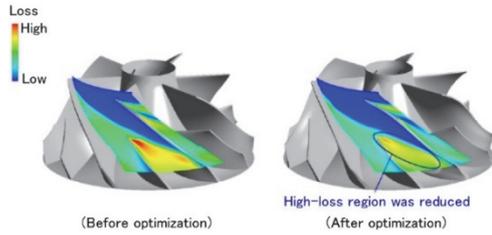


Turbomachinery Blade Design that Simultaneously Optimizes Performance and Strength Using Sensitivity Information



NAO TANIGUCHI*¹ TADASHI KANZAKA*²
 TOM VERSTRAETE*³ MOHAMED HASSANINE AISSA*⁴
 ARNAUD CHÂTEL*⁵

There is a strong trade-off between aerodynamic performance and blade strength in the shape of the blades used in turbomachinery. Designing shapes that satisfy requirements for both characteristics is extremely difficult. In light of this, Mitsubishi Heavy Industries, Ltd. has developed performance and strength multidisciplinary optimization technology using the adjoint method, which is a shape optimization technique, in order to design of high-performance turbomachinery blades while maintaining blade strength. Furthermore, by adding design parameters based on performance and strength sensitivity information, the search range for solutions in optimization was effectively expanded, and the prospect of even higher performance was achieved. This report presents a case study in which the developed technology was applied to centrifugal compressor blades, resulting in higher performance while maintaining blade strength.

1. Introduction

Turbomachinery, a major product of Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI), is used in various industries and supports the foundation of people's lives. Achieving higher performance in turbomachinery is an important mission for MHI, as it leads to the effective utilization of energy resources, improved infrastructure reliability, and ultimately leads to the realization of a carbon-neutral society. In addition, the demands of the turbomachinery market, including downsizing and increased capacity, have grown to enhance product performance, and consequently, possible combinations of design parameters that satisfy these required specifications are extremely limited.

To address such issues, application of optimization calculation technology is effective, and including shape optimization utilizing CFD (computational fluid dynamics) into the design process to improve the performance of blades and other components constituting turbomachinery has become common practice. MHI selects the appropriate optimization methods based on the development target, such as stochastic methods⁽¹⁾ using genetic algorithms and deterministic methods using the adjoint method, etc. Since there has been a tendency to set many complex design parameters in recent years, MHI has been advancing development focusing on deterministic methods, which offer advantages in computational cost.

On the other hand, while existing optimization methods can obtain optimal solutions for aerodynamic performance, the increasing complexity of blade shapes necessitates time-consuming design adjustments to improve reliability in terms of strength and vibration, and as a result, performance degradation and prolonged development cycles have become problematic. In response, measures to limit design parameters, such as blade height and blade thickness, are taken from the viewpoint of blade strength; however, this also prevents the full utilization of optimization potential and stands as a barrier to further performance enhancement. As such, MHI has developed a multidisciplinary optimization technology for aerodynamic performance and blade strength, which are in a strong trade-off relationship, by leveraging their respective sensitivity information. In this way, MHI has realized the creation of turbomachinery that achieves both performance and reliability. This report introduces a case study thereof.

*1 Intelligent Machine Systems Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

*2 Research Manager, Intelligent Machine Systems Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

*3 Professor, Turbomachinery and Propulsion Department, von Karman Institute for Fluid Dynamics

*4 Senior Project Manager, Turbomachinery and Propulsion Department, von Karman Institute for Fluid Dynamics

*5 Research Engineer, Turbomachinery and Propulsion Department, von Karman Institute for Fluid Dynamics

2. Development of multidisciplinary adjoint optimization technology

This report presents a case study in which multidisciplinary adjoint optimization was performed in the fields of performance and strength for the blades of a centrifugal compressor in an automotive turbocharger, as shown in **Figure 1**. The target centrifugal compressor consists of a 6+6 blade open impeller with splitter blades between the full blades.

