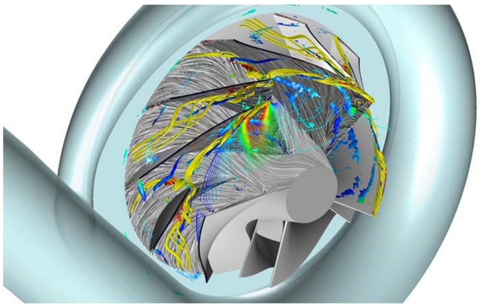
Advanced Aerodynamic Design Technologies for High Performance Turbochargers



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In recent years, the fuel efficiency of automobiles has been enhanced through the supercharged downsizing of engines for passenger vehicles. To meet increasingly stricter fuel efficiency regulations, however, turbochargers that have a wider operation range and are highly efficient in comparison with existing ones are strongly required. For this reason, Mitsubishi Heavy Industries, Ltd. (MHI) worked on the clarification of the internal flow phenomenon and design improvement through large-scale flow analysis of the turbine in consideration of the engine exhaust pulsation and visualization of the flow inside the compressor recirculation flow path, with the purpose of enhancing the performance of the compressor and the turbine that govern the performance of the turbocharger. In addition, a design optimization method was applied to plan a concept to enhance the efficiency of the compressor impeller and execute design improvement of the piping for a two-stage turbocharger. As a result, we enhanced the efficiency of a variable capacity turbine at minimal flow, the efficiency of a twin-scroll turbine and the extension of the operation range and efficiency of a compressor.

1. Introduction

As a measure against global warming, the reduction of CO_2 greenhouse gas is being promoted all over the world. Strict fuel consumption regulations have also been imposed on passenger vehicle engines, and are planned to be strengthened further in the future. One of the methods to enhance the fuel efficiency of an engine is supercharged downsizing using a turbocharger. The use of this method has quickly expanded to gasoline engines and diesel engines. In addition, the use of variable geometry turbines, electric compressors and two-stage turbochargers is increasing, and supercharging systems are becoming increasingly sophisticated in order to obtain high supercharging efficiency and high response in a wide range of engine operation points. Therefore, in addition to the enhancement of efficiency of single turbocharger units and the expansion of the operation range, the enhancement of the performance of the entire supercharging system is also required.

MHI has been working on enhancing the efficiency of turbochargers utilizing numerical flow analysis and internal flow measurement. However, it was necessary to analyze the flow structure in detail for the further enhancement of efficiency. For this reason, we worked on a detailed analysis of the internal flow using whole turbine flow analysis of a variable capacity turbine in the small nozzle opening region, unsteady flow analysis of a twin scroll turbine under an engine exhaust pulsation condition and stereo PIV (particle image velocimetry) measurement capable of measuring unsteady three-dimensional flow velocity in a two-dimensional plane. In addition, a new concept geometry to improve performance was established based on each obtained loss structure, and the enhancement of efficiency was verified using analysis and performance tests. Furthermore, we worked on short-time design optimization of complicated three-dimensional flow fields using an ANN-DE (artificial neural network - differential evolution) optimization method and an Adjoint method. This paper presents these efforts for the enhancement of turbocharger performance.

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2. Large-scale flow analysis

2.1 Variable geometry turbine

A variable geometry turbine has a rotatable nozzle vane with a throat area that is variable on the upstream side of the turbine rotor blade and therefore can control the turbine flow characteristics. A turbine can be driven in a wide range of engine rotation speeds from the low rotation speed region. In recent years, however, the enhancement of the performance at minimal flow is required in order to obtain the supercharging pressure from a lower engine rotation speed. When the turbine efficiency remains high on the high flow side, then supercharging pressure control becomes difficult at a high engine rotation speed in some cases, and therefore an increase of the maximum flow and the suppression of the turbine efficiency on the high flow side are also necessary.

When the flow rate is minimal, the opening of the nozzle vane becomes very small and the effect of the leak flow from the nozzle side clearance on the nozzle main stream becomes large. In addition, deviation between the flow speed at the nozzle outlet and the circumferential speed of the rotor blade expands and a large-scale separation flow is generated at the leading edge of the rotor blade, resulting in a complicated three-dimensional flow. We worked on a detailed analysis of the flow field using flow analysis in consideration of the narrow space of the side clearance targeting all areas including the scroll, nozzle vane and turbine rotor blade.

Figure 1 shows the flow line in the small nozzle opening region and the flow speed vector distribution at the leading edge of the rotor blade. In the case of an existing nozzle shown in Figure 1(a), the flow did not spread inside the rotor blade because of the minimal flow, and tends to be biased to the shroud by centrifugal force. For this reason, the blade load is not maintained by the entire blade face and the turbine efficiency decreases. In addition, because the flow speed at the rotor blade outlet becomes high on the shroud side and low on the hub side, the generated mixing loss increases due to the non-uniform flow distribution. Focusing on this flow, we invented a nozzle structure with a taper located on the shroud side. This concept changes the direction of the flow at the rotor blade inlet to the hub side as shown in Figure 1(b), and it was confirmed that the flow inside the rotor blade spreads to the hub side. **Figure 2** shows the results of the performance test for the verification of this concept. It could be confirmed that this concept enhances the turbine efficiency by 2.2% in the small nozzle opening and minimal flow region in comparison with the existing nozzle, while suppressing the turbine efficiency on the high flow side.

