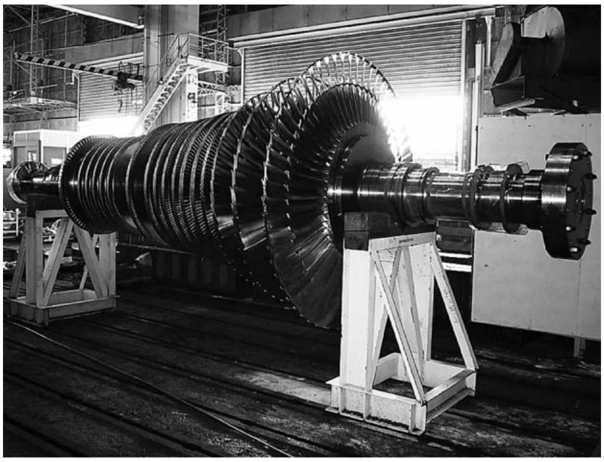

Development of 500 mm Long Blade for Variable-Speed, High-Loading Mechanical Drive Steam Turbine

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The GTL (Gas To Liquid) technology for converting natural gas directly into liquid fuel has been attracting global attention recently. Low-pressure blades for compressor-drive steam turbines used in this process are required to have a high load, high speed and variable speed hitherto unattained in the world. This is an introduction to the development of low-pressure blades in three stages, with the last stage blade of 500 mm applicable to such severe conditions.

1. Introduction

Recently, the GTL (Gas To Liquid) technology for converting natural gas directly into liquid fuel has been attracting attention globally. A large output exceeding 70 MW is required in the steam turbine for geared air compressor drivers used in this process, and since operation in a low-vacuum condition with an air-cooled condenser in desert locations is assumed, the flow rate in the low-pressure section exceeds 500 T/H. Accordingly, as shown in **Fig. 1**, it requires variable-speed blades capable of withstanding high load and high centrifugal force previously unheard in the world.

The low-pressure end blades are required to withstand a high load of 20 MW/stage, have a rated speed of 4 500 rpm, and is capable of variable speeds. Such blades have not existed previously in the world.

Mitsubishi Heavy Industries, Ltd. (MHI) has attempted to design a low-pressure blade by making use of the latest three-dimensional viscous flow analysis technology. The strength design has been evaluated by a three-dimensional solid FEM model. Prototype low pressure blades for three stages have been fabricated, and rotation and vibration tests have been conducted, after which the blades were confirmed to have the predicted vibration characteristics.

The results are reported below.

2. Basic specifications

2.1 Turbine specifications

The specifications of the straight condensing steam turbine are described below. Their plan is shown in **Fig. 2**. The inlet steam condition is a low pressure of 20 ata, but the required output is as large as 75 MW: the

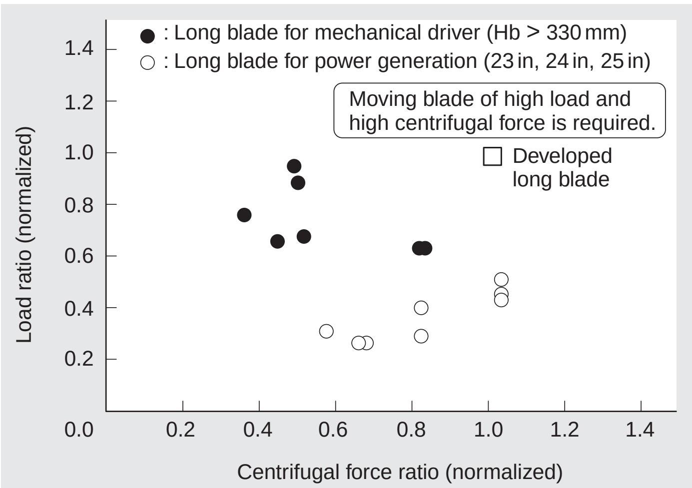

Fig. 1 Relation between centrifugal force and load acting on blade (comparison with conventional blades of MHI)

