

Development of Multi-disciplinary Optimization Design Assist System for Gas Turbine Rotor Blades

Taku AOKI¹

Toshihiro KAMATSUCHI, Ph.D.¹

Takashi SAKAKIBARA¹

Gaku OKUBO¹

Hisato TANAKA¹

Sebastian SCHMITT, Ph.D.²

ABSTRACT

An optimization design assist system was developed for gas turbine rotor blade design that integrates an optimization algorithm into a workflow automating blade shape creation and aerodynamic and structural analysis. In recent years, thinner blades and higher loads have been used to enhance aerodynamic performance. In view of the impact of increased blade shape design sensitivity on structural mechanics, the system was designed to enhance structural mechanics evaluation functions. This paper presents an overview of the system and example cases of its application to the design of a centrifugal compressor rotor blade and a radial turbine rotor blade. By introducing the system, engineers were able to consider a wide variety of design elements in aerodynamic and structural design, as well as to propose suitable solutions that simultaneously satisfy both aerodynamic and structural design goals and to present quantitative design prospects.

1. Introduction

Gas turbine engines are designed to have a finite life. Particularly, rotor blade components, which see use in environments under large centrifugal forces, pressure, and thermal stresses, require part inspection and replacement at operating times predetermined by the designers. Extending part life can reduce part replacement costs and increase marketability.

As fuel economy performance also contributes to increase marketability, the designers provide the maximum stress and weight of the components, the specific vibration mode frequencies of the rotor blade, and other necessary structural constraints, and pursue longer component life and higher aerodynamic performance.

Given the nature of gas turbine engines, which start with the compression of intake air and then extract energy from the combustion gas using a turbine, the compressor and turbine rotor blades exert a major impact on engine fuel economy performance. However, sufficient structural strength needs to be ensured under the harsh operating environment.

In the design of rotor blades to date, aerodynamic design and structural design have been performed in successive order. If targets are not met, both are repeated in succession until satisfied.

In recent years, however, there has been a trend toward thinner rotor blades and higher loads to increase

aerodynamic performance^{(1), (2)}, increasing the impact of blade shape changes on the structural strength compared to conventional design. Thus, more care is required in the detailed design to help ensure the prerequisite structural strength. For these reasons, a front-loading design method that considers both aerodynamics and structural strength at the initial design stage is needed.

We have therefore created a workflow with the aim of designing gas turbine rotor blades that automates the process from blade shape definition through to analysis and, in combination with an optimization algorithm, developed a design assist system that considers aerodynamics and structural mechanics concurrently.

This paper first gives an overview of the system, and then explains the structural analysis module in detail. In many cases, general turbomachinery optimization calculations only consider aerodynamic performance, or only examine relatively simple evaluation metrics for the structural design, such as aerodynamic performance and disk center stress⁽³⁾⁻⁽⁶⁾. In this system, the structural evaluation function was enhanced to first satisfy the necessary structural constraints and then to increase product competitiveness by increasing aerodynamic performance and service life. Finally, example cases are presented of the system being applied in design of centrifugal compressors and radial turbine rotor blades which are widely used in turbomachinery.

¹ Innovative Research Excellence Power Unit & Energy

E-mail: taku_aoki@jp.honda

² Honda Research Institute Europe GmbH

2. Composition of the Multi-disciplinary Design Assist System

The overall system is as shown in Fig. 1. The system searches for blades by simultaneously analyzing aerodynamics and structural mechanics and evaluating the results with the optimization algorithm.

The optimization software used in this system is HScriptOpt, developed by the Honda Research Institute Europe based on next-generation optimization algorithms.

2.1. Optimization Calculation Flow

As shown in Fig. 1, this system consists of four processes, starting with A. Blade definition, then passing through two analysis modules in B. Aero module and C. Structure module before ending with D. Evaluation.

At the start of the calculation, 11 different blades are generated in A. Blade definition, either at random with predefined ranges for the possible design variables or from concrete given initial values. We call this the first generation. This first generation is then subjected to aerodynamic analysis and structural analysis using B. Aero module and C. Structure module, respectively. During the optimization, both modules are run in parallel.