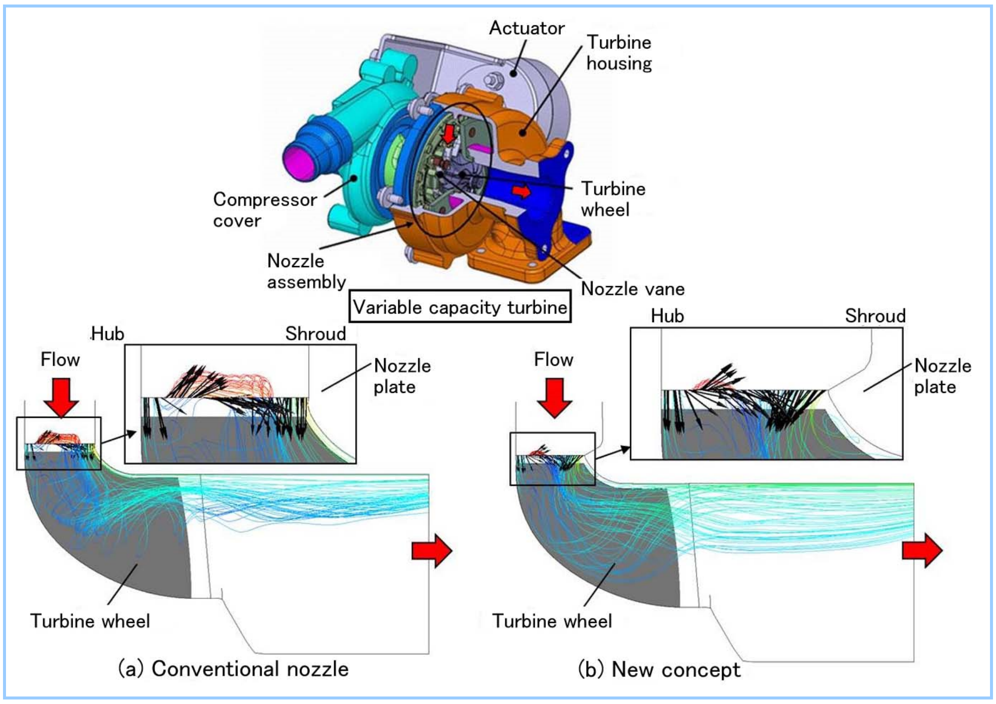

Figure 1 Flow line and flow speed vector distribution at leading edge of rotor blade (small nozzle opening)

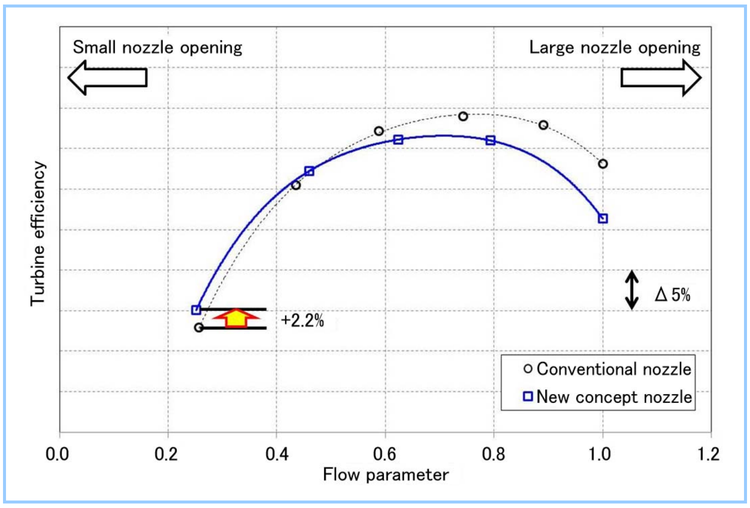

Figure 2 Results of VG turbine performance test

2.2 Twin scroll

One of the technologies for the enhancement of turbine output at a low engine speed is a twin scroll. The twin scroll effectively utilizes exhaust pulsation from the engine by axially separating a turbine scroll cross section into two and connecting the two to different engine cylinders. On the other hand, the twin scroll has an asymmetric cross section because of the constraint of size reduction, and there is the issue where the inflow efficiency on the rear side decreases in comparison with the front side. This issue must be improved because an efficiency difference during partial inflow causes performance deviation between engine cylinders.