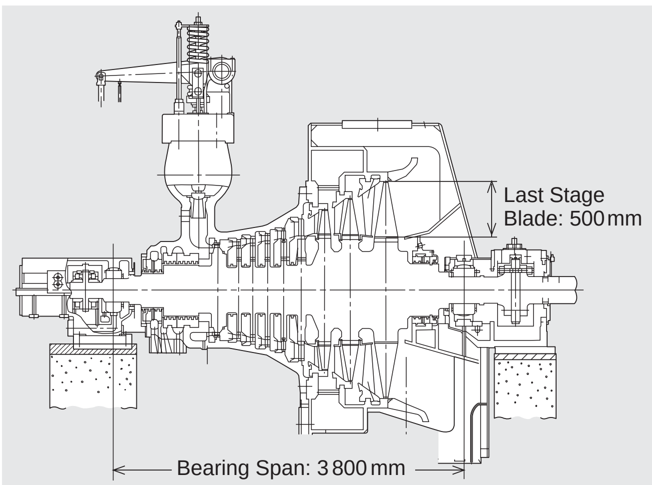

Fig. 2 Plan of steam turbine for GTL plant

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steam flow rate is 550 t/h at maximum, and such a large flow rate has not been experienced in the past. The exhaust vacuum assumes use of an air-cooled condenser as mentioned above, and the operation condition is for low exhaust vacuum.

[Turbine specifications]

- Inlet steam pressure × temperature
  Normal: 20 ata × 260°C
  Max.: 30 ata × 300°C
- Exhaust pressure: 0.3 ata
- Maximum output: 75 MW
- Rotating speed: 4 500 rpm
  Rotating speed range: 3 600 rpm (80%) – 4 725 rpm (105%)
- Maximum flow rate: 550 T/H

2.2 Specifications of low-pressure blade

The plan is to develop low-pressure blades (L-0, L-1, L-2 stages), including the 500 mm long last-stage blade, applicable to variable-speed operation of 80% to 105% in the above condition, and the target output of a single stage is 20 MW. The design specification range of low-pressure blades is shown in **Fig. 3**.

In this condition, the basic specifications of the blade are determined to obtain optimum performance in the entire range.

3. Aerodynamic design

3.1 Three-dimensional viscous flow analysis

During development, the aerodynamic design of turbine blades was done by utilizing three-dimensional blade viscous flow analysis. The calculation grid is shown in **Fig. 4**. The features of the analytical technique are as follows, and multi-stage blade analysis of three stages of low-pressure blades was done.

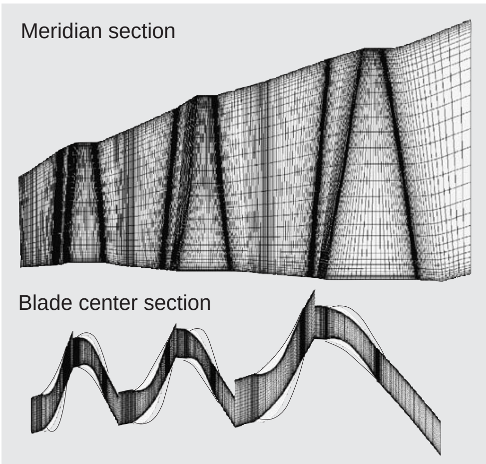

Fig. 4 Calculation grid of three-dimensional viscous flow analysis

(1) Since a steam table is incorporated, the steam characteristics of low-pressure turbines can be simulated accurately.
(2) Multiple blades are analyzed simultaneously, and the effects of distorsion in the flow field based on loss generated in the upper-stage blade are taken into consideration, while the potential effect of upper and lower blades can also be evaluated.
(3) Since the verification using cascade and turbine test result is performed, a turbine efficiency can be predicted with sufficient accuracy.

Fig. 5 shows an example of the analysis results of the flow pattern for the L-0 stage. The developed 500 mm long blade is characterized by a larger degree of reaction in the blade root than with a conventional design, and in spite of its being a high-load blade, the relative inlet mach number in the moving blade root is small, and no shock is generated in the moving blade inlet. The flow turning angle is also small, and the secondary flow vortex generation region is narrow in this high-performance blade.

