Noise Reduction Technology for Automobile Double Scroll Turbochargers

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In response to recent CO_2 emissions regulations, the compatibility of acceleration performance and fuel efficiency improvement is indispensable as a product quality, and turbochargers are required to provide high boost pressures to generate high torques at low engine speed ranges. Double-scroll turbines, which have two flow passages and a valve, can achieve performance characteristics similar to single-scroll turbines by opening the valve at high engine speed ranges while realizing the performance characteristics of multi-entry turbines in low engine speed ranges. However, the two passages cause pressure distribution in the circumferential direction of the turbine, which results in problematic excessive aerodynamic noise. Mitsubishi Heavy Industries, Ltd. (MHI) has achieved a significant reduction in the noise by utilizing analytical technology and testing verification, and this report describes the results of our initiatives.

1. Introduction

Passenger car turbochargers have a turbine that rotates by recovering the engine exhaust gas energy and drives the compressor impeller installed coaxially to supply compressed air to the engine. Conventional turbochargers use a single-scroll turbine, whose turbine rotor blade is connected to the engine exhaust pipe using a single pipe. Since single-scroll turbines are designed to achieve the rated output at high engine speed ranges, the boost pressure decreases at low engine speed ranges due to the reduced exhaust gas flow velocity. As methods to improve performance in both low-speed and high-speed ranges of the engine, variable geometry turbines with variable mechanisms and multi-entry turbines that actively utilize the exhaust pulsation of the engine have been developed. This report describes the product development status of a double-scroll turbine, one type of multi-entry turbines, that achieves both aerodynamic and low-noise performance.

2. Double-scroll turbine

A double-scroll turbine is one type of multi-entry turbines. In the case of 4-cylinder engine, multi-entry turbines have a scroll in the turbine housing that is divided into two flow passages, each of which is independently connected to the exhaust port of the engine. By combining the #1 cylinder with the #4 cylinder and the #2 cylinder with the #3 cylinder, it is possible to reduce the exhaust interference of the engine and to achieve higher boost pressure than a single-scroll turbine by introducing gas into only one side of the scroll (partial-admission).

Figure 1 compares two types of multi-entry turbines: a twin-scroll turbine and a double-scroll turbine. The scroll of twin-scroll turbines is divided into two in the axial direction, and of double-scroll turbines in the circumferential direction.

In the twin scroll turbine, the clearance is possible between the tip of the dividing wall and the rotor blade tip, but it is difficult to keep this clearance small while ensuring manufacturability and

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strength, and gas leakage from one scroll to the other scroll occurs in the whole circumference of the rotor blade. Since there is no dividing wall in the double scroll turbine, and it is relatively easy to reduce the clearance formed only at the end of the scroll (tongue) position, it is possible to both secure manufacturability and strength and reduce gas leakage, and it is possible to obtain higher boost pressure than that of the twin scroll turbine. On the other hand, in the engine low speed range, the Blade Passing Frequency (BPF) noise becomes higher than that of single scroll turbine and twin scroll turbine because the pressure difference before and after the rotor blade tip passes through the tongue part is large from the effect of the exhaust pulsation, and reducing BPF noise has been a major issue, especially for vehicles that require quietness.

