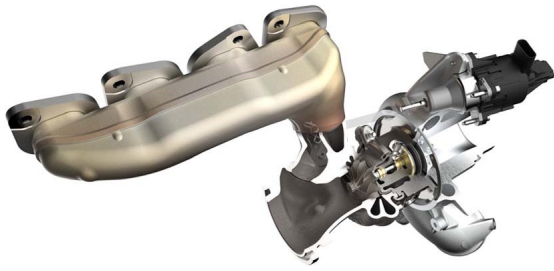


Technology for Enhancement of Turbine Performance Under Exhaust Pulsation for High-Performance Automotive Turbocharger



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In recent years, the fuel efficiency of passenger vehicles has been enhanced through engine downsizing by turbocharging. 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. This paper presents turbine performance analysis and efforts to achieve high performance under exhaust pulsation focusing on the fact that a turbocharger installed on an engine is driven under exhaust pulsation. Through collaborative research with Imperial College, which can measure the unsteady performance of a turbine under exhaust pulsation, and the University of Cambridge, experts in enhancing turbine performance, the flow phenomenon was elucidated by unsteady performance measurement and large-scale flow simulation. It was found that turbine performance under exhaust pulsation cannot be evaluated in a quasi-steady state and has a hysteresis characteristic, and that under a pulsation peak pressure with high exhaust gas energy, the blade leading-edge incidence loss increases excessively. Mitsubishi Heavy Industries, Ltd. (MHI) utilized these findings for the development of a new mixed-flow turbine and achieved the enhancement of turbine performance under exhaust pulsation.

1. Introduction

As a measure against global warming, the reduction of CO₂, which is one of the greenhouse gases, is being promoted all over the world. Strict fuel consumption regulations have also been imposed on passenger vehicle engines and are planned to be further strengthened in the future. One of the methods to enhance the fuel efficiency of an engine is downsizing by turbocharging. The use of this method has quickly expanded to gasoline engines in addition to diesel engines.

MHI has been promoting efforts to enhance the efficiency of turbochargers utilizing numerical flow simulation and internal flow measurement, but a more detailed analysis of the flow structure was indispensable for further improvement in efficiency. In particular, turbines driven under unsteady pressure fluctuation caused by engine exhaust pulsation have been evaluated and designed in a steady state because of the difficulty of evaluation.

This paper describes an unsteady performance test implemented in collaborative research with Imperial College to understand the performance characteristics of a turbine under exhaust pulsation. Imperial college has focused on turbine performance characteristics under exhaust pulsation for many years and has reported numerous measurement examples using unsteady performance test equipment that they designed and manufactured.¹ In addition, we analyzed the internal flow in detail in collaboration with the University of Cambridge, which has a great deal of knowledge in aerodynamics research on turbomachinery, and we worked on the analysis of the performance under exhaust pulsation by reviewing from the setting of a numerical flow simulation method. This paper presents our efforts to elucidate the flow phenomenon by collaborating with these universities with state-of-the-art technologies to achieve enhanced performance.

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2. Unsteady performance characteristics of turbine under exhaust pulsation

This chapter describes the analysis of turbine performance under exhaust pulsation by measuring unsteady performance.

(1) Test equipment

Figure 1 shows Imperial College's performance measurement equipment. Pressure pulsation is generated by the pulse generator, and turbine unsteady output is measured based on the torque and rotational speed fluctuation acting on the dynamo. The pulse generator generates arbitrary pressure pulsation by opening and closing the passage by rotating the notched plate. The flow velocity profile under pulsation is understood beforehand by a hot wire traverse and during the performance test, the unsteady flow rate is calculated by measuring the representative flow velocity at the center of the flow path with the hot wire. Since the dynamo absorbs the load of the turbine, measurement can be characteristically performed at a wide range of operating points.