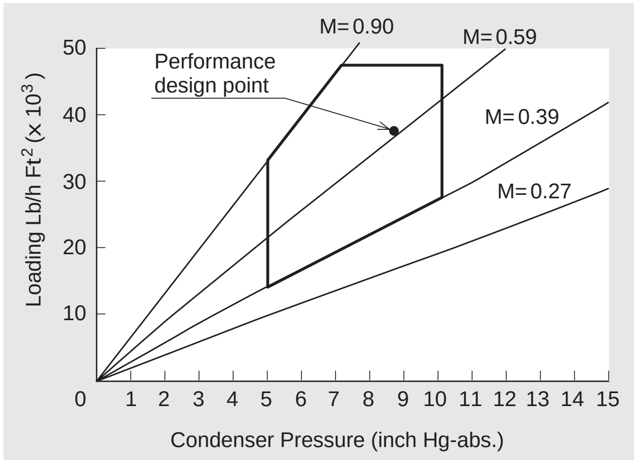

Fig. 3 Design specification range of low-pressure blade
Thick solid line area is design range of present low-pressure blade.

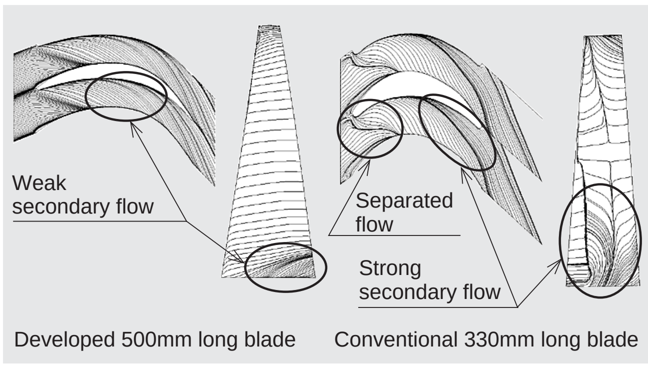

Fig. 5 Results of three-dimensional viscosity fluid analysis (Comparison with conventional blade in L-0 stage)

3.2 Performance evaluation

Fig. 6 shows the results of the performance evaluation of three stages of low-pressure blades by three-dimensional viscous flow analysis. The axis of abscissas denotes the blade height, and the axis of ordinates represents the internal efficiency. The solid line represents the developed 500 mm long last stage blade, and the broken line represents the conventional 330 mm blade used in MHI steam turbines for mechanical driving, each respectively showing changes in internal efficiency. In the developed 500 mm long blade, as a result of the decrease of secondary flow by design of high degree of reaction, the performance in the blade root has been substantially improved. Also, as a result of the design for a small turning angle, the blade efficiency has been enhanced in the whole region in the blade height direction, and the blade efficiency has been improved by about 8% in the rated rotating speed condition.

Further, in the rotating speed range of 80% to 105% for the rating and in the entire assumed operation application range (Fig. 3), performance changes are between −2% and +2%, and the high performance can be maintained over a wide range.

4. Strength design

4.1 Strength evaluation method

In strength evaluation, to determine the blade skeleton, partial use was made of a shell model, but it was eventually evaluated by a complete three-dimensional solid model. **Fig. 7** shows a finite element model under evaluation. The analysis tool was NASTRAN. In the last stage blade, an intermediate stub is used for improving the blade rigidity, and an initial gap is also provided for decreasing local stress.

4.2 Strength evaluation results

Static strength was evaluated by calculating the mean stress, local stress and deformation of representative sections at maximum continuous rotating speed. **Fig. 8** shows an example of analysis of local stress at L-0 stage. All evaluation items including this were within allowable values.

Regarding dynamic strength, the fatigue strength was evaluated at resonance points. For example, the L-0 stage is shown. The natural frequency of the blade group was analysed by using the cyclic symmetry method, and a Campbell diagram, as shown in **Fig. 9**, was obtained.