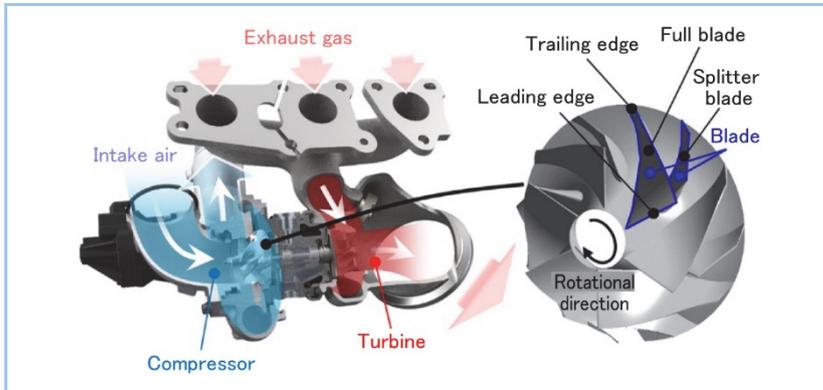


Figure 1 Blades of centrifugal compressor in automotive turbocharger

The adjoint method is a type of deterministic method that solves an adjoint equation linking the governing equations of the target problem with the objective function, and performs optimization based on the sensitivity of the objective function to changes in shape. While it cannot search for a global optimal solution like a stochastic method, it can offer high optimization calculation efficiency and obtain an optimal solution in a short time because the sensitivities for all design parameters can be determined at once. It should be noted that adjoint methods used for general-purpose solvers typically adopt a node-based approach, in which the optimal solution is obtained by directly displacing the surface geometry being evaluated. Here, when considering application to blades, which are the primary aerodynamic components of turbomachinery, the blade tips have an edge shape and the blades are thin. Consequently, depending on the obtained sensitivity information, the blade shape can collapse, resulting in optimization failure.

To address this, as shown in **Figure 2**, a parametric adjoint optimization method was developed, in which blade shape is defined using Bézier curve with control points based on physical design parameters, such as blade angle. By determining the sensitivity of each design parameter and varying the control points according to those sensitivities, it becomes possible to search for the optimal blade without causing shape collapse. The optimization flow in the parametric adjoint optimization is shown in **Figure 3**. Here, α denotes the design parameter, X denotes the entire set of analysis grid points, X_b denotes the surface grid point, U denotes the conserved quantity, J denotes the objective function, and the subscript k denotes the number of iterations of the optimization calculation. Static strength and vibration strength are solved based on CSM (computational structural mechanics).

In parametric adjoint optimization, sensitivity of objective function J with respect to the design parameter α is calculated using the following chain rule.

$$\frac{dJ}{d\alpha} = \frac{dJ}{dX} \frac{dX}{d\alpha}$$

The first term on the right side is determined by solving an adjoint equation where the analysis residual vector is used as a constraint condition, with the compressible RANS (Reynolds Averaged Navier-Stokes) equations used as the governing equations for fluid calculations, and the equations of motion used for static and vibration strength calculations. The second term on the right side represents displacement of the calculation grid points when each design parameter changes infinitesimally, and is calculated using the complex-step method. Sequential quadratic programming is used as the optimization algorithm for the solution search, and the optimal solution is obtained by repeating the optimization flow shown in **Figure 3**, until improvement in the objective function is no longer observed.