In D. Evaluation, the individual different designs are evaluated by defining an evaluation function called Fitness. An example of Fitness function is shown in Eq. (1). Here, the weight of the isentropic efficiency is taken as α , with the remaining weight given to low-cycle fatigue (LCF) life. Maximizing their sum is the target of the optimization problem. Note that there is no limit to the number of objective variables that can be incorporated into the Fitness function.

$$\text{Fitness} = \alpha \times (\text{isentropic efficiency}) + (1 - \alpha) \times (\text{LCF life}) \quad (1)$$

The key variables that are often set in the system as objective variables and constraints are summarized in Table 1. The variables have been grouped from the viewpoints of aerodynamics and structural mechanics.

System optimization calculations repeatedly generate individual cases for subsequent generations based on Fitness and evaluate the results. The Covariance Matrix

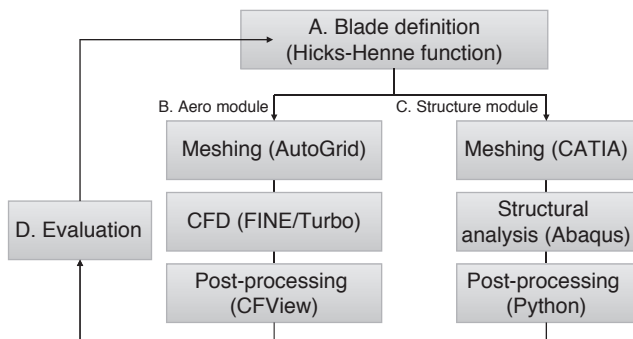


Fig. 1 Optimization workflow

Table 1 Objective variables

	Objectives
Aero performance	Efficiency
	Mach number
	Flow rate
	Pressure ratio
	Expansion ratio
Mechanics	Stress
	LCF life
	Modal frequency
	Vibration modes number
	Mass

Adaptation Evolution Strategy (CMA-ES)⁽⁷⁾ was used as the optimization algorithm for verifying the effectiveness of the system implemented in Chapter 4.

Each process was automated using Python. Each process from A to C is described below.

2.2. A. Blade definition

If too many input variables are used in the optimization calculations, the calculation results will take a long time to converge. To avoid this, the input variables used in defining the optimization problem need to be reduced while increasing design variation.

Blades are generally defined by a free curve using a Bézier curve⁽⁸⁾, but adding more nodes to increase the degrees of freedom will increase the number of input variables. Thus, blades for this program are defined using a Hicks-Henne function⁽⁹⁾, which can represent complex curved surfaces with fewer input variables.

Blades can be defined with any number of sections. A sample 5-section blade as defined with this system is shown in Fig. 2. Adding Hicks-Henne functions to a

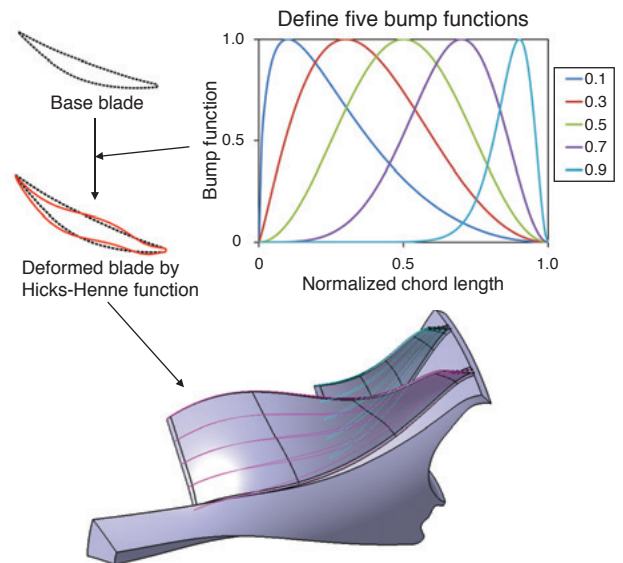


Fig. 2 Blade definition

baseline shape generates a curve by superimposing waves and defining the blade shape by changing the height of the waves at each position with an input variable. By using Hicks-Henne functions, blades can be defined to a similar precision as when using a normal Bézier curve but with about half of the input variables per cross-section.

2.3. B. Aero module

The blade shapes defined in A are subjected to aerodynamic meshing and aerodynamic analysis, and the results are post-processed. An example mesh is given in Fig. 3. Meshes are generated using Cadence Autogrid 14.2 meshing software, and aerodynamic analysis is performed using Cadence Fine/Turbo 14.2.

