Development of Turbocharger for New Energy Vehicles

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In response to regulations on the automobile industry being tightened around the world as a measure against global warming, a shift to new energy vehicles (electric vehicles, plug-in hybrid electric vehicles, range-extender electric vehicles, and fuel cell vehicles) has been accelerating. This report describes our efforts to develop a turbocharger suitable for plug-in hybrid electric vehicles. The improvement in the fuel efficiency of the engine for plug-in hybrid electric vehicles is an important issue and the turbocharger is therefore required to be highly efficient at the optimum fuel efficiency point. As such, we worked on improving the elements that contribute to performance (matching, aerodynamic performance, and bearing mechanical loss) and now have the prospect of improving the overall efficiency of the turbocharger and the fuel efficiency of the engine.

1. Introduction

Global warming due to an increase in greenhouse gases will cause rising sea levels, the spread of infectious diseases and other climate change problems, and taking measures to prevent this is an urgent issue. In response, countries around the world are working to reduce CO_2 emissions based on the mid-term (by 2030) reduction targets set under the Paris Agreement. The majority of CO_2 emissions come from the energy conversion, industrial, and transportation sectors, and the emissions from the transportation sector are dominated by those from the automotive industry. In the automotive industry, regulations have been tightened year by year, and the electrification of vehicles is accelerating, while the adoption of various fuels (hydrogen, synthetic fuels, etc.) is being studied. European countries have agreed to ban the sale of passenger cars and light commercial vehicles that emit carbon dioxide (excluding vehicles that use synthetic fuels) in Europe by 2035, and the shift to electric vehicles has been accelerating. Also in Japan, the government has announced a policy that all commercially available new cars must be electric vehicles by 2035, and the shift to electric vehicles has been accelerating. In China, on the other hand, approaches to increasing the ratio of new energy vehicles and reducing CO_2 emissions have been undertaken based on the double credit regulation (i.e., regulation on the number of new energy vehicles produced by each automaker and regulation on CO_2 emissions). New energy vehicles is the generic term for electric vehicles (hereinafter referred to as BEVs), plug-in hybrid electric vehicles (hereinafter referred to as PHEVs), range-extender electric vehicles (hereinafter referred to as REEVs), and fuel cell electric vehicles (hereinafter referred to as FCEVs). Among these, PHEVs and REEVs are equipped with turbocharged engines. While demand growth for BEVs has been slowing due to concerns about their driving range, demand growth for PHEVs has been accelerating. As a result, automakers are developing engines for PHEVs, and improving fuel efficiency has become an important issue. Aiming to increase orders in the Chinese market, we have developed a turbocharger that is suitable for engines for PHEVs.

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2. Characteristics required for turbochargers for engines for plug-in hybrid electric vehicles

Hybrid electric vehicles include many types of hybrid systems. Mainstream in the current Chinese market is the series-parallel type, which is equipped with multiple motors. As shown in **Figure 1**, the series-parallel-type hybrid system has four drive modes: I. parallel mode (for rapid accelerating and towing), in which the driving force is provided by the engine and assisted by the motor, II. series mode (for normal driving), in which the driving force is provided only by the motor with the engine operated at a high thermal efficiency region (hereinafter referred to as optimum fuel efficiency point) for power generation, III. direct mode (for high-speed driving), in which the driving force is provided only by the engine, and IV. EV mode (for starting up and normal driving), in which the driving force is provided only by the motor. In the case of PHEVs, which have increased battery capacity and motor output, the operating range of mode II expands and the operating range of mode III narrows. **Figure 2** compares typical turbocharger operating points of engines for internal combustion engine vehicles (hereinafter referred to as ICEVs) and PHEVs. When driving in mode I, where torque and output are demanded, PHEVs are assisted by their increased-output motor, and therefore require the engine to provide less low-speed torque and maximum output, making the turbocharger's required operating range narrower. On the other hand, PHEVs, whose frequently used mode II operating range is wider, require the engine to further improve thermal efficiency at the optimum fuel efficiency point. While this improvement in the engine's thermal efficiency reduces the exhaust energy, the turbocharger needs to provide the necessary boost pressure, which requires further improvement in its efficiency at the optimum fuel efficiency point. Based on the above required characteristics, we aimed to improve the efficiency of the turbocharger at the optimum fuel efficiency point of the engine for PHEVs, and worked to improve its elements (matching, aerodynamic performance, and bearing mechanical loss) that contribute to performance.