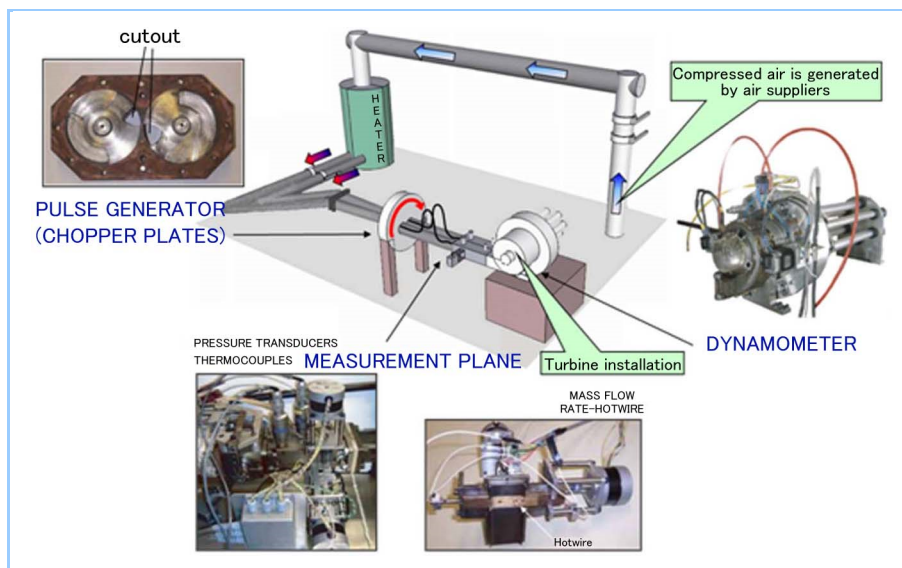


Figure 1 Imperial College's test equipment

(2) Test conditions

Test conditions and test pieces were selected for a small gasoline engine (1.4-liter gasoline engine), the market for which has been expanding in recent years. Although the actual engine has a turbine outer diameter of about 40 mm, the test turbine outer diameter was set to 74 mm because of constraints of the test equipment, and approximate conditions were calculated in which various dimensionless numbers (speed ratio U/C_0 (ratio of gas flow velocity to turbine peripheral speed), pulsation Strouhal numbers MSt and $PMSt$) coincide. In this case, the low-speed torque point of the engine of 2000 rpm corresponds to the pulsation frequency of 20 Hz in the test apparatus, and the high-speed output point of 6000 rpm corresponds to the pulsation frequency of 60 Hz. **Figure 2** illustrates the test piece. The test turbine is a similarly-enlarged model for passenger vehicles and is driven by low temperature air, and the turbine blade was machined out of aluminum.

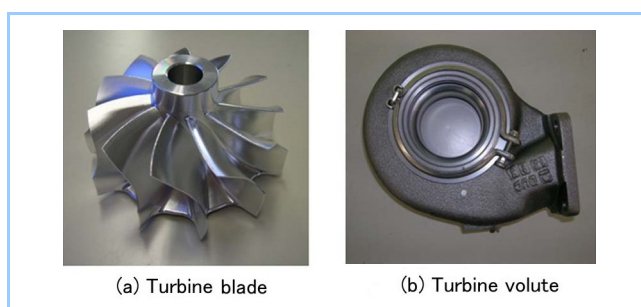


Figure 2 Test turbine (turbine diameter of 74 mm)

(3) Measurement of unsteady performance

Unsteady turbine performance was measured under an exhaust pulsation condition. **Figure 3** gives an example of the pulsation state quantity (turbocharger rotating speed 50000 rpm, pulsation frequency 60 Hz) and **Figure 4** is an example of the performance measurement results. The pressure begins to rise at the phase of 0 degrees, reaches the maximum at the phase of 120 degrees, and then gradually decreases to 360 degrees (Figure 3 (a)). On the other hand, the flow rate nearly reaches maximum earlier than the pressure at the phase of 70 degrees and reaches a local peak in the vicinity of the phase of 240 degrees, which are features different from the pressure ratio (Figure 3 (b)). In fact, when the corrected flow rate is plotted with respect to the pressure ratio, the unsteady flow characteristic indicates a hysteresis surrounding the steady flow characteristic. In the first half of the pulsation, first the flow rate increases and the scroll is filled, and then the pressure rises. On the contrary, in the latter half of the pulsation, first the flow rate decreases and the scroll becomes empty, and then the pressure decreases, which is indicated as a hysteresis. The turbine output in Figure 4(b) also shows a deviation from that in a steady state, and it is confirmed that it fluctuates considerably. In general, the time scale of exhaust pulsation is considerably larger than the time scale of turbine internal flow, and it was thought that the turbine performance would be a quasi-steady state. However, it was found that this indicates hysteresis and cannot be represented in a quasi-steady state.