2.4. C. Structure module

For the structural analysis model, meshes as shown in Fig. 4 are generated for the blades defined in A. During mesh generation, inputting different mesh definition data for each part such as the blade surface, blade root fillet, and disk allows the model to maintain mesh quality and produce highly precise analysis results.

When mesh generation is complete, a structural analysis input file including the mesh data and boundary conditions is generated. The process sequence is automated using

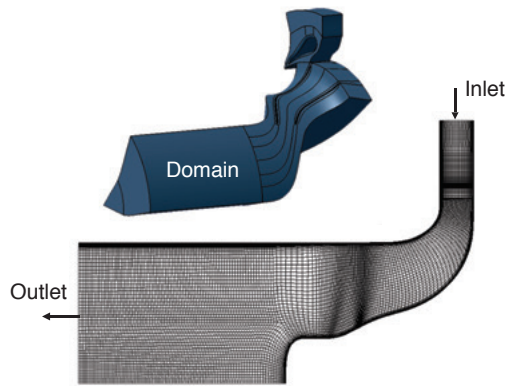


Fig. 3 CFD mesh



Fig. 4 Structural analysis mesh

CATIA Script⁽¹⁰⁾, a CATIA-specific macro language. When handling component weights and shape measurement results during optimization calculations, data can be extracted here. The structural analysis was performed using Dassault Systèmes Abaqus/standard 2018. As structural analysis results in CATIA can be extracted individually for each mesh definition part, the analysis results can be imposed with fine constraints.

The system's structural analysis includes multiple selectable functions, such as Stress Analysis and Modal Analysis. The necessary analyses can be selected in isolation to shorten analysis time for producing the analysis results.

3. Structural Mechanics Evaluation Items in Detail

The structural mechanics evaluation function for this system was enhanced during rotor blade design in order to maximize aerodynamic performance and service life.

The structural mechanics evaluation items break down from (i) to (v) as shown in Fig. 5. In (i) Temperature mapping, the temperature history is mapped, and in (ii) Hot-to-cold conversion, the blades are converted for reasons described below. Next, (iii) Stress analysis calculates blade surface stress and maximum stress at random locations; (iv) Modal analysis calculates resonance points and natural frequencies; and (v) LCF analysis calculates the LCF life based on the stress history during engine operation.

3.1. (i) Temperature mapping

This process presents temperature data for the structural analysis model in the form of the temperature profile during operation. The temperature profile is calculated from a thermal conductivity analysis based on gas temperatures as determined by CFD and component heat transfer rates.

In the system, the three-dimensional temperature profile, which is the result of thermal conductivity analysis for the initial blade shape, is mapped three-dimensionally to a

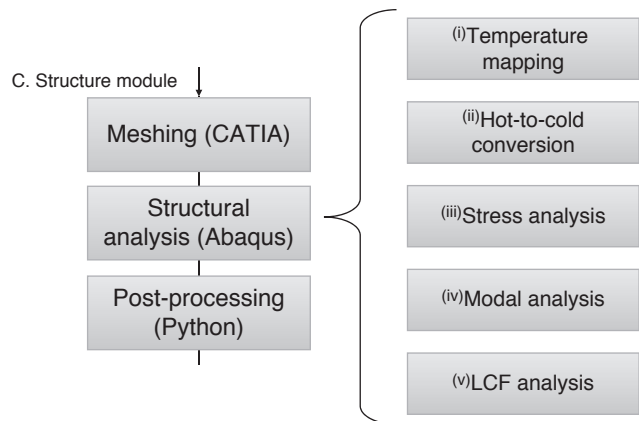


Fig. 5 Structure module

random blade. A mapped temperature profile is shown in Fig. 6.

The model is given the temperatures for required times, such as the temperature at the time to evaluate LCF life. Here, an in-house tool was used for thermal mapping. Generally, thermal stress greatly impacts structural design given that the absolute temperature values for the turbine are greater than those for the compressor and, consequently, large gradients arise.

3.2. (ii) Hot-to-cold conversion

In blade aerodynamic design, there are a number of typical conditions for determining engine performance, such as for takeoff and cruising at high altitude. This section will focus on the most important of these conditions. The rotational speed determined from these conditions is called the aerodynamic design rotational speed.