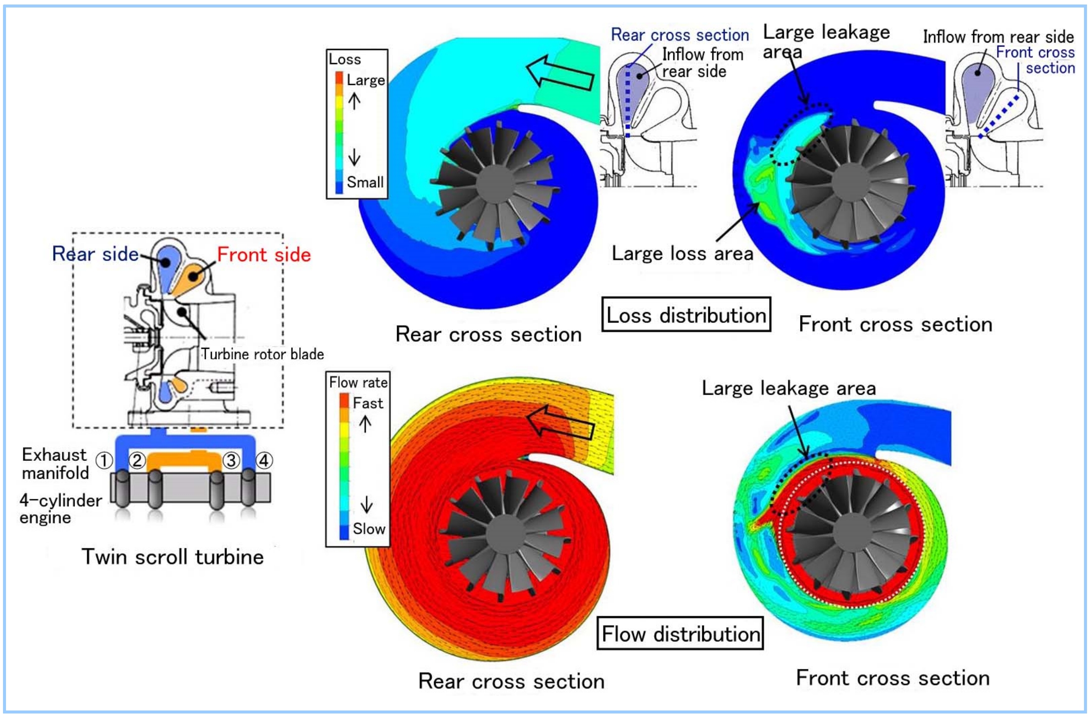

Figure 3 Turbine scroll internal flow in rear side inflow

On an engine, because exhaust pulsation flows into the two separated scrolls alternately, strong unsteady flow occurs on the upstream of the turbine rotor blade where they join together. We worked on unsteady flow analysis using the exhaust pulsation as a boundary condition and understood the flow issue where a loss caused by leak flow on the front side occurred, particularly in the case of rear-side inflow as described in a previous paper.[1] **Figure 3** shows the loss distribution and the flow distribution of the rear cross section (inflow side) and the front cross section (non-inflow side) in the rear side inflow. It could be confirmed that leak flow from the rear side to the front side occurred and a large-scale loss region was generated on the front side. In the case of a twin scroll, exhaust pulsation flows into the rear side and the front side alternately and generates a difference in pressure between the two sides, resulting in the occurrence of leak flow to the low pressure side. We focused on the flow structure and invented an outlet shape that can suppress leak flow from the rear side to the front side, and obtained an estimated enhancement in efficiency of 1.9% in flow analysis. As shown in **Figure 4**, an evaluation of the turbine heat insulation efficiency was executed in a performance test, and it was confirmed that the performance in the rear-side inflow was enhanced by 2.1% as expected. The new shape also improves the flow balance and the efficiency balance between the front-side inflow and the rear-side inflow, and performance enhancement on an engine can be expected. In this way, unsteady flow analysis in consideration of exhaust pulsation was verified to be effective.