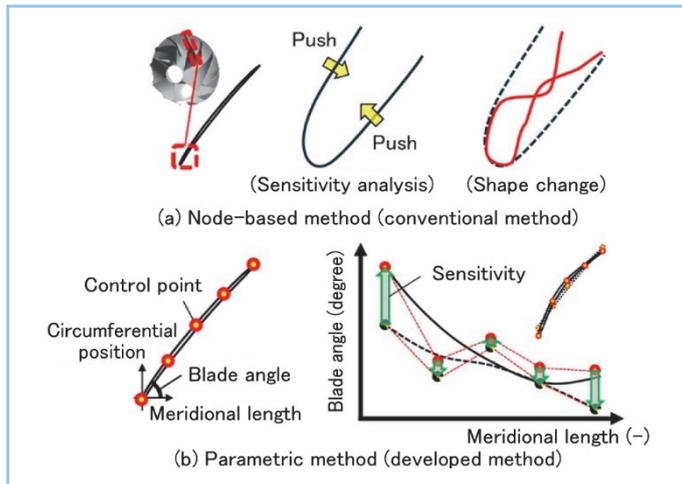


Figure 2 Parameterization of blade shape

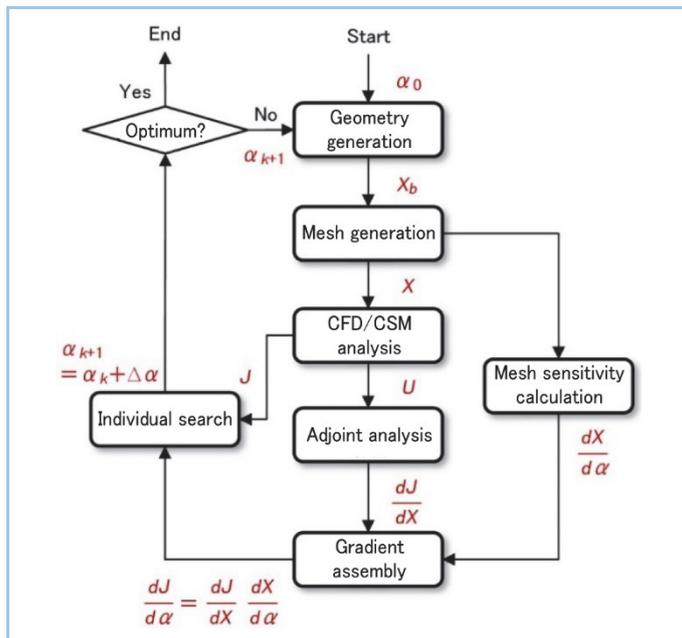


Figure 3 Adjoint optimization flow chart

3. Verification of effectiveness using optimization calculations

3.1 Problem setup for multidisciplinary optimization

To confirm the effectiveness of the developed method, optimization calculations were performed. Computational models are shown in **Figure 4**. For CFD, a single passage model was created using a structured grid of approximately 2.3 million elements, with an inlet pipe and a vaneless diffuser provided upstream and downstream of the blade. For CSM, a single passage model, including nose and back surface geometry, was created using a structured grid of approximately 0.28 million elements.

The fluid simulation was performed using an in-house code. The governing equations were comprised of the continuity, energy conservation, and compressible RANS equations. The advection terms were made higher-order accurate using the MUSCL (monotone upwind scheme for conservation laws) scheme with the Roe method, which is an approximate Riemann solver, while the viscous terms were evaluated using second-order accurate central differences based on the Gauss divergence theorem. For time integration, an Implicit Runge-Kutta method was used, and for the turbulence model, the one-equation Negative Spalart-Allmaras model was used. The structure analysis also utilized an in-house code, solving the governing equations based on a finite element method formulated with hexahedral second-order elements.

In the optimization, the objective function was set to maximize total pressure efficiency as defined at the vaneless diffuser outlet, focusing on the peak efficiency point at the evaluation

rotational speed. Total pressure and total temperature were provided at the CFD inflow boundary, and static pressure was specified at the outflow boundary. In the CSM, von Mises stress and the first order eigenfrequency were solved at the same rotational speed and imposed as constraint conditions on the optimization problem, thereby performing a multidisciplinary optimization.

The three-dimensional blade shape was defined based on the design parameters shown in **Table 1** and **Figure 5**. First, the meridional position of the splitter blade leading edge, the blade angles of the full and splitter blades including the mid-span section, and the fillet radius added to the root of the blade was selected as design parameters (Level 1, 45 parameters). The sensitivity of each evaluation index with respect to the set design parameters is shown in **Figure 6**. The diagrams in the figure visualize sensitivities to total pressure efficiency, von Mises stress, first order eigenfrequency, etc. with red and blue areas indicating the direction of the sensitivity relative to the objective function. These are shown alongside the ideal sensitivity information for cases where blade surface geometry is displaced directly. It can be observed that high sensitivity exists across the entire blade for total pressure efficiency, in the rear and back portions of the blade for von Mises stress, and on the tip side of the full blade leading edge for the first order eigenfrequency. On the other hand, in Level 1, it is confirmed that the blade shape which can be expressed by the design parameters is limited and the ideal sensitivity information is not sufficiently reproduced. Based on these results, the sensitivity information available for optimization is maximized and the total pressure efficiency is further improved by adding control points to blade angles at spans of 40%, 60%, and 85%, where high sensitivity was obtained (Level 2, 88 parameters).