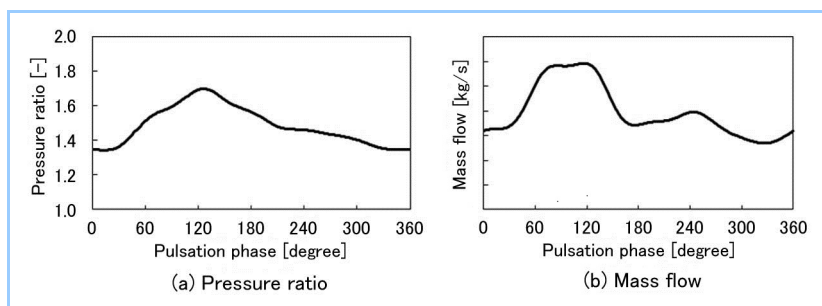


Figure 3 Turbine inlet conditions
(results of measurement by Imperial College)

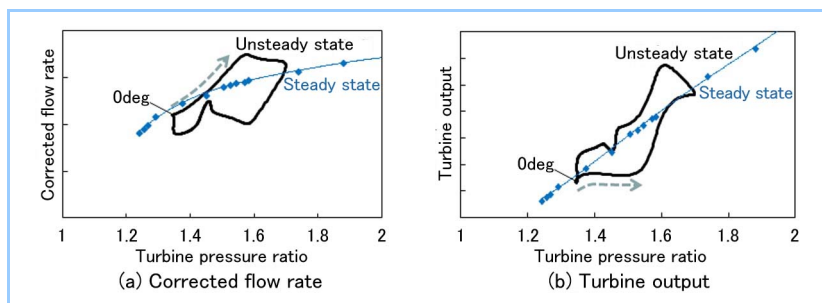


Figure 4 Unsteady turbine performance
(results of measurement by Imperial College)

3. Analysis of turbine internal flow

This chapter describes the analysis of turbine internal flow under exhaust pulsation using unsteady flow simulation.

(1) Unsteady flow simulation

Turbine internal flow under exhaust pulsation was analyzed in detail using unsteady flow simulation. As can be seen from the difference between the orders of the engine rotating speed (10^3 rpm) and the turbocharger rotating speed (10^5 rpm), the time and space scales of both flows differ significantly, and the analytical load becomes excessive in order to capture the flow phenomena of both to a high degree of precision. Therefore, internal flow simulation was carried out while finding flow simulation conditions suitable for a turbine under exhaust pulsation.

Figure 5 is the analysis area. The inlet duct, the turbine volute, and the turbine blade were considered in accordance with Imperial College's test equipment. The applied numerical flow simulation code was TBLOCK 10.9 (mixed length turbulence model, SCREE scheme,

finite volume method) developed by the University of Cambridge. The internal flow of the radial turbine has a flow distortion due to a leading-edge collision and a vortex due to tip leakage flow. Therefore, the mesh density was increased centering around the wall surface where there was such a large change in the flow velocity. In addition, we conducted a parameter study in increments of the number of meshes and the time in advance in order to extract the settings that can reduce the analysis load while obtaining a hysteresis of the turbine flow rate and the output hysteresis obtained from the test results.

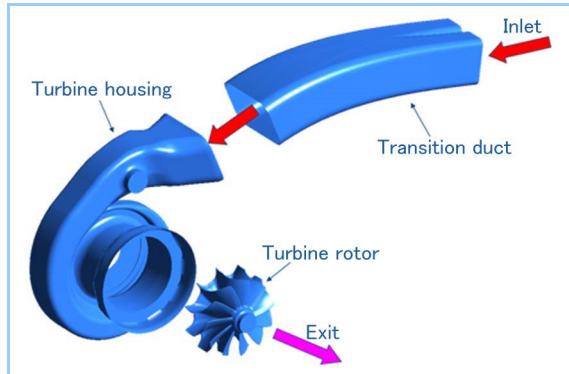


Figure 5 Simulation area

(2) Simulation results

Unsteady CFD was carried out based on the test conditions. For the total pressure and total temperature at the inlet boundary, the measured time series data under pulsation is directly given. **Figure 6** provides the analysis results. Comparing the flow characteristics, the analysis results indicate shorter cycle fluctuations than those of the measurement results, but the hysteresis is well understood. The turbine output was calculated from the static pressure acting on the blade surface, which was in good agreement with the measurement results qualitatively and quantitatively. Comparing the cycle average output of one pulse of pulsation, the error was suppressed to -2.4% at 60 Hz and 50 krpm.