As the blades defined by this system are hot shapes, which are deformed by external forces at aerodynamic design rotational speeds, the blades need to be reverse deformed to their cold shapes at the zero-state rotational speed prior to structural analysis. This is a hot-to-cold conversion.

The difference between hot and cold shapes is illustrated in Fig. 7. In the front view, the hot shape has deflected to the left compared to the cold shape. Meanwhile, in the side view, the hot shape has a slightly higher blade height than the cold shape.

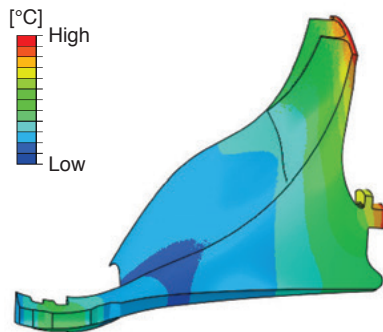


Fig. 6 Mapped temperature

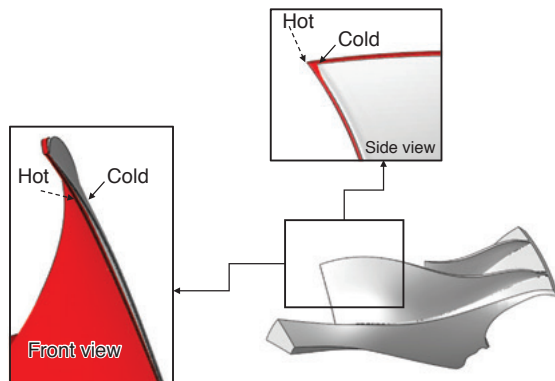


Fig. 7 Hot to cold

If the hot shape is used as the initial shape for structural mechanics calculation, the external forces will be duplicated in the shape calculations. Thus, hot blade shapes are converted to their cold shapes to evaluate structural mechanics precisely. Within this process, calculations are iterated using the finite element method (FEM), reverse calculating to determine the cold shape from the aerodynamic design shape.

3.3. (iii) Stress analysis

As rotor blades rotate at high speed, they generate centrifugal stress, pressure, and thermal stress. As shown in Fig. 8, stress peaks are observed in each of the fillet, disk bore, and blade region. Structural mechanics is to be evaluated to help ensure that no major plastic deformation occurs beyond the yield stress.

3.4. (iv) Modal analysis

A rotor blade may resonate with a blade natural frequency or generate large vibrational stress, when vibrations generated by the nozzle or stator blade located upstream act as the source of excitation. The Campbell diagram shown in Fig. 9 illustrates the number of excitation

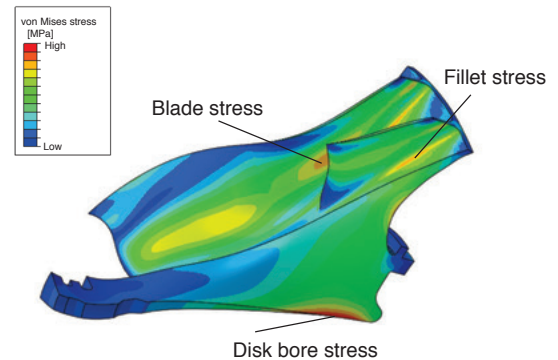


Fig. 8 Stress contour

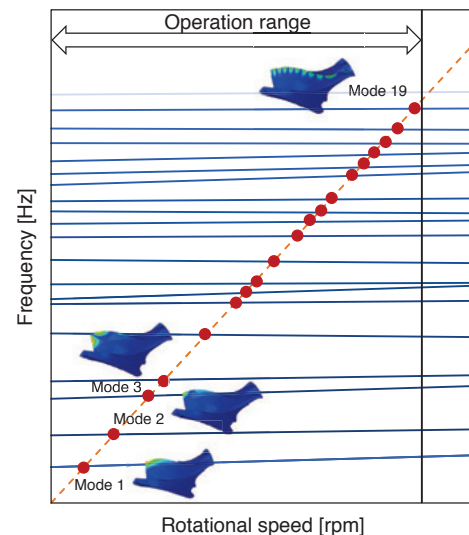


Fig. 9 Campbell diagram

force frequencies and resonance points with the blade natural frequencies (points where the diagonal dashed line and solid lines for each vibration mode intersect, denoted in the diagram by dots). In this example, 19 resonance points are found in the operation range.