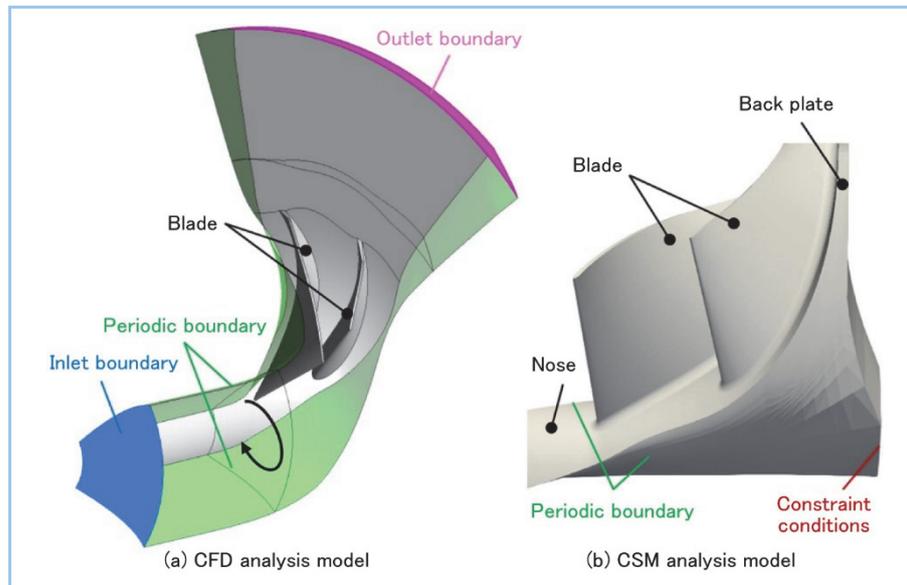


Figure 4 Computational models

Table 1 Design parameters and control points

Design parameter / Control points		Level 1	Level 2
Meridional geometry		2	11
Full blade	Blade angle	15	21
	Fillet R	10	10
	Blade thickness	0	14
Splitter blade	Blade angle	8	8
	Fillet R	10	10
	Blade thickness	0	14
Total		45	88