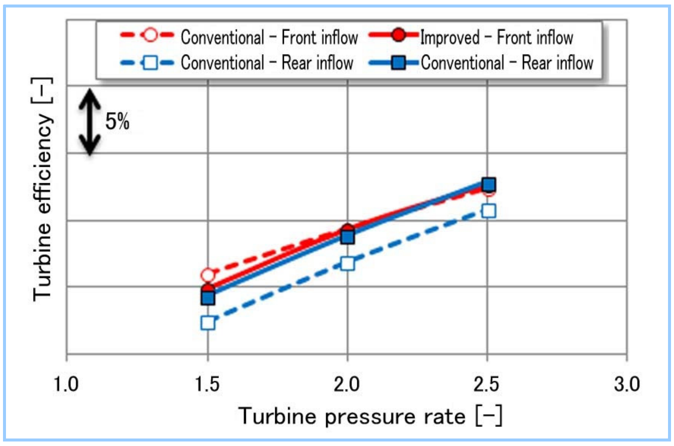

Figure 4 Results of twin-scroll turbine performance test

3. Three-dimensional internal flow measurement

A casing treatment is used as one of the compressor operating range extention devices. The casing treatment consists of a slit installed near the impeller throat on the compressor cover, a recirculation flow path, and several struts that forms the flow path. In the low flow rate condition near the surging limit, part of the flow into the impeller recirculates through the slit to the upstream pipe to increase the flow on the upstream of the impeller and suppress leading edge separation. This effect allows the improvement of the pressure characteristics and the reduction of the surging limit flow. **Figure 5** compares compressor performances with the number of struts in the recirculation flow path when changed. It is known that the surging flow varies depending on the number of struts, and it is necessary to analyze the flow in the recirculation flow path to understand the phenomenon. Because the flow near the casing treatment is a mix of normal flow and reverse flow and has a strong swirling flow due to the effect of the impeller, the flow has a strong three-dimensionality. Therefore, we used stereo Particle Image Velocimetry (PIV), which can measure three-dimensional flow components in a two-dimensional plane to work on a detailed analysis of the internal flow.[2]

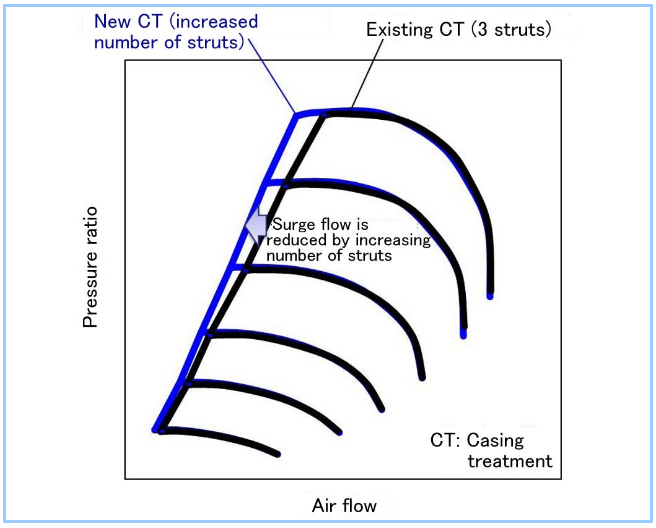

Figure 5 Results of casing treatment performance test

Figure 6 shows the targeted compressor. In this measurement, three dimensional velocity components at the exit of the circulation flow path were measured for each of (1) the three-strut configuration and (2) the thirteen-strut configuration. **Figure 7** shows the color contour of the axial flow velocity at the exit of the circulation flow path and the in-plane flow vector. The flow velocity region in blue represents the circulation from the slit. It was confirmed that circulation flow occurred with both the three-strut configuration and the thirteen-strut configuration. In the case of the three-strut configuration, large swirling flow occurred in the center of the flow path. This indicates that swirling flow passing through the slit from the impeller remains even at the outlet of the circulation path. In the case of the thirteen-strut configuration, on the other hand, it was confirmed that the swirling flow in the flow path was suppressed. Consequently, it was verified that the number of struts affected the swirling flow in the circulation flow.

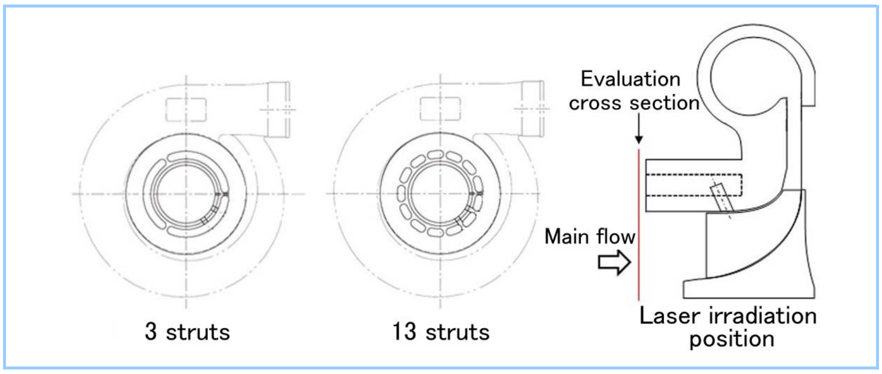

Figure 6 Measurement of casing treatment internal flow

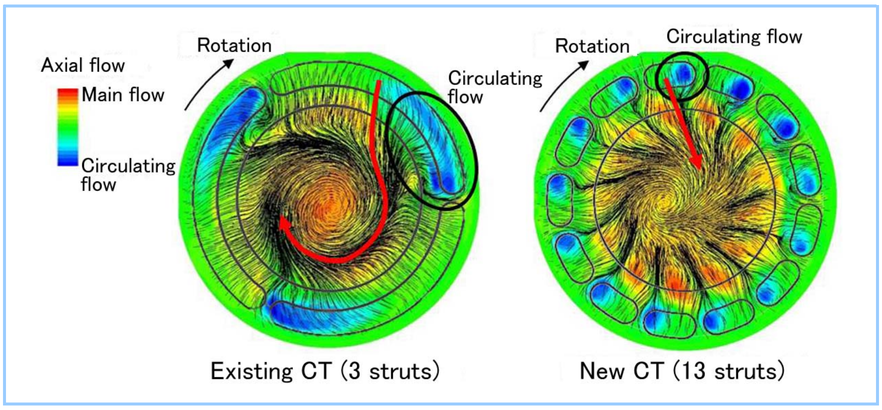

Figure 7 Measurement results of casing treatment internal flow

Based on the results of the internal flow measurement described above, we invented a new device that controls the swirling flow.[3] **Figure 8** shows a bird's eye view of the new device. The new device has a guide vane near the circulation path outlet of existing casing treatment. The guide vane is installed in the direction opposite that of the impeller rotation and controls the swirling flow occurring in the circulation flow path.