If a design with resonance points in the operation range is unavoidable, verification is needed to help ensure that no resonance modes generate harmful vibration stress. When thinner blades are promoted in the interest of aerodynamic performance, higher order modes tend to increase, making it harder to measure vibrational stress and identify each vibrational mode. This issue becomes easier to address by reducing the number of vibration modes included in the operation range, which is therefore one target of the design process.

3.5. (v) LCF analysis

With rotor blades designed to have a finite life, it is necessary to ensure a certain minimum LCF life, and extending this LCF life can reduce part replacement costs. The LCF life of rotor blades is governed mainly by centrifugal and thermal stress time history. Given the difference in time constants between centrifugal and thermal stresses, this difference produces response delays that will differ depending on the location. Thus, assuming blades with multiple operating states, LCF life is calculated based on the time history at each location within the component by performing multiple centrifugal stress analyses under different operating conditions, as shown in Fig. 10.

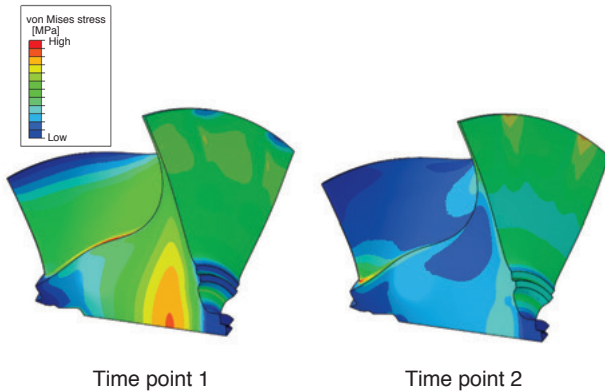


Fig. 10 Stress analysis result for LCF calculation

4. Effectiveness of System Application

Here, two cases of blade design will be considered to verify the effectiveness of applying the design assist system. The first case is an optimization calculation for a centrifugal compressor, evaluating the relationship between the number of blade vibration modes, disk bore stress, and isentropic efficiency. The second case is a calculation for a

radial turbine, evaluating the relationship between LCF life and isentropic efficiency considering temperature gradients.

4.1. Centrifugal Compressor Optimization Calculations

In considering how to reduce the number of rotor blade vibration modes within the operation range, the impact of the number of vibration modes on stress and isentropic efficiency was evaluated. The aim of these calculations was to maximize isentropic efficiency and minimize the number of vibration modes, with at least a 10% reduction in the number of vibration modes as the constraint. A part of the optimization calculation results is shown in Fig. 11. Here, the initial base line design is shown with a black square (■), and other individual cases with white circles (○). The vertical axis represents disk bore stress (disk bore stress positions shown in the figure), while the horizontal axis represents the number of vibration modes. Both horizontal and vertical axes were normalized to the base line value.

As seen in Fig. 11, disk bore stress increases as the number of natural vibration modes decreases. This relationship appears as a dotted line, illustrating the trade-off between disk bore stress and the number of vibration modes. This relationship results because blade rigidity increased due to the increased blade thickness, while disk bore stress increased due to the increased self-weight.

Next, the relationship between isentropic efficiency and number of vibration modes is shown in Fig. 12. Here, the vertical axis represents the isentropic efficiency, and the horizontal axis represents the number of natural vibration modes. The figure illustrates that isentropic efficiency decreases as the number of vibration modes decreases from the base line.

Presumably, this reduction is due to increased blade thickness to reduce the number of vibration modes, resulting in reduced isentropic efficiency. These results indicate that

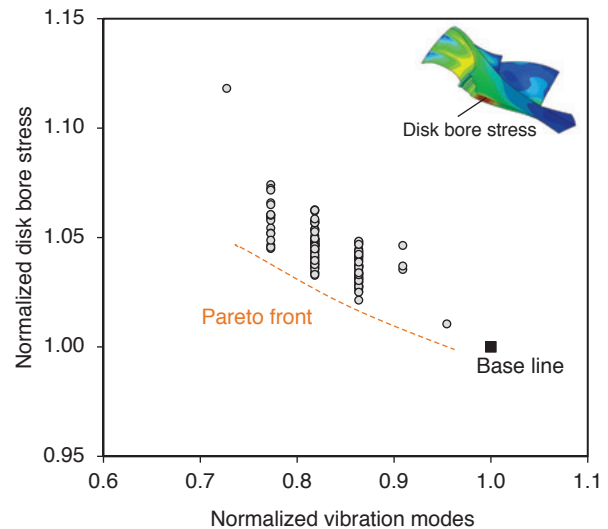


Fig. 11 Disk bore stress vs. vibration modes

a decrease in isentropic efficiency of approximately 0.7% will reduce the number of vibration modes by 10%.