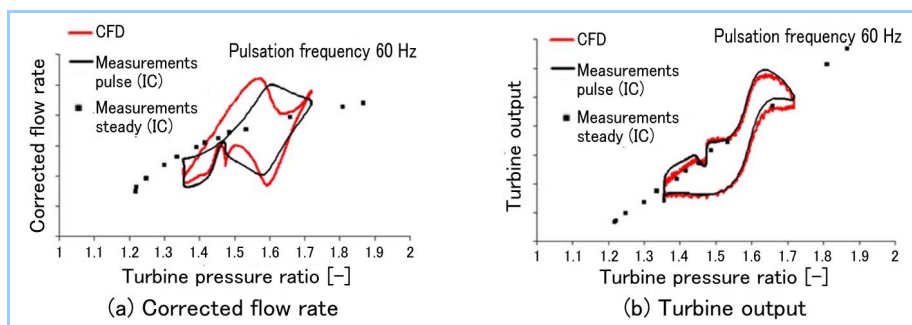


Figure 6 Unsteady turbine performance (flow simulation results)

(3) Elucidation of loss mechanism

Figure 7 illustrates the internal flow structure of one turbine blade pitch. As described above, major losses of radial turbines include leading-edge incidence loss, backside leakage loss, and tip clearance leakage loss. Under a pulsation condition, these losses become more conspicuous under a high-pressure ratio condition in comparison with a low-pressure ratio condition, indicating that a high loss is generated. Under a high-pressure ratio condition, the turbine inlet relative flow velocity tilts to the pressure surface side, so the angular difference between the turbine blade leading-edge metal angle and the flow angle increases, and the incidence loss also increases. In addition, as the blade load increases, the flow leakage loss from the backside and a clearance such as tip clearance increases.

Next, the loss structure under exhaust pulsation was analyzed. Turbine losses are roughly classified into exhaust loss (Kinetic energy loss) and irreversibility. By changing the integration range of the loss generation rate, the loss in each layer was compared. In addition, for the inside of the turbine blade, the leading-edge incidence loss, clearance leakage flow loss, etc., were separated by subdividing the integration range into the areas shown in **Figure 8**.

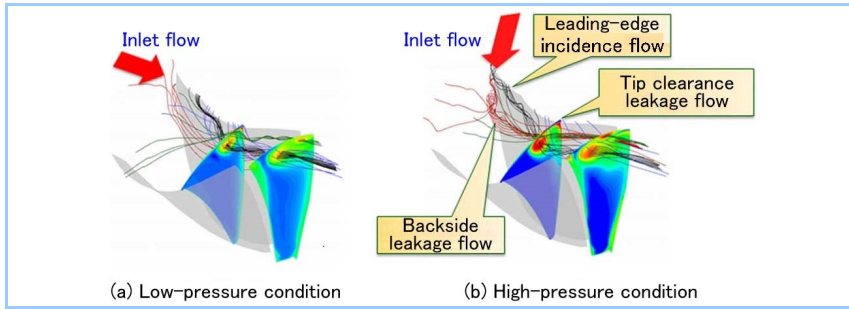


Figure 7 Turbine blade internal loss and streamlines (results of flow simulation)