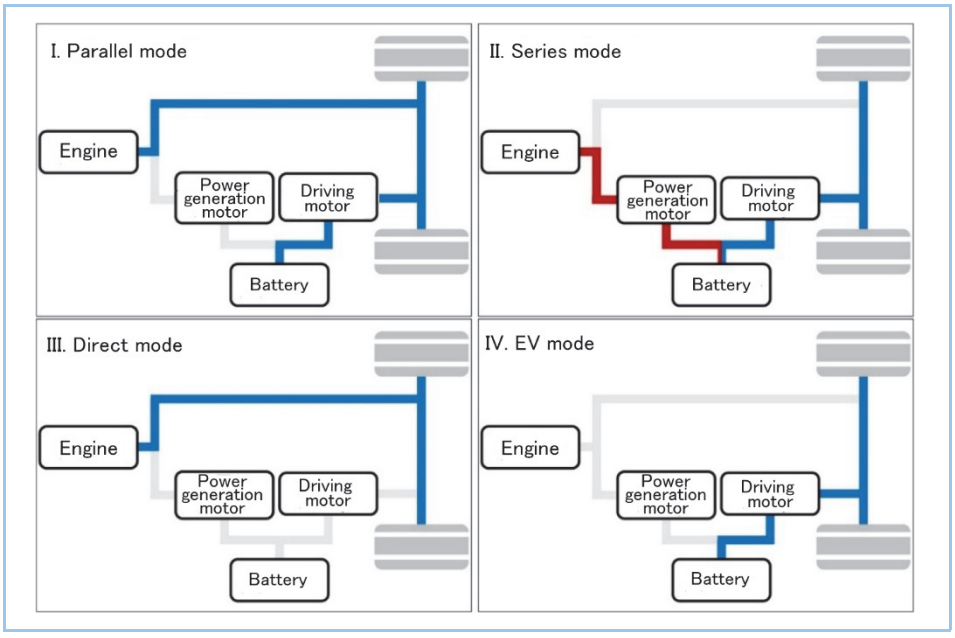

Figure 1 Driving modes of series-parallel-type hybrid system

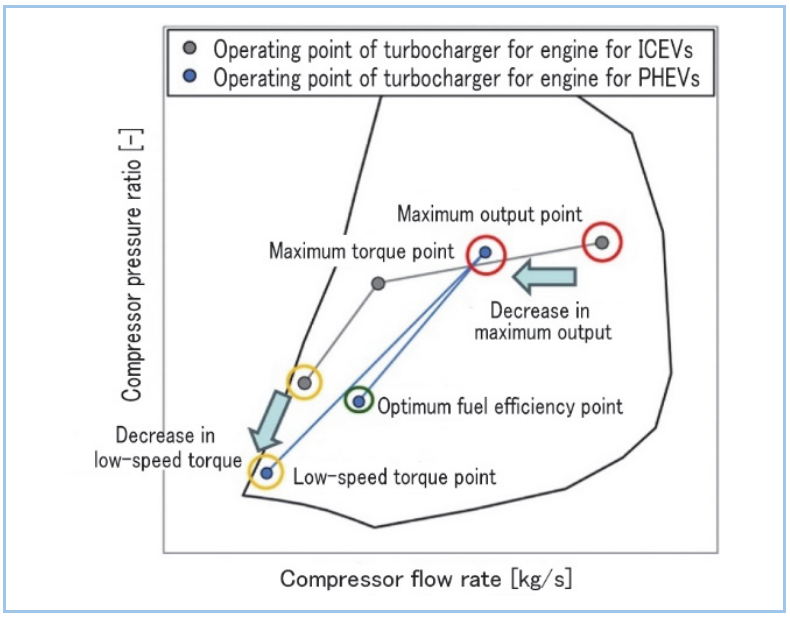

Figure 2 Comparison of typical turbocharger operating points of engines for ICEVs and PHEVs

3. Optimization of matching

Matching refers to selecting a combination of the compressor and turbine that matches the required performance of the engine. We studied matching specifically for engines for PHEVs, based on their required characteristics.