4.2. Radial Turbine Optimization Calculations

The isentropic efficiency of the radial turbine and the LCF life of the blade root fillet were increased. Figure 13 shows the calculation results, along with the root fillet position of the blade for which LCF life is calculated. Here, centrifugal and thermal stresses were calculated for two points during operation to regulate LCF life, and LCF life was calculated.

The base line is shown as a black square (■), and other individual cases are shown as white circles (○). The horizontal axis represents the isentropic efficiency, and the vertical axis represents LCF life. Both horizontal and vertical axes were normalized to the base line value. The Pareto front of LCF life and isentropic efficiency is shown

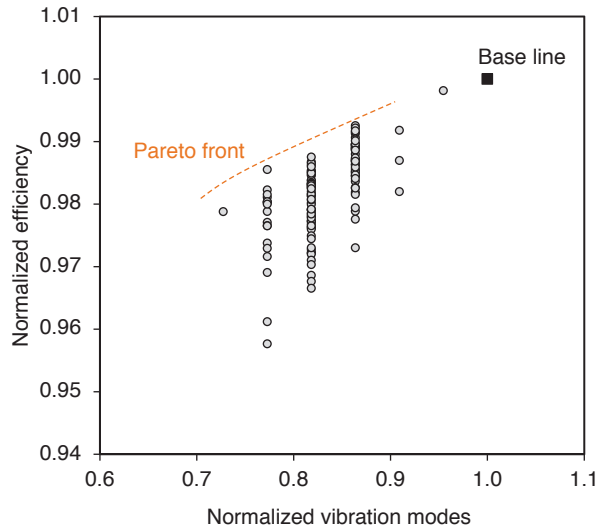


Fig. 12 Efficiency vs. vibration modes

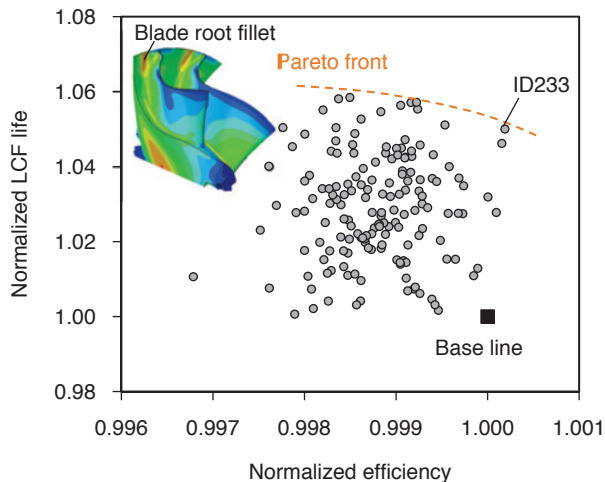


Fig. 13 Efficiency vs. LCF life

by the dotted line. The most efficient solution on the Pareto front is ID233. Focusing now on ID233, a comparison superimposing the blades of ID233 and the base line is shown in Fig. 14. While there are no major changes in blade thickness or airfoil between the two, the inclination angle of the blade tip is increased. As a result, while no major changes were observed in the flow field, reducing the blade root fillet stress by a few percentage points increased LCF life by 5%.

From these optimization calculation results for the radial turbine, in studying how to maximize isentropic efficiency and LCF life, it is predicted that LCF life can be increased by about 6% at the same isentropic efficiency. When further extending LCF life, it is expected that isentropic efficiency would inevitably be decreased. In addition, with the current design constraints left unchanged, it can be surmised that dramatically increasing isentropic efficiency while maintaining LCF life would be no trivial task.