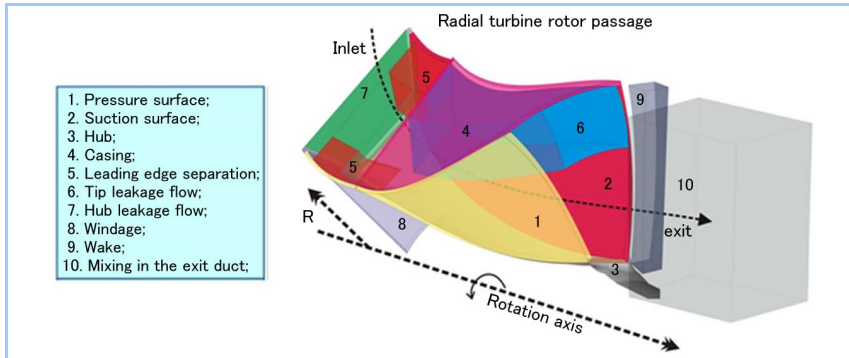


Figure 8 Loss analysis areas

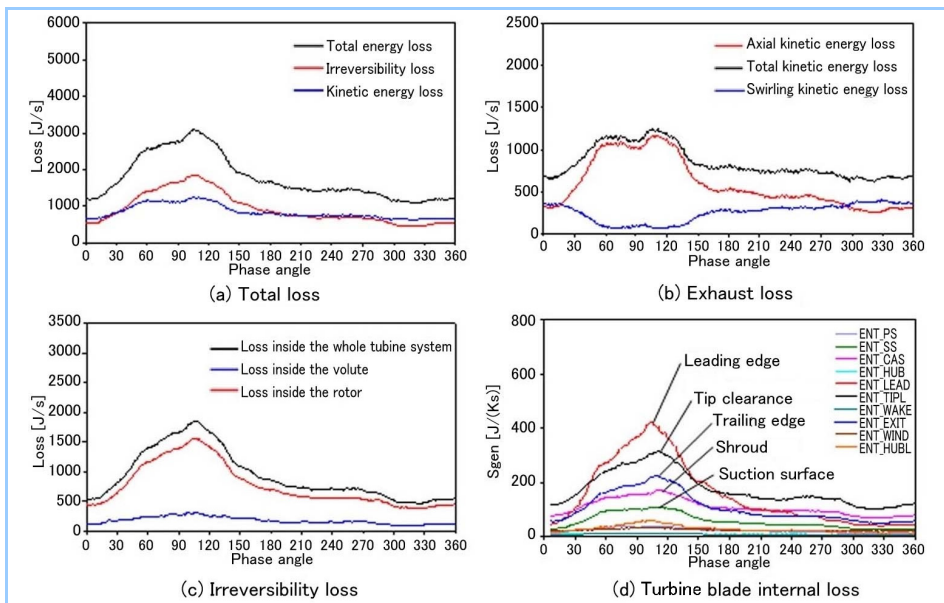


Figure 9 Loss distribution (results of flow simulation)

Figure 9 indicates the results of the loss analysis. In the vicinity of the phase where the pulsation pressure reached the peak (90 to 120 degrees), the total loss increased, and in particular the increase in the irreversibility loss was larger than the exhaust loss. Figure 9 (b) separates the exhaust loss into the axial direction and radial direction components. At the pulsation pressure peak (phase of 120 degrees), the loss in the axial direction increases and the loss in the circumferential direction is suppressed. That is, it is indicated that the outlet swirl is suppressed at the pulsation pressure peak, so the speed triangle formed by the turbine blade outlet blade angle is in a state suitable for the pulsation peak and there is little room for improvement. On the other hand, when the irreversibility loss is separated into turbine blade loss and volute loss (Figure 9(c)), the volute loss is constant and small regardless of the pulsation phase, while the turbine blade loss increases at the pulsation pressure peak (90 to 120 degrees). A similar tendency is also obtained for the loss ratio, and the loss ratio of the turbine blade at the pulsation pressure peak is large. Figure 9(d) separates each loss inside the turbine blade and indicates that the leading-edge loss increases near the pulsation pressure peak, which is the pulsation phase of 90 degrees.

Based on the aforementioned analysis of the turbine loss structure under exhaust pulsation, it was found that the turbine leading-edge loss increased the most at the pulsation pressure peak where the gas energy was large. In order to improve turbine efficiency, it is important to reduce this leading-edge loss. **Figure 10** gives the flow angle at the leading edge of the turbine blade obtained by the unsteady CFD, and indicated that at the pulsation pressure peak, the incidence angle of the leading edge was reduced to -5 degrees. Empirically, the favorable leading-edge incidence angle of a radial turbine is considered to be around -20 degrees, so the angle in this case exceeds the favorable angle by 15 degrees.

In the case of a radial turbine, it is difficult to adjust the leading-edge metal angle because of the restriction on the strength. Therefore, in order to reduce this incidence loss, the application of a mixed-flow turbine was examined. The mixed-flow turbine can change the leading-edge metal angle while maintaining the same strength as the radial turbine. The details are described below.