Studying matching requires consideration of performance characteristics of the turbine, and one of the parameters that represent performance characteristics is the velocity ratio. The velocity ratio is the ratio of the turbine rotor blade inlet peripheral velocity U to the theoretical velocity C_0 that flows through the turbine rotor blade while adiabatically expanding (hereinafter referred to as U/C_0). Turbine rotor blades for turbochargers have a characteristic of achieving peak efficiency at around $U/C_0 = 0.65$. The turbocharger operating speed is determined by the compressor, and since U depends on the ratio of the compressor impeller diameter D_c to the turbine rotor blade diameter D_t (hereinafter referred to as D_c/D_t), D_c/D_t is an important parameter for matching.

For conventional turbochargers for engines for ICEVs, which are required to meet transient response requirements, matching is made so that the turbine rotor blades having large specific gravity are relatively small in diameter and D_c/D_t is around 1.2. On the other hand, for turbochargers for engines for PHEVs, which are less required to meet transient response requirements, matching can be made using larger diameter turbine rotor blades, resulting in smaller D_c/D_t is possible. Here, **Figure 3** shows the turbine operating line under exhaust pulsation at the optimum fuel efficiency point, and **Figure 4** shows the energy density of exhaust gas on the turbine operating line. As shown in Figure 3, the turbine operating line under exhaust pulsation shifts in parallel by changing D_c/D_t. As shown in Figure 4, the exhaust gas has high energy density regions at each of the high, medium, and low expansion ratios. When D_c/D_t is set to the conventional value of 1.2, the operating U/C_0 in the high expansion ratio region with the highest energy density becomes lower than the appropriate value, resulting in lower average turbine efficiency. On the other hand, if D_c/D_t is made too small, the turbine efficiency in the high expansion ratio region improves, but the operating U/C_0 in the low expansion ratio region becomes higher than the appropriate value, resulting in lower average turbine efficiency. In this study, we optimized D_c/D_t in consideration of the operating U/C_0 under exhaust pulsation and the efficiency characteristics of the turbine rotor blades. The energy density of the exhaust gas was high at the points with an expansion ratio of 1.5 and $U/C_0 = 0.60$ (design point 1) and with an expansion ratio of 2.0 and $U/C_0 = 0.50$ (design point 2), and therefore we worked to improve the turbine to increase the efficiency at design point 1 and design point 2.