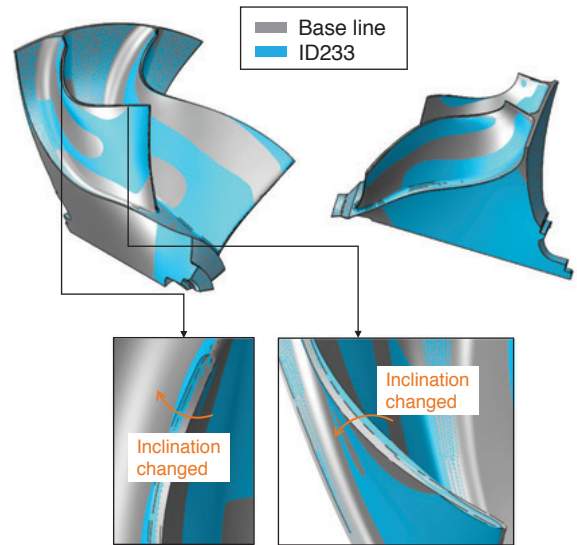


Fig. 14 Base line design vs. ID233 design

5. Conclusion

This paper introduced a design assist system for gas turbine rotor blades. In confirming system effectiveness, a case study was presented considering the two areas of aerodynamics and structural mechanics.

By utilizing this system, it is possible both to select suitable solutions for design variables, and to quantitatively demonstrate the impact on design elements with associated trade-offs, such as varying disk bore stress by b% and isentropic efficiency by c%, respectively, to reduce the number of vibration modes by a%.

The ability to propose suitable solutions that satisfy both aerodynamic and structural design goals while satisfying the required structural constraints and to present quantitative

design prospects, all at the initial blade design stage, should help in streamlining design and be effective in the development of gas turbines.

References

- (1) Funazaki, K., Tanaka, N., Shiba, T., Tanimitsu, H., Hamabe, M.: Studies on two-dimensional contouring of high-lift turbine airfoil suction surface as separation-control device: separation suppression under steady-state flow conditions, Proceedings of ASME Turbo Expo 2011, GT2011-45156, (2011)
- (2) Chen, P.-P., Qiao, W.-Y., Luo, H.-L., Farhan Ali Hashmi: Investigation of low solidity LP turbine cascade with flow control: Part 1 – active flow control using jet-flap, Proceedings of ASME Turbo Expo 2010, GT2010-22328, (2010)
- (3) Elliott, M., Spence, S., Seiler, M., Geron, M.: Aeromechanical optimization of scalloping in mixed flow turbines, Proceedings of ASME Turbo Expo 2021, GT2021-58901, (2021)
- (4) Cuciumita, C., John, A., Qin, N., Shahpar, S.: Structurally Constrained Aerodynamic adjoint optimisation of highly loaded compressor blades, Proceedings of ASME Turbo Expo 2021, GT2021-59717, (2021)
- (5) Itou, S., Oka, N., Furukawa, M., Yamada, K., Ibaraki, S., Iwakiri, K., Hayashi, Y.: Optimum Aerodynamic Design of Centrifugal Compressor using a Genetic Algorithm and an Inverse Method based on Meridional Viscous Flow Analysis, 17th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAC2017), hal-02981000, (2017)
- (6) Walther, B., Nadarajah, S.: Constrained Adjoint-Based Aerodynamic Shape Optimization of a Single-Stage Transonic Compressor, ASME Journal of Turbomachinery, Vol. 135, No. 2, Paper No. 021017, (2013)
- (7) Hansen, N., Ostermeier, A.: Adapting arbitrary normal mutation distributions in evolution strategies: The covariance matrix adaptation, Proceedings of IEEE International Conference on Evolutionary Computation, p. 312-317, (1996)
- (8) Sonoda, T., Yamaguchi, Y., Arima, T., Olhofer, M., Sendhoff, B., Schreiber, H.-A.: Advanced high turning compressor airfoils for low Reynolds number condition – part 1: design and optimization, Proceedings of ASME Turbo Expo 2003, GT2003-38458, (2003)
- (9) Hicks, R. M., Henne, P. A.: Wing Design by Numerical Optimization, J. Aircraft, Vol. 15, No. 7, (1978)
- (10) Ziethen, D. R.: CATIA V5: Macro Programming with Visual Basic Script, 1st Edition, McGraw-Hill Education, (2013)

■ Author ■



Taku AOKI



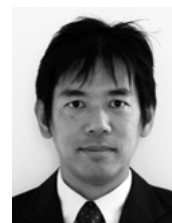
Toshihiro KAMATSUCHI



Takashi SAKAKIBARA



Gaku OKUBO



Hisato TANAKA



Sebastian SCHMITT