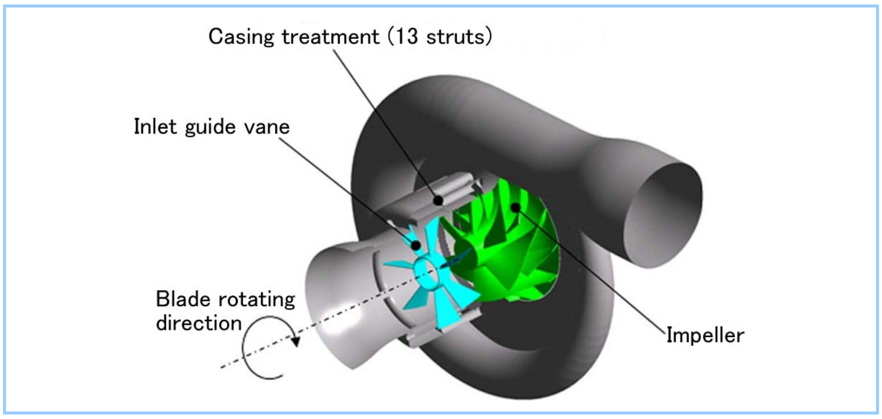

Figure 8 Bird's eye view of new device

Figure 9 shows the distribution of the Mach number around the impeller tip at near surging point. In the case of the existing casing treatment, the stall of the blade was suppressed, but the distribution of the Mach number on the negative pressure surface of the blade was non-uniform in the circumferential direction. In the case of the new device, the velocity difference between the suction surface and pressure surface of the blade was large, and therefore the distribution of the Mach number was uniform in the circumferential direction and the blade load could also be maintained. The surge limit flow was evaluated by a performance test and it was confirmed that the new device reduces the surge limit flow in the entire region from a low pressure ratio to a high pressure ratio. Consequently, the new device was verified to be effective.

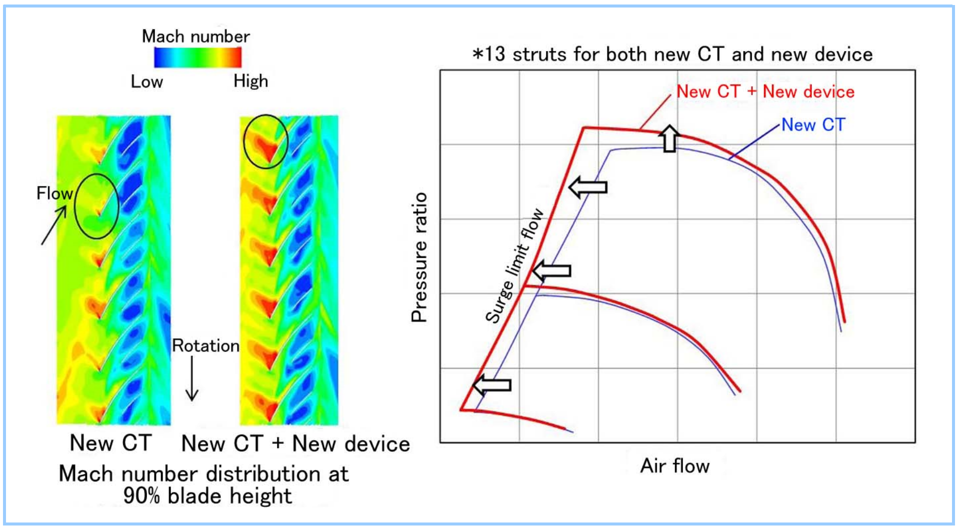

Figure 9 Internal flow and performance of new device

4. Design optimization method

4.1 Neural network and optimization algorithm

For engines of passenger vehicles, a supercharging pressure even at a low engine rotation speed is required in order to compensate for the lowered engine torque due to downsizing. Accordingly, it is necessary to reduce compressor surge flow and improve the efficiency near surging. The design of the flow field near surging requires a significant amount of time because the enhancement of efficiency is difficult due to separation and stall of the flow inside an impeller, and at the same time the suppression of the decrease in efficiency and the reduction of the flow on the choke side is also required.