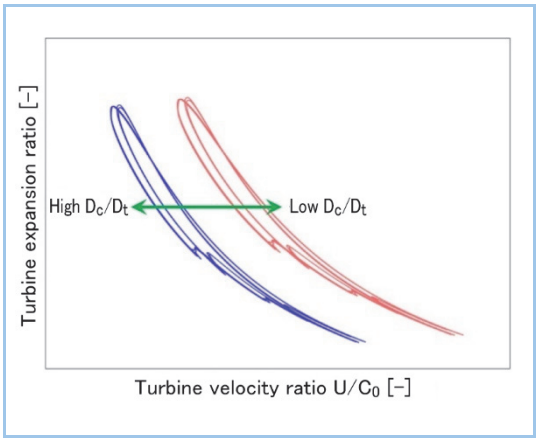

Figure 3 Turbine operating line of engine for PHEV under exhaust pulsation

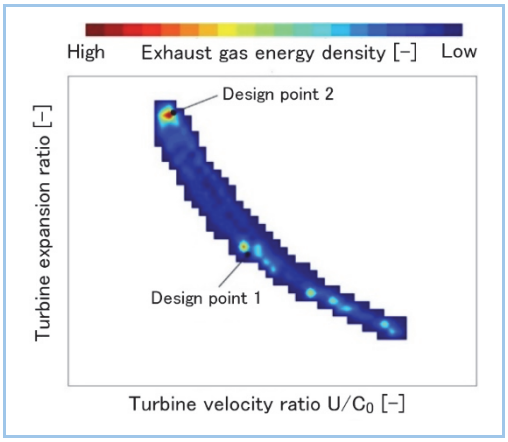

Figure 4 Energy density distribution of exhaust gas of engine for PHEV

4. Improvement in aerodynamic performance

4.1 Improvement in compressor performance

As described in chapter 2, compressors of the turbocharger for engines for PHEVs are required to meet relaxed requirements for the maximum flow rate and the small operating flow rate limit, and are required to be highly efficient at the optimum fuel efficiency point. To meet these requirements, we designed a new impeller based on the conventional impeller of engines for ICEVs. Specifically, the blade height was adjusted to suit the operating point near the optimum fuel efficiency point, and the leading edge blade angle was matched to the flow angle at the optimum fuel efficiency point. Furthermore, we searched for an impeller geometry that minimizes the loss at the optimum fuel efficiency point using an optimization algorithm. **Figure 5** shows the visualization results of the internal flow analysis near the optimum fuel efficiency point as well as the distribution of loss generation in the flow direction for the conventional and newly designed impellers. Figure 5(a) indicates that the flow path of the conventional impeller is blocked at the leading edge, resulting in loss generation, while the flow path blockage is eliminated in the newly designed impeller. Figure 5(b) indicates that the newly designed impeller has lower loss than the conventional impeller over the entire blade chord, and especially the loss generation at the leading edge of the blade is significantly reduced. **Figure 6** shows the performance test results of the newly designed impeller and the conventional impeller. Despite its maximum flow rate moving to the lower flow rate side compared to the conventional impeller, the newly designed impeller was confirmed to improve the efficiency near the optimum fuel efficiency point by 2.0 ppt while fully covering the engine operating range.

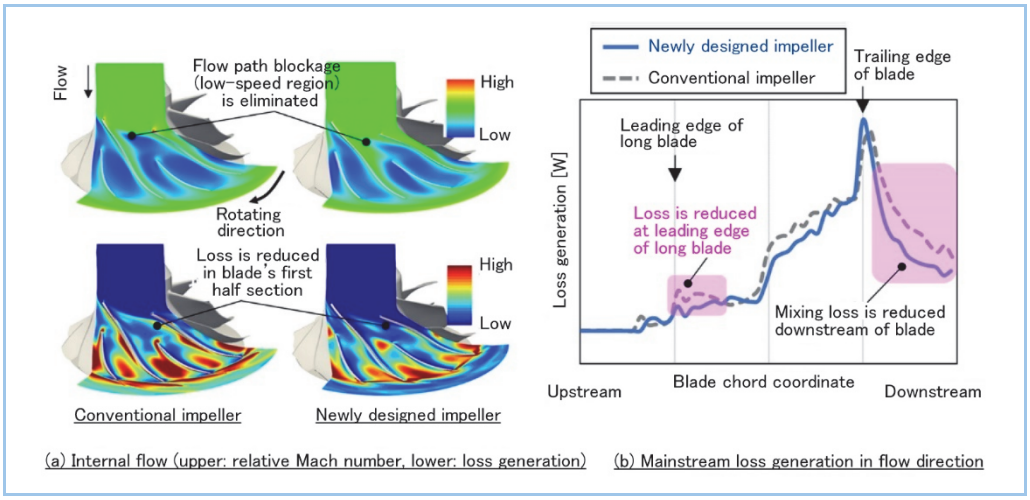

Figure 5 Internal flow of newly designed impeller and its loss generation in flow direction

