blades exhibit excellent vibration characteristics without any resonance points near their rated speed. We also obtained good agreement between measured and calculated values even as we varied the vibration characteristics by changing the rotation speed.

Knowledge and feedback accumulated in the course of this development will accelerate the pace of CCB long blade development and open the way to even more accurate vibration analysis and prediction.

CONCLUSIONS

This article presented an overview of the main features of CCB long blades, and surveyed some of the latest design technologies contributing to the superior performance of the long blades.



(a) Calculated Campbell diagram **(b) Measured Campbell diagram**

Fig. 8—Comparison of Campbell Diagrams.
Both calculated results and measured reliability test results verify excellent vibration characteristics without any resonance points near the rated speed.

Giving primary consideration to the needs of our worldwide customers, research and development efforts are continuing on new CCB long blade designs. Blades are being developed not only for deployment in new power plants but also to provide refurbished blading for turbines that are already in service.

To satisfy the increasingly diversified needs of our worldwide clients in a timely manner, Hitachi remains committed to the development and provisioning of the most efficient and reliable CCB long blades available.

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