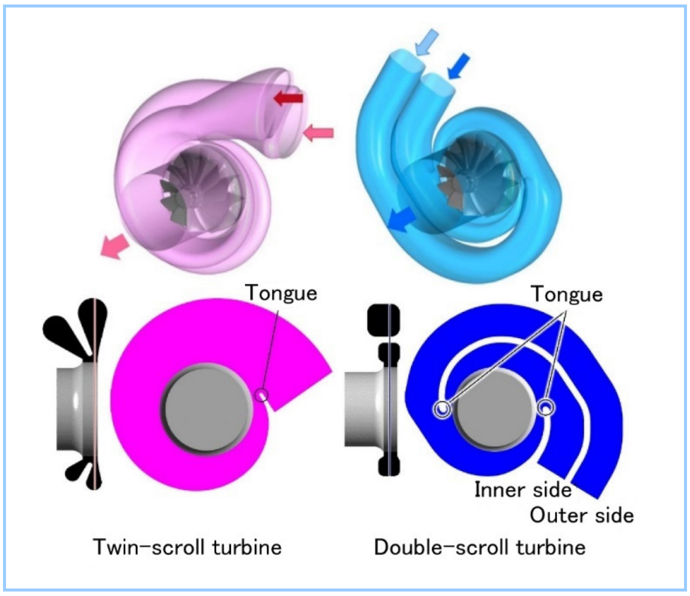

Figure 1 Split-scroll turbine

3. Reduction of turbine aerodynamic noise

In order to reduce the problematic aerodynamic noise of double-scroll turbines, we first conducted Computational Fluid Dynamics (CFD) and acoustic analysis to elucidate the noise generation mechanism and identify the location of the sound source. For the CFD analysis, a general-purpose three-dimensional viscous flow analysis code ANSYS CFX was used, and the k-ω SST model was used for the turbulence model. Using an analytical mesh prepared by modeling the region from the inner and outer scrolls to the turbine rotor blade, unsteady CFD analysis was performed to evaluate the flow. The acoustic analysis utilized general-purpose software MSC Actran to calculate sound sources based on Mohring analogy and to analyze the propagation, using as input conditions the flow field information such as the flow velocity and density obtained from the CFD analysis. Based on the results, we elucidated the mechanism of noise generation, identified the location of major noise sources, and formulated a countermeasure policy.

Figure 2 shows the flow velocity distribution obtained from the CFD analysis and sound pressure level distribution obtained from the acoustic analysis. The conventional specification, which had a problem with noise, had a small clearance between the tongue and turbine rotor blade, causing large pressure fluctuations due to interference between the turbine rotor blade and the wakes generated from the tongue. The acoustic analysis results also showed a trend that the sound pressure level near the tongue was high, and the main cause of the increased noise was estimated to be potential interference at the tongue. In addition to the tongue, the sound pressure level tended to be high at circumferential positions of the turbine rotor blade, and it was estimated that the pressure fluctuation caused by the passage of the blades was also a cause of the increased noise.

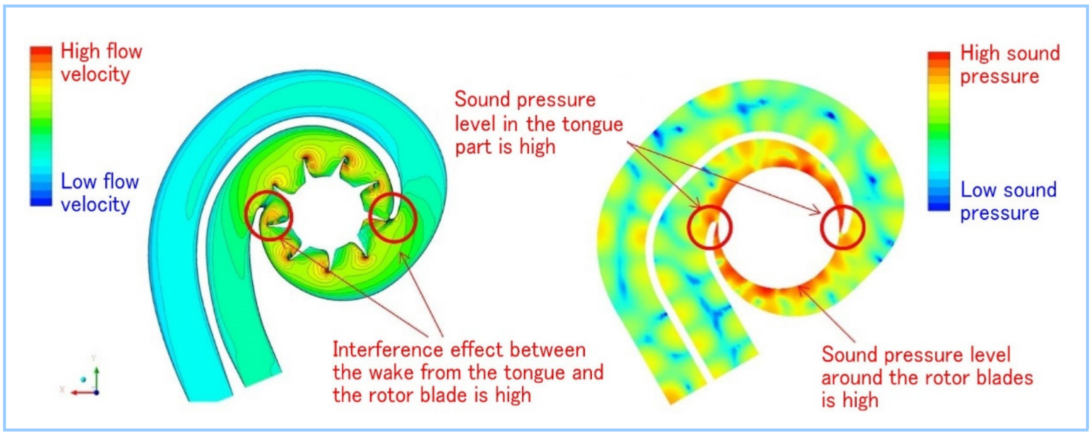

Figure 2 Flow velocity and sound pressure level distribution of conventional specification