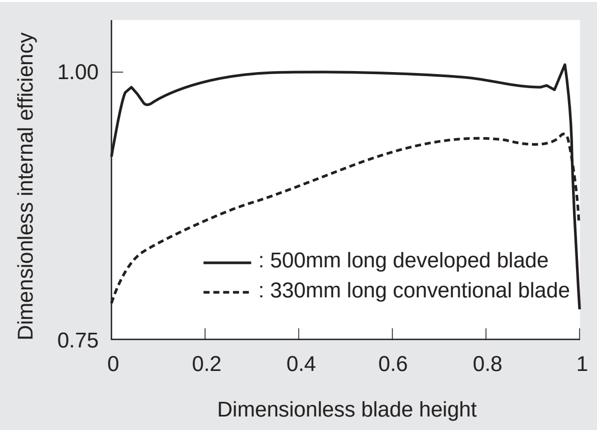

Fig. 6 Evaluation of performance of low-pressure blades (three stages) (Comparison with conventional blade)

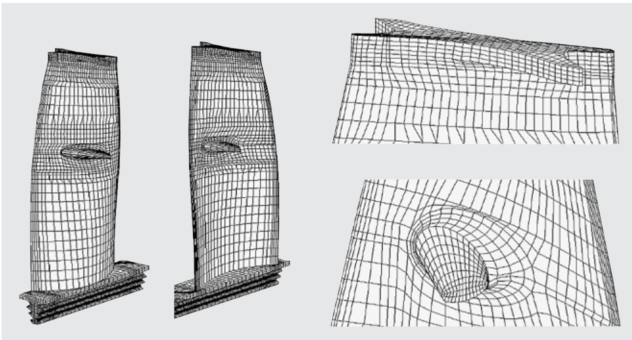

Fig. 7 Finite element model of L-0 stage

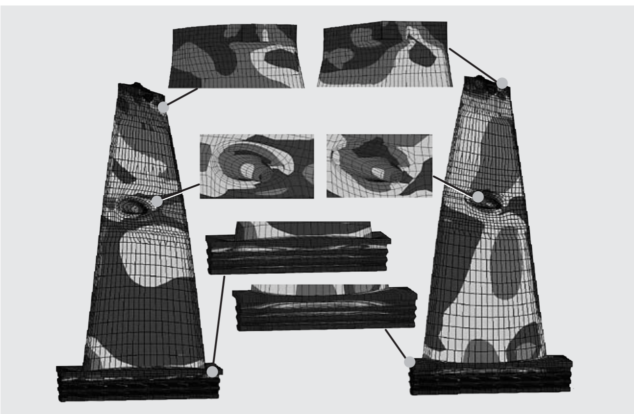

Fig. 8 Static deformation diagram of L-0 stage

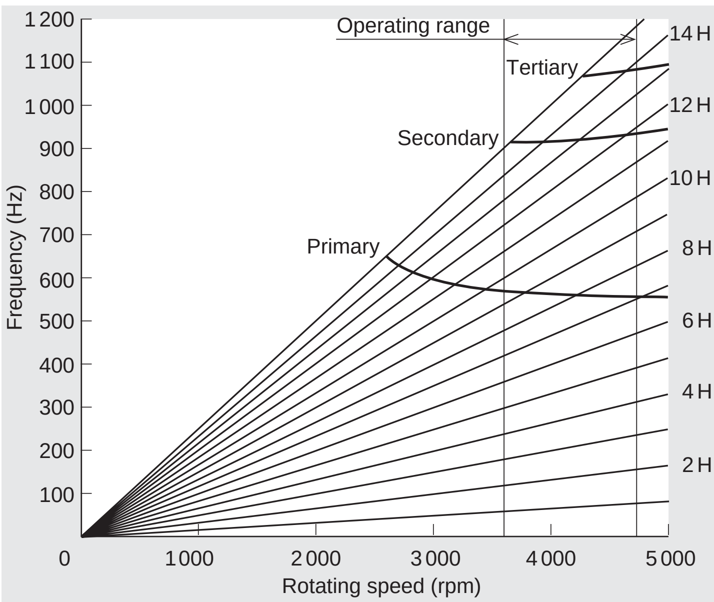

Fig. 9 Campbell diagram of L-0 stage (result of analysis)