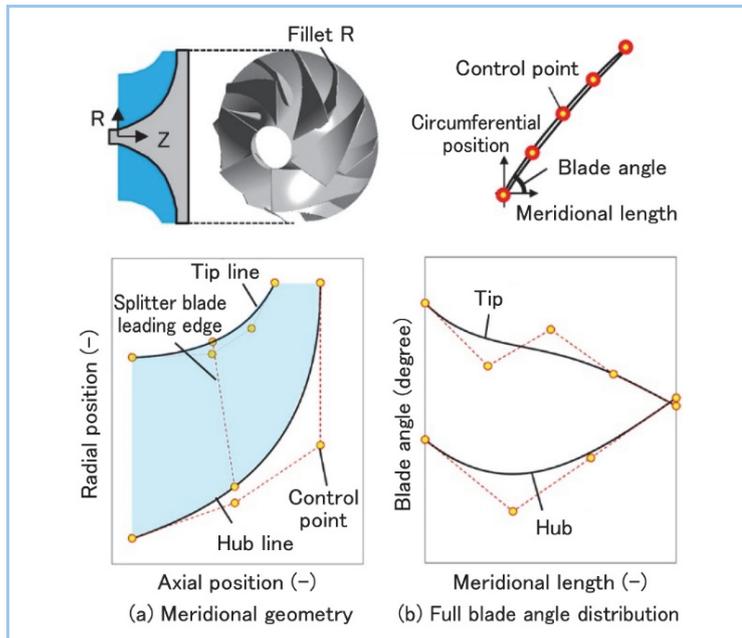


Figure 5 Design parameters for expressing blade shape

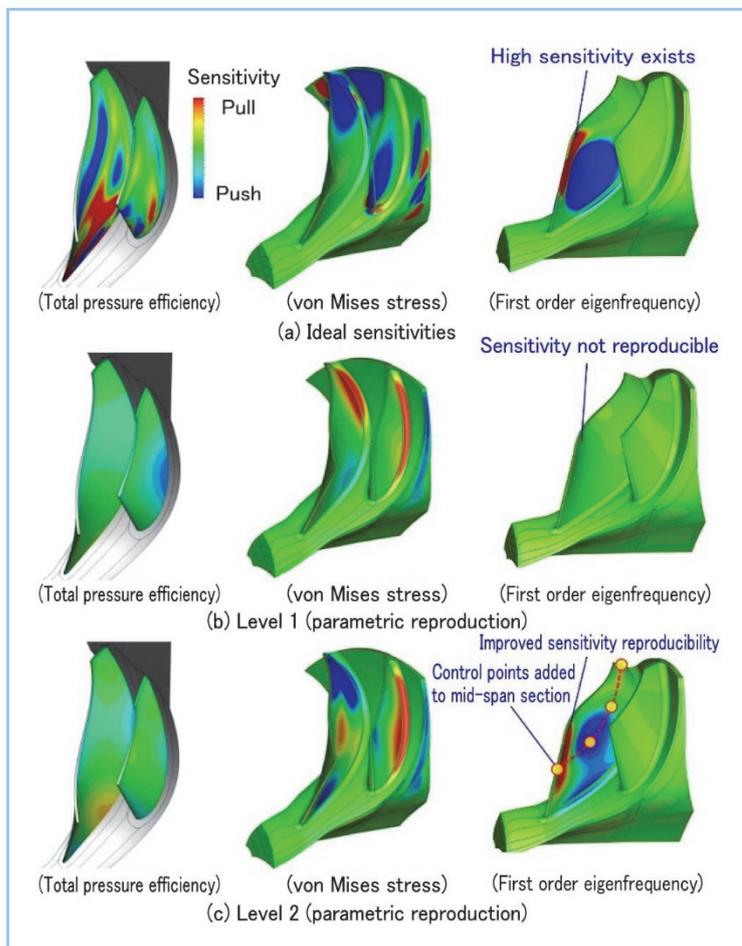


Figure 6 Sensitivity with respect to each evaluation index

3.2 Optimization calculation for improving total pressure efficiency

The optimization calculation history is shown in **Figure 7**. The horizontal axis represents the number of optimization iterations, while the vertical axis shows the improvement in total pressure efficiency relative to base shape, variation in von Mises stress, and variation in the first order eigenfrequency.

Level 1 exhibits a +2.0% point improvement in total pressure efficiency while maintaining equivalent von Mises stress and first order eigenfrequency relative to the base shape, demonstrating successful optimization that balances total pressure efficiency and blade strength. Conversely,

imposing constraints related to blade strength limits the extent to which the shape can be changed through optimization, resulting in a tendency for smaller gains in the total pressure efficiency improvement.

Next, based on the optimal solution for Level 1, additional design parameters were incorporated, and Level 2 optimization was subsequently performed. As a result, Level 2 achieved a 2.3% point improvement in total pressure efficiency compared to Level 1 while maintaining an equivalent blade strength. It is considered that the sensitivity of the optimization could be utilized by adding effective control points based on the shape sensitivity. In particular, the numerical value was improved by utilizing the sensitivity of the first order eigenfrequency, and the blade vibration characteristics were improved.

The Mach number and losses near the tip section are shown in **Figure 8**. In Level 2, compared with Level 1, the shock wave at the leading edge of the full blade was reduced by reducing the blade tip inlet diameter based on the flow and adjusting the leading edge blade angle. Furthermore, a further reduction in the high-loss region at the splitter blade inlet due to the optimization of the meridional surface curvature of the blade tip line in addition to the blade angle and blade thickness distributions was confirmed. Thus, technology that enables further performance enhancement could be established by adding design parameters based on sensitivity information, even when improvement in total pressure efficiency through optimization slows.