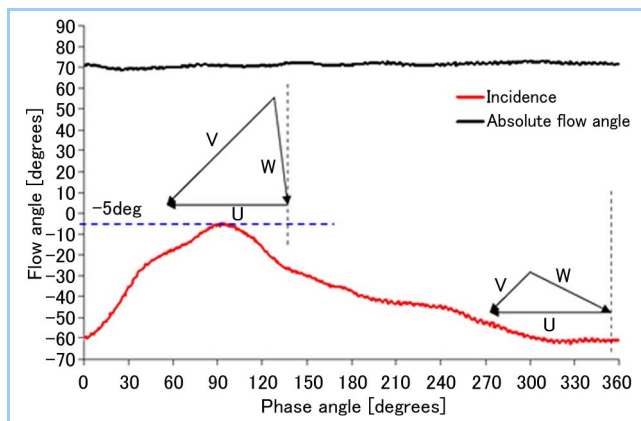


Figure 10 Turbine blade inlet flow angle distribution (results of flow simulation)

4. Efficiency enhancement of turbine under exhaust pulsation

Based on the results of performance analysis and internal flow simulation obtained above, we worked on the design enhancement of turbine efficiency. This chapter describes the outline of turbine blade improvement design.

(1) Turbine blade improvement design

A mixed-flow turbine can tilt the leading-edge blade angle to the pressure surface side and has better performance at lower U/C_0 than a radial turbine. Using these features, we developed a new mixed-flow turbine suitable for an exhaust pulsation condition.

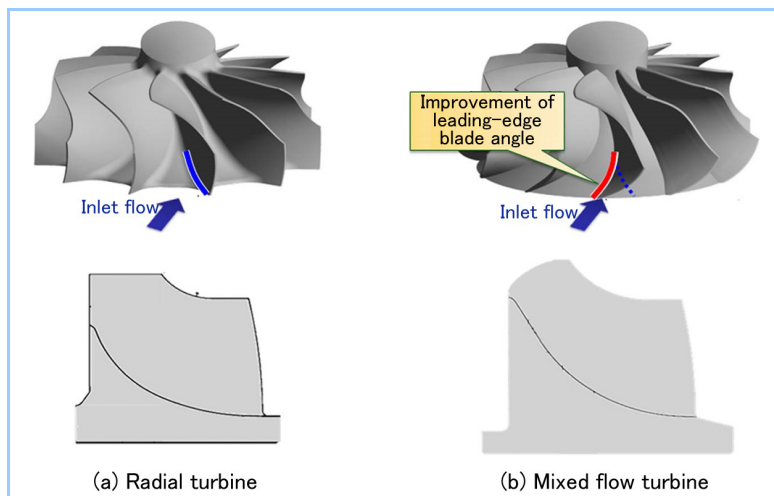


Figure 11 Turbine shapes

Figure 11 presents the designed turbine. As analyzed in Figure 9, the leading-edge incidence loss and the tip clearance leakage loss are relatively large under exhaust pulsation. Focusing on the fact that the cause of clearance leakage flow is the blade surface pressure difference, that is, the blade load, the blade angle distribution was set so as to reduce the load

distribution mainly on the shroud side. Regarding the leading-edge incidence loss, the relative flow angle was adjusted by increasing the blade tip speed by the leading-edge circular arc meridian plane, while adjusting the leading-edge angle by applying a mixed-flow turbine. If the leading-edge blade angle is excessively inclined, there are concerns about the increase in clearance leakage loss and the strength due to the increase in blade load, so we combined the adjustment of the leading-edge angle and the meridian plane improvement.

(2) Flow simulation evaluation

The improved mixed-flow turbine blade was evaluated by steady flow simulation. As shown in the analysis results in **Figure 12**, efficiency improvement was confirmed at low $U/C0$, which is important for pulsation peak pressure, while maintaining the peak efficiency equal to that of the radial turbine (efficiency improvement of 4% at $U/C0 = 0.5$). On the other hand, as a contradictory event, a substantial efficiency deterioration was confirmed at high $U/C0$ (efficiency lowering of 3% at $U/C0 = 0.8$). Therefore, overall evaluation by averaging the efficiency improvement in cycles under pulsation is necessary for determining whether the improved turbine blade is good. In the turbine blade internal loss distribution presented in **Figure 13**, it was confirmed that the leading-edge incidence loss and the clearance leakage loss were reduced as planned in the design. Furthermore, the entropy accumulated on the trailing edge side was suppressed.