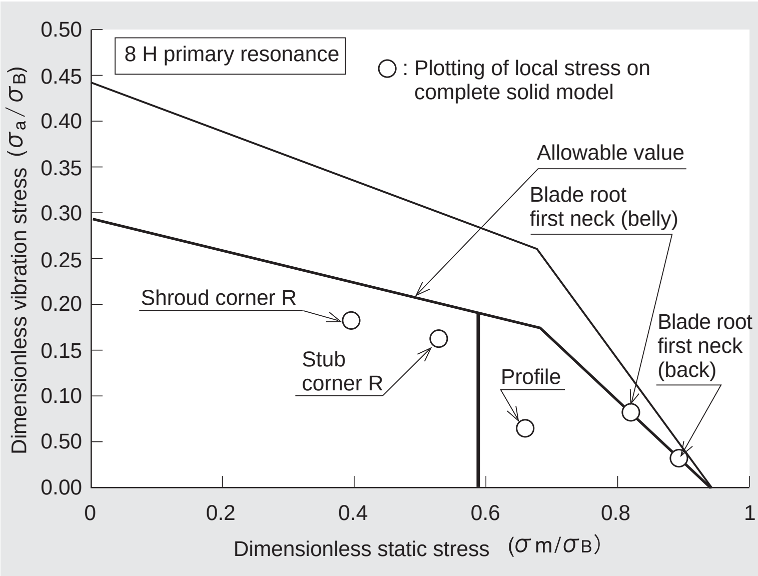

Fig. 10 Goodman diagram of L-0 stage

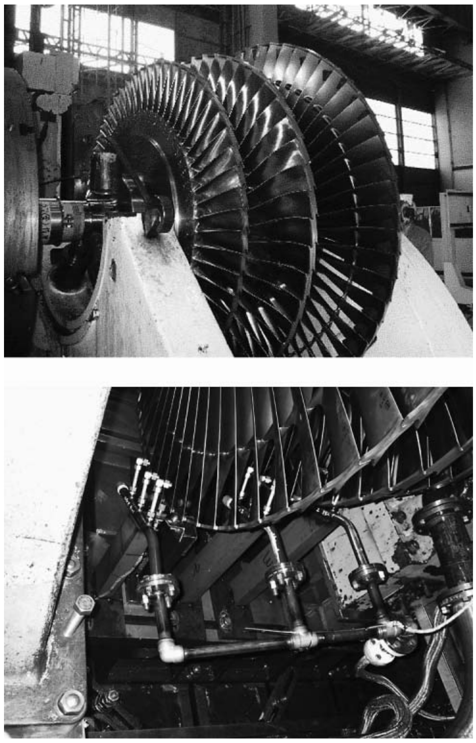

Fig. 11 Test rotor
Top: overall view of test rotor, bottom: details of installation of air nozzle for vibration application