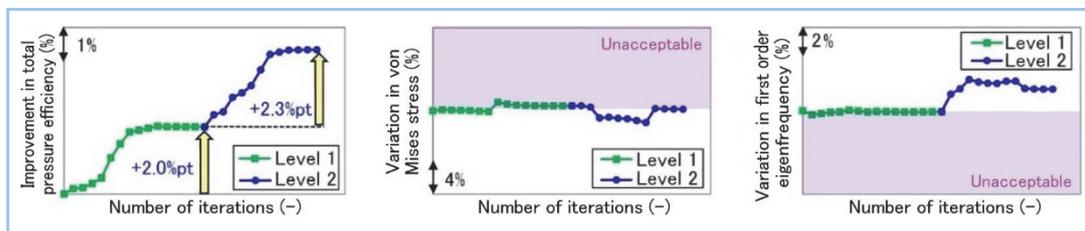


Figure 7 Optimization calculation history

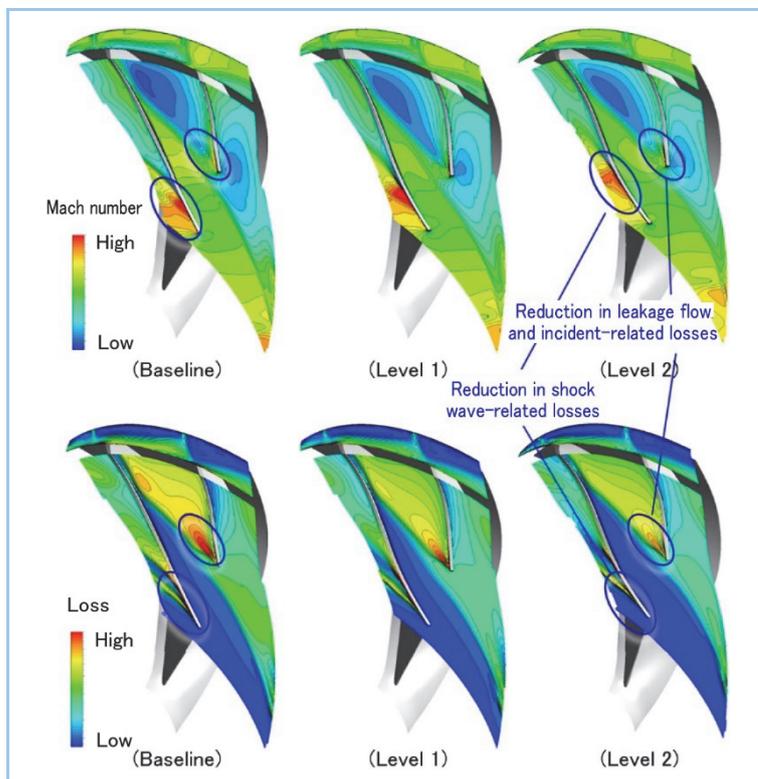


Figure 8 Comparison of internal impeller flow

4. Conclusion

The technology which extracts and optimizes the sensitivity of the blade strength by the adjoint method in addition to the aerodynamic performance was developed, and the acquisition of the high-performance blade shape after the blade strength was established was enabled. In addition, when the amount of performance improvement becomes limited due to the constraint of strength, further performance enhancement was achieved by adding design parameters for maximally utilizing the sensitivity information, and the prospect that performance and reliability can be compatible at a high level was obtained.

The environment surrounding the industrial sector is changing rapidly, and turbomachinery, which is essential to this sector, is also facing strong demands for higher-performance that meet the needs of the market. By utilizing the developed optimization technology, MHI will achieve early performance enhancement of turbomachinery, and contribute to the development of society by leading the way towards improved energy utilization efficiency.

The adjoint optimization technology presented in this report was jointly developed with the von Karman Institute for Fluid Dynamics (Belgium). The authors would like to express their gratitude to Professor Tom Verstraete, Dr. Mohamed Hassanine Aissa, and Dr. Arnaud Châtel of the Institute.

References

- (1) T. Yokoyama et al., Advanced Aerodynamic Design Technologies for High Performance Turbochargers, Mitsubishi Heavy Industries Technical Review, Vol.54, No.1 (2017)