MHI has already established a design optimization method capable of quick performance evaluation and optimized shape extraction, combining the performance and strength evaluation using ANN (artificial neural network) and the individual search using DE (differential evolution). As described in a previous paper,[4] improvement in efficiency was carried out by using a 1-pitch impeller. This time, we reconsidered the design parameters and the evaluation function, and worked on the expansion of the operation range through design optimization of multiple operation points.

Figure 10 compares impeller shapes and internal flow between before and after optimization. While the shape before optimization has a straight leading edge, the shape after optimization has a three-dimensionally bent blade leading edge. A comparison of loss distribution near the tip indicates that the loss region on the suction surface was significantly reduced by the optimization.

Figure 11 shows the results of a performance test. The results indicate that the pressure ratio characteristics were improved, the surge limit flow was reduced and the compressor operating range was extended by the optimization. Consequently, the operation range extension method through optimization using ANN and DE was verified to be effective.

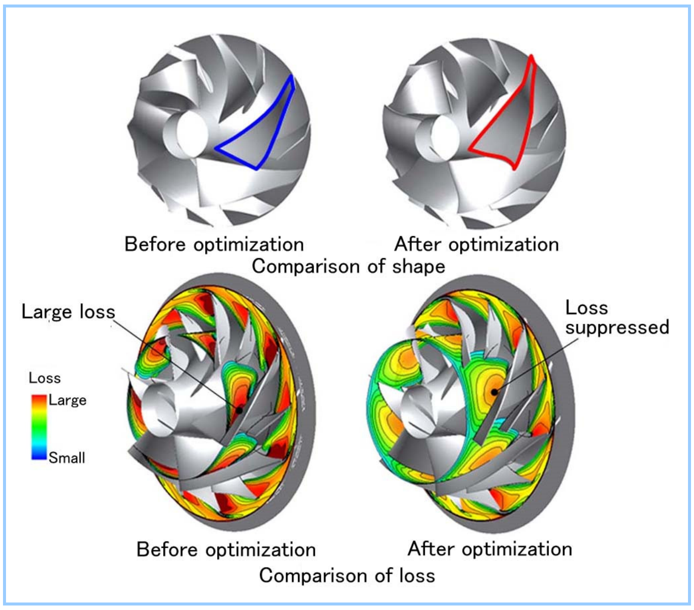

Figure 10 Comparison of compressor impeller shape and internal flow between before and after optimization

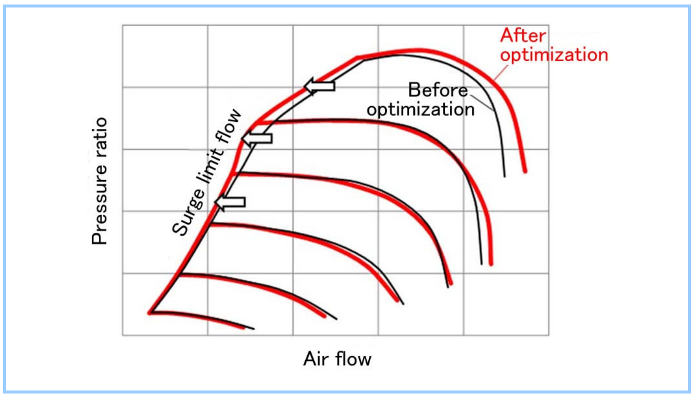

Figure 11 Comparison of performance test results between before and after optimization of compressor impeller

4.2 Adjoint method

Because of the constraint of the engine layout, the adoption of a two-stage turbocharger, etc., the shape of intake and exhaust pipes that affects the turbocharger performance has become sophisticated and has caused the reduction of the operation range and the degradation of efficiency. The shape of pipes depends on the engine specifications of customers, and therefore flow issues such as pressure loss vary on a case-by-case basis. For this reason, we worked on design optimization of a compressor scroll and two-stage turbocharger pipes using the Adjoint method.

The Adjoint method (adjoint variable method), one of the deterministic optimization methods, optimizes a shape by obtaining sensitivity of the design variable to the objective function. This method cannot search globally for an optimum solution in comparison with a probabilistic optimization method (such as an evolutionary algorithm described above), but can obtain gradients of objective functions for all design variables at one time (can perform optimization using all contact points that represent the shape as design variables) and it has a high calculation efficiency that advantageously allows optimization in a short amount of time.

(1) Compressor scroll

Figure 12 shows the shapes of the target compressor scroll before and after optimization and the results of internal flow analysis. This compressor scroll has a layout with a discharge port that is bent 90 degrees in the rotation axis direction. Such a layout has been increasing in recent years, but the bent part causes the generation of flow distortion and an increase of pressure loss. The optimized shape has a reduced curvature of the bent part and therefore the flow is improved. In addition, the optimized shape that the cross-sectional shape of the scroll changes three-dimensionally in the circumferential direction allows the recirculation flow generated in the scroll to be smoothened and the recirculation loss to be reduced. As a result, it was expected that the optimized scroll, in comparison with its original shape, would reduce the pressure loss coefficient in the entire operation range and enhance the efficiency. **Figure 13** shows the performance test results. The performance enhancement effect of the optimized scroll was also verified in a test where the efficiency was enhanced by up to 1.3% while the operation range remained unchanged.