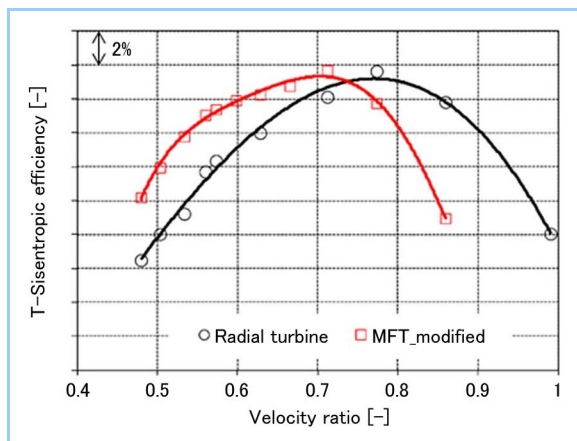


Figure 12 Turbine efficiency (results of flow simulation)

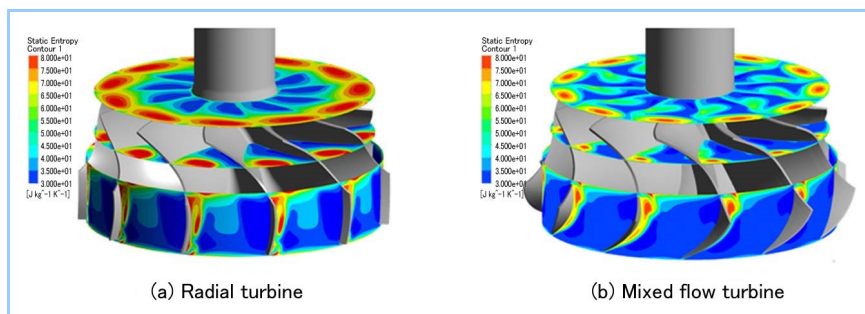


Figure 13 Internal loss distribution (results of flow simulation)

(3) Test evaluation

A performance test of the new mixed-flow turbine was carried out using Imperial College's test equipment. **Figure 14** gives the cycle average turbine efficiencies in three cases where the pulsation frequency was 20, 40, and 60 Hz with the turbine average pressure of 1.5. At 20 Hz simulating an engine low-speed torque point, the efficiency decreased by 0.3%. However, at 60 Hz simulating an engine high-speed output point, an efficiency improvement of 3.1% was obtained. At 40 Hz, which is between the other two, the efficiency was improved by 3.0%. In this way, performance improvement using the improved mixed-flow turbine under exhaust pulsation was confirmed.

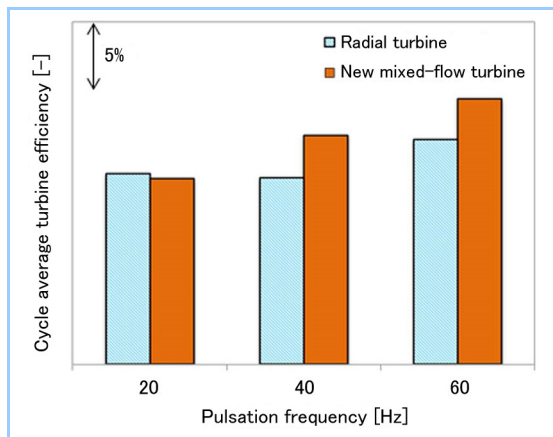


Figure 14 Unsteady turbine performance (measurement results)

5. Conclusion

For the purpose of improving the performance of turbochargers, we worked on increasing the turbine efficiency under engine exhaust pulsation. We obtained the unsteady turbine performance and understood the flow rate and efficiency hysteresis, which could not be detected by a conventional steady-state test. Based on these measurement results, we constructed a flow simulation method of a turbine under exhaust pulsation, clarified the turbine loss structure generated under pulsation, and utilized it for the development of a new mixed-flow turbine. The new mixed-flow turbine was evaluated by Imperial College's test equipment and performance enhancement was achieved in a pulsation condition simulating an engine high-speed output point.

The trend of strengthening regulations on passenger vehicle engines will continue. Therefore, passenger vehicle manufacturers are assuming various developments including the electrification of the powertrain, and it is expected that the required supercharging technology will constantly change. We will continue to constantly incorporate the latest evaluation method and design method through collaboration with leading research institutes and further develop aerodynamic design technology to promote rapid and innovative turbocharger development.

Special thanks to Professor Martinez-Botas and Dr. Yang (now transferred to Shanghai Jiao Tong University) of Imperial College, and Dr. Xu and Dr. Cao of the University of Cambridge for their cooperation for this development through collaborative research.

References

1. Arcoumanis, C. et al., Performance of a Mixed Flow Turbocharger Turbine Under Pulsating Flow Conditions, ASME Paper, 95-GT-210