From the above, in order to reduce the aerodynamic noise of the turbine, the following were attempted: (i) mitigation of the potential interference of the tongue part and (ii) design of the countermeasure specification which can realize the reduction of the pressure fluctuation with the blade passage. As for (i), by expanding the clearance between the tongue and the turbine rotor blade and optimizing the shape of the tongue, the specification which can both maintain the turbine performance while realizing the noise reduction was examined (the effect on the turbine performance is described in detail in Chapter 4). Regarding (ii) the load per blade was reduced by optimizing the blade shape and number of blades, and the strength of the sound source was reduced. The effect of the above items was verified using CFD analysis and acoustic analysis technology, and the new turbine specification which can realize the noise reduction was planned based on the analysis result, and the reduction effect was evaluated in the actual turbocharger testing. The test was conducted on a turbine test bench at MHI Research & Innovation Center (Nagasaki District), and the turbine BPF noise, which is a frequency component determined by the turbine speed and the number of blades, was evaluated. **Figure 3** illustrates the testing overview. We placed several microphones around the turbocharger to comprehensively obtain noise data, and thus conducted evaluations while eliminating as much as possible the effects of measurement errors caused by differences in the sound directivity. **Figure 4** is the comparison of the obtained test results of the sonagram analysis of turbine BPF noise between the turbine specifications before and after taking the measures. In each result, the horizontal axis represents the turbine speed [rpm] and the vertical axis represents the frequency [Hz], and the noise level is indicated by a color contour. It can be estimated that the conventional-specification turbine, before taking the measures, generated a significant turbine BPF noise with a higher level compared to the noise in surrounding frequency band which could be problematically harsh noise. On the other hand, the new-specification turbine, after taking the measures (employing the expanded tongue clearance, optimized blade shape, etc.), reduced the BPF noise and the drastic improvement was observed. **Figure 5** compares the BPF noise levels calculated with respect to the turbine speed between the conventional specification and the specification after taking the measures. The horizontal axis represents the turbine speed [rpm] and the vertical axis represents the BPF noise level [dBA]. As shown in Figure 5, the new turbine specification can realize a high noise reduction of more than 10dBA over almost the entire turbine speed range, and the significant noise reduction can be achieved.