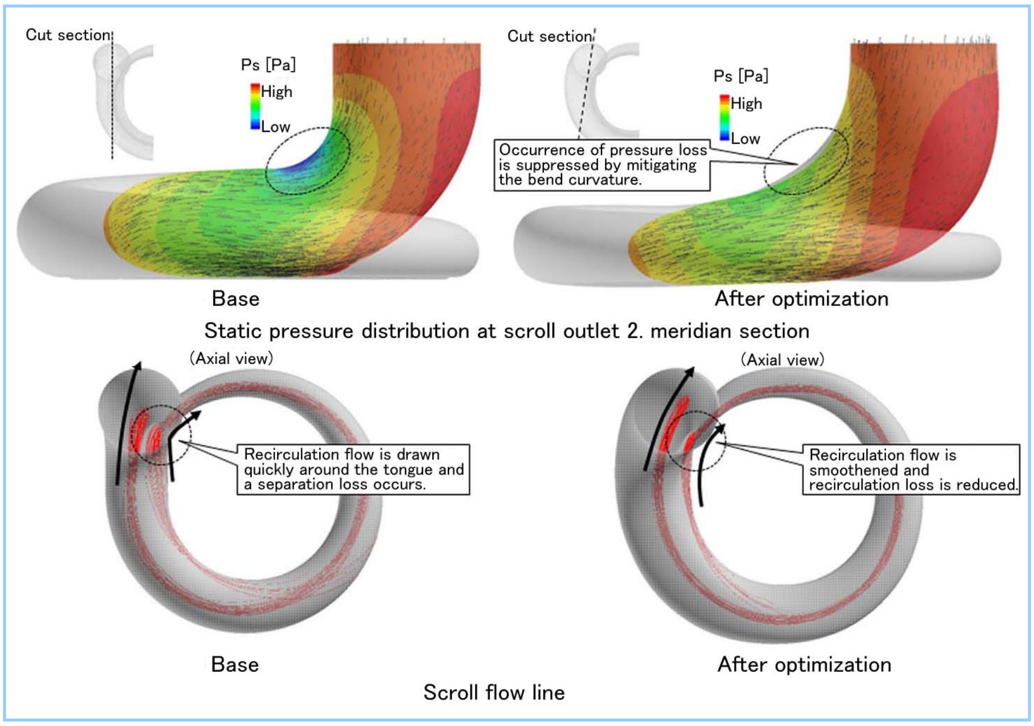

Figure 12 Comparison of compressor scroll shape and internal flow between before and after optimization

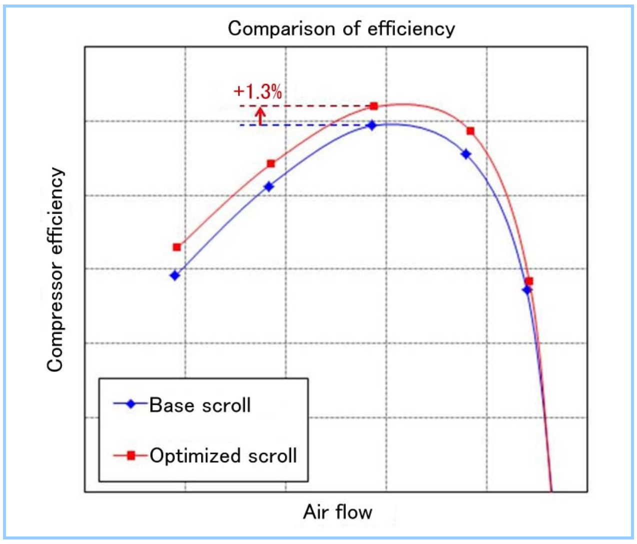

Figure 13 Comparison of performance test results between before and after optimization of compressor scroll

(2) Two-stage turbocharger pipes

A two-stage turbocharger, which is a combination of two turbochargers of a high-pressure stage and a low-pressure stage, can provide supercharging pressure at a wide range of engine rotation speeds. Because two turbochargers are housed in a narrow and small space in the engine compartment, there is the issue where performance is degraded by the multiple high-curvature bent parts of the pipes as shown in Figure 13. Therefore, the shapes of the two-stage turbocharger pipes were optimized using the Adjoint method.

Figure 14 compares the shapes and the internal flows between before and after optimization. Section 2, which leads from the outlet of the high-pressure stage turbine to the confluence of the bypass valve, had a sharp bend just downstream of the high-pressure stage outlet and separation occurring thereat. However, the separation was suppressed by the optimization that secured the length of the high-pressure turbine outlet and the expansion of the area of the bent part. Section 3, which is the confluence of the bypass line, generated strong swirling flow in the clearance when the bypass valve was closed. However, the swirling flow was suppressed by the optimization that reduced the curvature of the high-pressure stage side confluence. **Figure 15** shows the performance analysis results. The effectiveness of the pipe shape optimization using the Adjoint method was verified in the analysis where the pressure loss coefficient was reduced by 2%, 45% and 48% at Sections 1, 2 and 3, respectively, under the condition of the valve being closed, and the overall efficiency was enhanced by 1.9%.