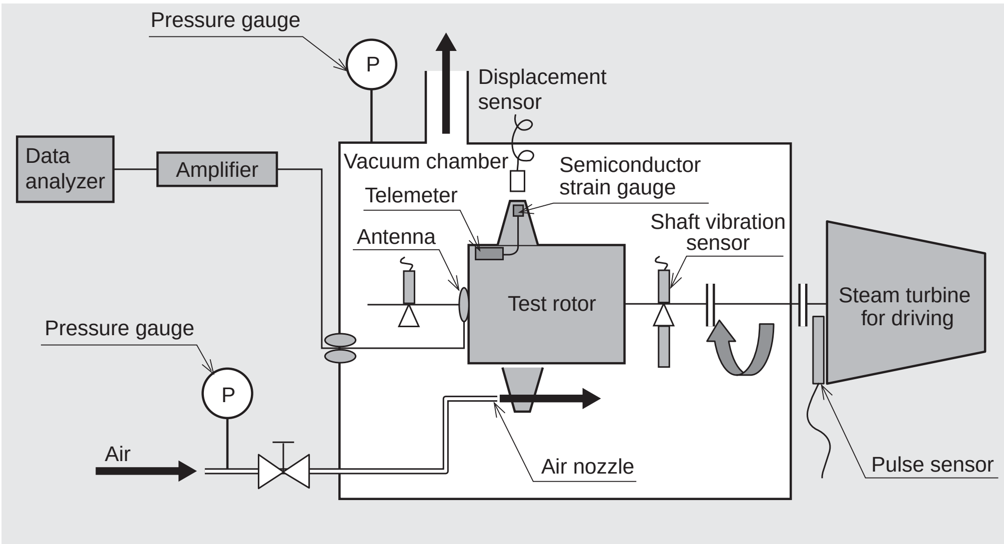

Fig. 12 Configuration of measuring equipment of rotation vibration test

In this diagram, the intersection of the harmonics (H) line and the natural frequency with nodal diameter equal to harmonics is the resonance point, and the fatigue strength was evaluated by the Goodman diagram at these reasonance points. An example of the results is shown in **Fig. 10**, in which all resonance points are within the allowable values, and sufficient strength against fatigue breakdown has been verified.

5. Vibration test

5.1 Test method

A prototype model of the developed blade was fabricated, and presented for vibration test in the high-speed rotor rotating equipment of MHI. The test rotor is shown in **Fig. 11**, and the configuration of measuring equipment is given in **Fig. 12**. A strain gauge is attached to the blade of each stage, and its signal is recorded in a measuring instrument installed in the measurement room by way of an FM telemeter. By analyzing the recorded signals, the dynamic characteristic of the blades was evaluated. An air nozzle was attached to the stationary side, and excitation force was applied to the blades continuously up to the trip speed of 5 197 rpm. Static blade deformation was measured by a displacement sensor.

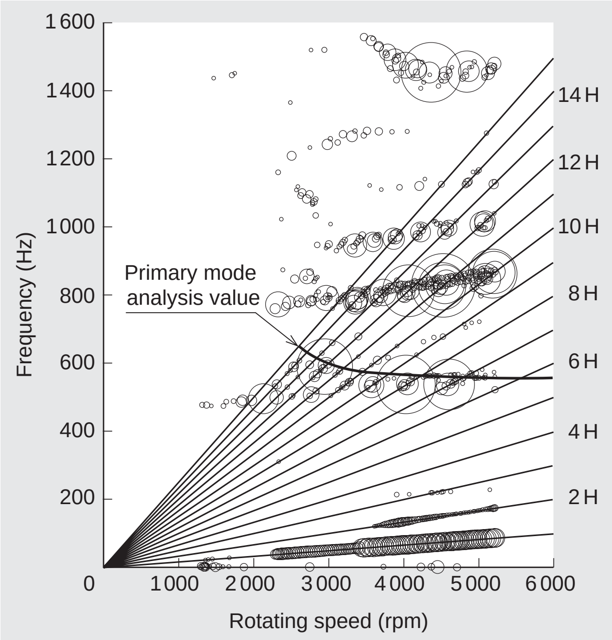

Fig. 13 Campbell diagram of L-0 stage

5.2 Test results

Fig. 13 shows a Campbell diagram of the L-0 stage obtained from test results. The curved solid line in the diagram denotes the analytical value. The primary resonance frequency almost agrees with the analytical value, and the validity of the design is confirmed. Blade deformation approximately agrees with the analytical value, and it is considered to be adequate for practical operation.

6. Conclusions

This report concerns the development of low-pressure blades (three stages) with a last stage blade length of 500 mm applicable to a high load of 20 MW/stage, high-speed rotation with a 4 500 rpm rating, and variable speeds.

As a result of three-dimensional viscous flow analysis, the developed blade has roughly 8% higher performance than the conventional long blades of MHI, and almost no change in blade efficiency was noted in the rotating speed range of variable speed operation (80% to 105% of rated rotating speed). Static strength and vibration strength were analyzed by a complete three-dimensional solid model. For principal resonance evaluation, the periodic boundary method was applied, and sufficient strength has been confirmed at resonance points.

Finally, a trial machine with the developed blades was fabricated, and a vibration test was conducted. As a result, infinite blades were achieved in the operating range, and the natural frequency characteristics were almost as predicted. This is judged to be adequate for practical use.

This 500 mm long variable speed blade for high loading has been developed for the first time in the world, and on the basis of this method of development, further efforts will be made in the future to achieve higher performance of low-pressure blades and the steam turbine.


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