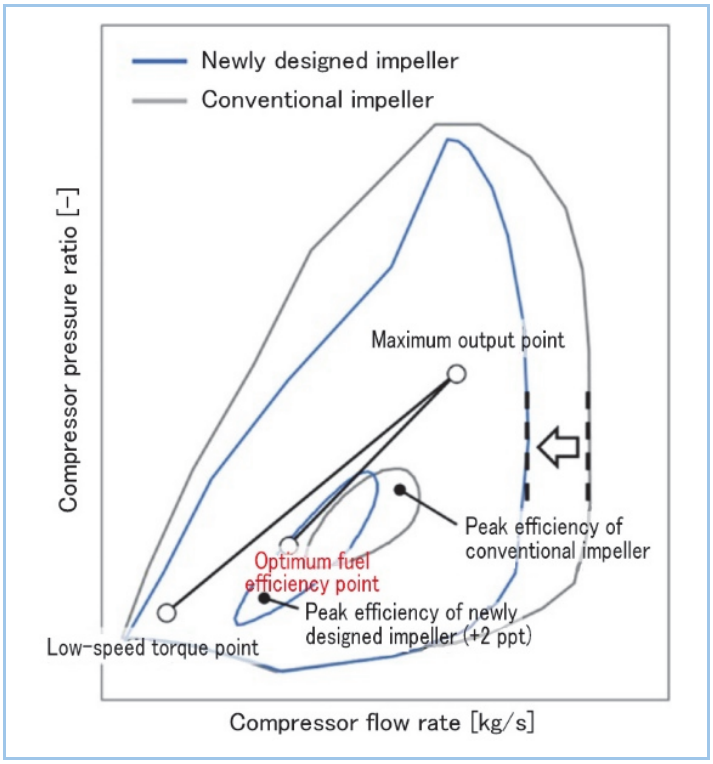

Figure 6 Performance test results of newly designed impeller

4.2 Improvement in turbine performance

As described in chapter 3, turbines of the turbocharger for engines for PHEVs are less constrained by transient response requirements and are instead required to have higher efficiency at design point 1 and design point 2. To meet this requirement, we have newly designed a rotor blade based on the conventional rotor blade of engines for ICEVs. There are two key points in the new design. The first key point is to reduce leakage flow between the rotor blades and the housing. The turbine rotor blades have a clearance at the blade tip to avoid contact with the housing. This clearance leads to leakage flow due to the pressure difference between the front and rear of the blades, resulting in energy loss. Especially in the case of small turbochargers, the clearance is relatively large in relation to the height of the flow path, and the leakage flow has a significant effect. In contrast to the conventional rotor blade, the new rotor blade was designed to optimize the inclination angle of the leading edge and the blade angle distribution from the leading edge to the trailing edge, specifically for design point 2. **Figure 7** shows the flow velocity distribution in the cross-section perpendicular to the flow path for the conventional and newly designed rotor blades. This figure indicates that the low-speed region of the leakage vortex has been suppressed due to the improvement of the blade geometry. This improved the internal flow of the turbine rotor blades and increased the efficiency at design point 2. The second key point is to reduce loss caused by the exhaust diffuser. The exhaust diffuser of a turbocharger is required to have a small-sized design from the viewpoint of the mountability on the engine. However, when the exhaust diffuser is small-size, it is difficult to sufficiently recover the dynamic pressure energy downstream of the rotor blades. As such, to improve the flow velocity distribution from the rotor blades to the exhaust diffuser, we modified the outlet blade angle distribution and the meridional geometry of the rotor blades. As a result of this improvement, the pressure recovery rate of the exhaust diffuser was increased, resulting in improved efficiency at design point 1 and design point 2. **Figure 8** shows the flow analysis results for the conventional and newly designed rotor blades. It was confirmed that the efficiency was improved by 2.0 ppt at design point 1 and by 4.2 ppt at design point 2 compared to the conventional rotor blade.

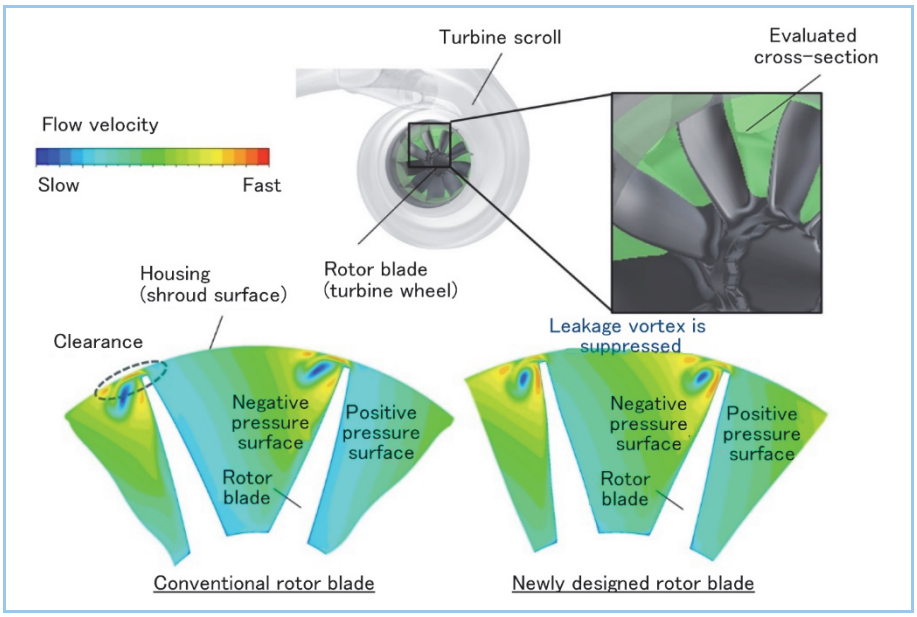

Figure 7 Reduction of blade tip leakage flow velocity due to improvement of blade geometry