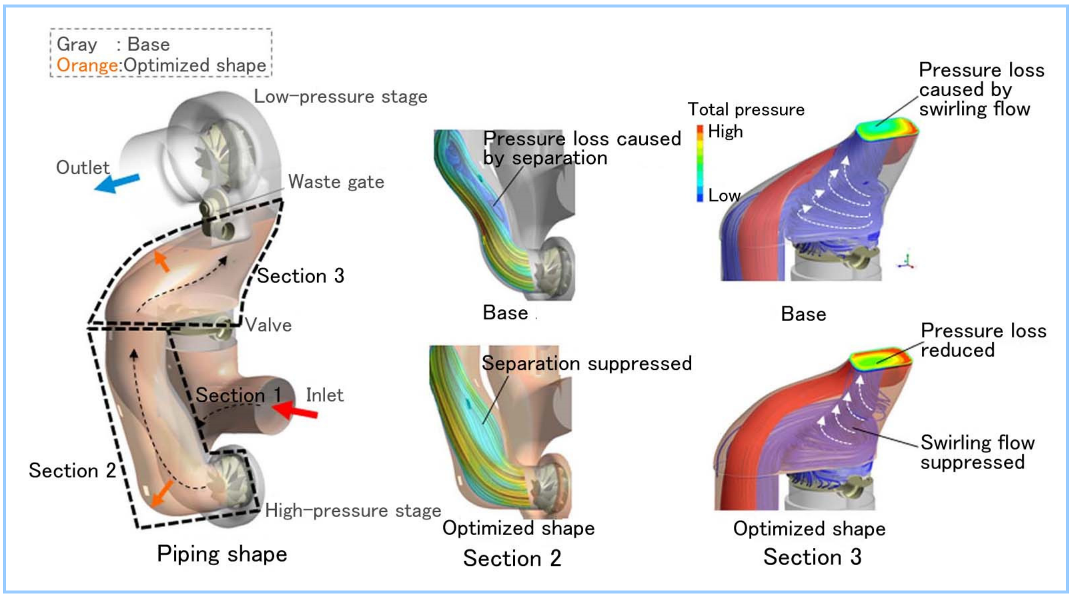

Figure 14 Comparison of two-stage turbine shape and internal flow between before and after optimization

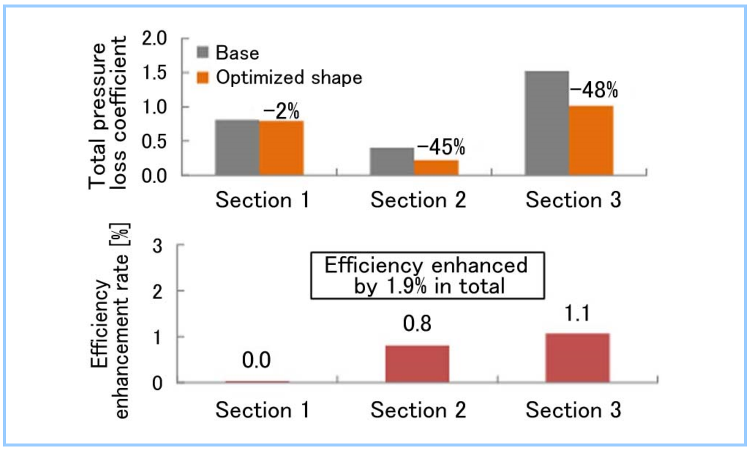

Figure 15 Comparison of performance analysis results between before and after optimization of two-stage turbine

5. Conclusion

We worked on a detailed analysis of internal flow and the improvement of design using large-scale flow analysis, three-dimensional internal flow measurement, and design optimization in order to enhance the performance of turbochargers. In the large-scale flow analysis, the loss mechanism on an actual engine was understood and enhancement in efficiency was attained through the setting of a wide range and detailed areas and in consideration of the unsteady conditions of the engine exhaust pulsation. In the three-dimensional internal flow measurement of a casing treatment, the flow structure of a complicated three-dimensional flow field where normal, reverse and swirling flows were mixed was visualized, which led to the development of new devices. In design optimization, we worked on design improvement of compressor impellers and two-stage pipes that had many design variables, resulting in the improvement of the internal flow in a short amount of time and enhancement in efficiency.

Because the trend of strengthening regulations related to engines for passenger vehicles will continue into the future, passenger vehicle manufacturers are assuming various developments including the motorizing of powertrains, and it is expected that necessary supercharging technologies will continuously change. We are willing to promote the swift and innovative development of turbochargers through analysis capabilities that continue to evolve year after year, internal flow measurement technologies that are advancing and design optimization methods to further develop aerodynamic design technologies.

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