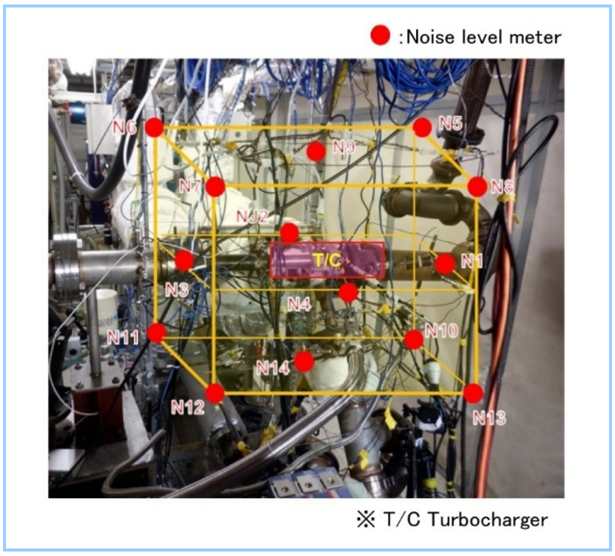

Figure 3　Testing Overview

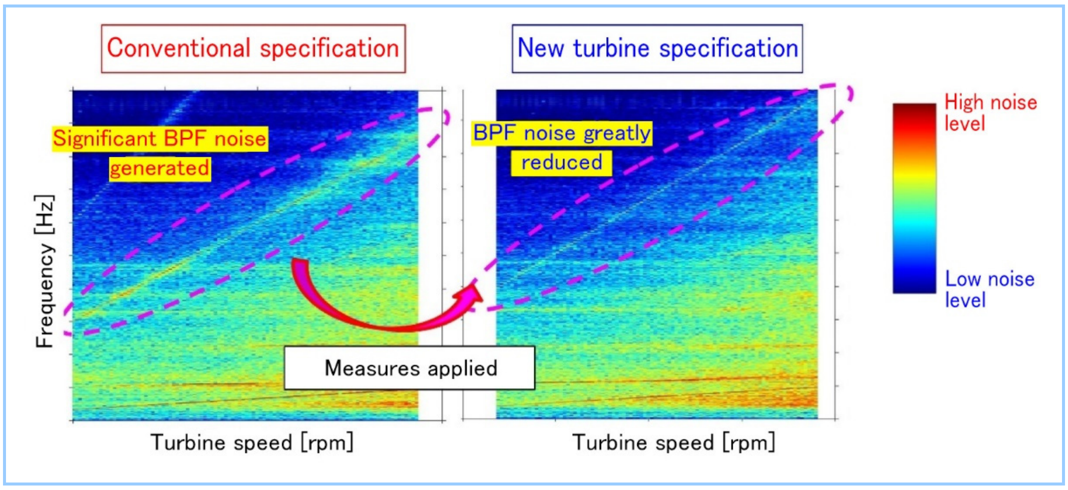

Figure 4　Results of sonagram analysis

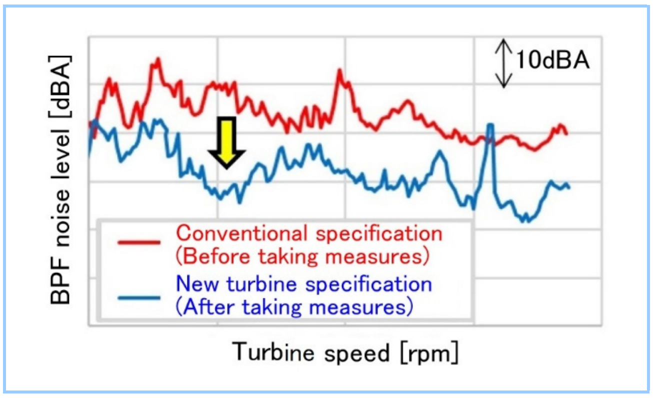

Figure 5　Comparison of BPF noise levels with respect to turbine speed

4. Evaluation of turbine performance

In order to effectively utilize the characteristics of double-scroll turbines, the tongue clearance of the scroll needs to be designed appropriately. As mentioned above, noise can be reduced by enlarging the tongue clearance. On the other hand, that approach entails a trade-off that this decreases the boost pressure due to the increase of gas leakage to the other scroll through the tongue clearance. Therefore, to achieve both higher boost pressure and lower noise at low engine speed ranges, we improved the design of the tongue shape and turbine rotor blades and optimized their reaction degree to achieve higher turbine efficiency. **Figure 6** shows the improvement result of the turbine efficiency compared to the conventional specification. The horizontal axis represents the turbine expansion ratio and the vertical axis represents the turbine efficiency. The new turbine specification achieved the improvement in the efficiency on the high expansion ratio side by 0.4 pt and on the low expansion ratio side by 1.5 pt.

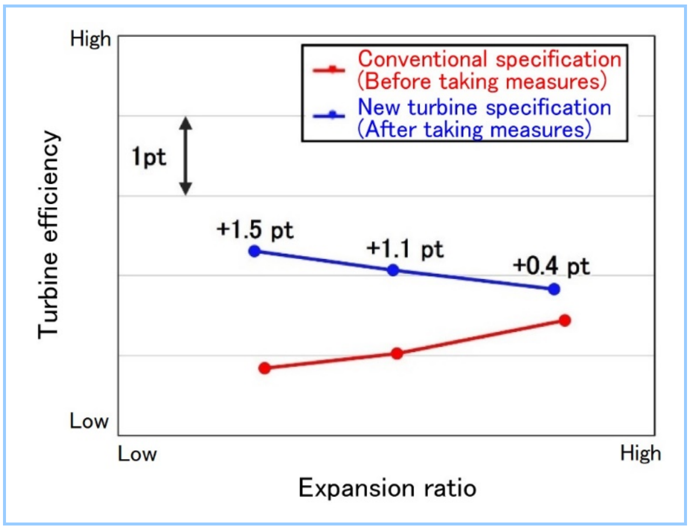

Figure 6 Improvement in turbine efficiency

The main losses in turbine rotor blades of turbocharger include leading-edge impingement loss, backside leakage loss, and blade tip leakage loss. One of the factors of the efficiency improvement achieved with the new turbine specification is the reduction of blade tip leakage loss. **Figure 7** compares the blade tip leakage flow of the conventional and new turbine specification in the CFD analysis results. The improved turbine blade design, including the addition of a tongue shape and the number of blades, reduced the leakage flow from the positive-pressure side to the negative-pressure side through the blade tip clearance. The turbine efficiency was improved over the entire expansion ratio range due to the reduction of blade tip leakage loss.

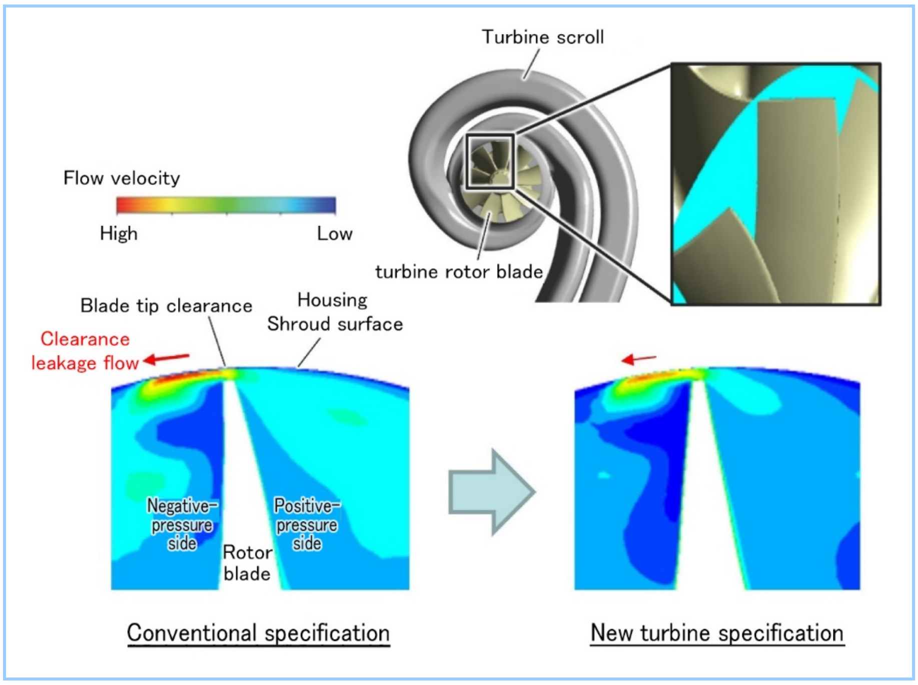

Figure 7 Reduction in blade tip leakage flow

Another factor that improves the efficiency is the optimization of the degree of reaction. By adjusting the degree of reaction, the characteristics of the change in efficiency with respect to the turbine expansion ratio can be controlled. The new turbine specification achieved a higher degree of reaction by reducing the ratio of the throat area of the turbine rotor blades to the throat area of the scroll rather that of the conventional specification. The turbine efficiency during low-speed engine operation was improved by shifting of the peak turbine efficiency to the low expansion ratio side due to the high degree of reaction. In addition, the gas flow velocity at the turbine blade inlet is reduced by the higher degree of reaction. This reduces pressure fluctuations around the tongue, which contributes to noise reduction as well as efficiency improvement.

5. Conclusion

Double-scroll turbines, which have been the focus of attention in recent years from the viewpoint of environmental regulations and performance requirements, are faced with the problem of aerodynamic noise (BPF noise) reduction. Therefore, we worked on the development of noise reduction turbine specification through CFD, acoustic analyses and operational tests on actual turbocharger.

The analyses evaluation showed that the main cause of the noise increase was interference between the wake generated by the scroll tongue and the turbine rotor blade. Therefore, based on the analysis results obtained, we performed analysis to predict the reduction effect on specifications for taking measures items and formulated new turbine specifications that noise reduction was expected. As a result of testing the newly designed turbine specifications and verifying the reduction effect through operational tests using actual turbocharger, the new specifications achieved a significant noise reduction of approximately 10dBA over almost the entire rotation speed range compared to the conventional specification turbine. We also believe that we have achieved both improved aerodynamic performance and made a significant contribution to the noise reduction of our double-scroll turbines. The effects of each measure items obtained through this initiative, and series of evaluation processes from mechanism estimation and measure planning using CFD and acoustic analysis, to subsequent actual turbocharger verification, analytical evaluation, and planning of noise reduction specifications can be applied to the development of various products not just automobile turbochargers. We would like to contribute to further improvement of the noise reduction design technology for our products by utilizing the results of this study in the development of our various products.