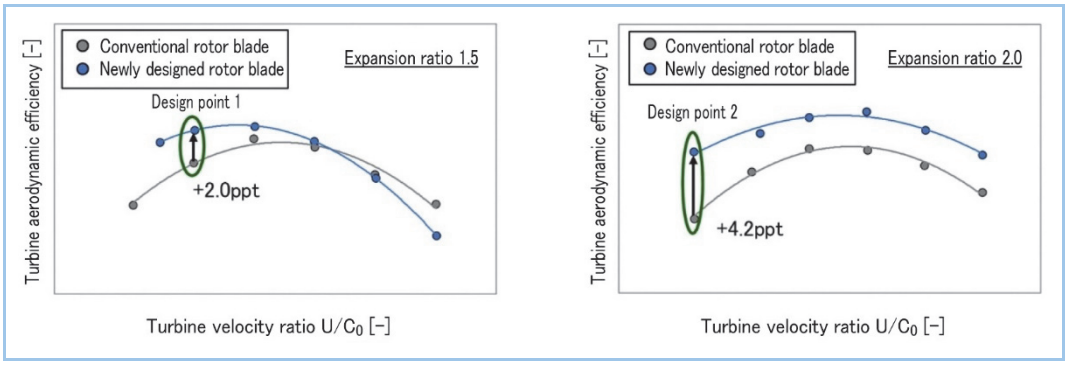

Figure 8 Turbine efficiency resulting from analysis of newly designed rotor blade

5. Improvement of bearing mechanical loss

Among full-float bearings, semi-float bearings, ball bearings, etc., for bearings for turbochargers, we adopt full-float bearings. To reduce bearing mechanical loss, it is effective to reduce the shaft diameter. However, the shaft diameter of full-float bearings cannot be reduced any further due to restrictions with respect to the rotational stability. Therefore, to reduce the shaft diameter to reduce the bearing mechanical loss, a semi-float bearing having a high rotational stability structure was developed. The dimensions of the semi-float bearing were set using an in-house shaft vibration analysis tool. The distance between the backs of the blades was shortened by about 10%, and the shaft diameter and the width across the bearing faces were reduced by about 15% and 30%, respectively, compared to the full float bearing (**Figure 9**). As a result of tests on actual equipment, it was confirmed that the turbine efficiency can be improved by approximately 1 ppt by adopting the semi-float bearing (**Figure 10**). It was also confirmed that the semi-float bearing has a rotational stability that allows the shaft vibration amplitude to be kept at a low level up to the maximum speed without increasing even when using low-viscosity oil 0W-8 (Figure 10). The newly designed semi-float bearing has lower bearing loss than a full float bearing, can be used with low viscosity oil, and has excellent mountability on vehicles due to its smaller size. Therefore, we are planning to develop new models based on this specification.

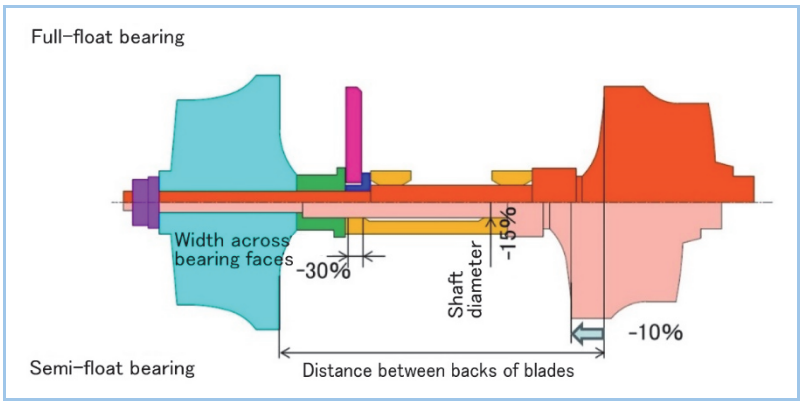

Figure 9 Cross-sectional view of full-float bearing and semi-float bearing

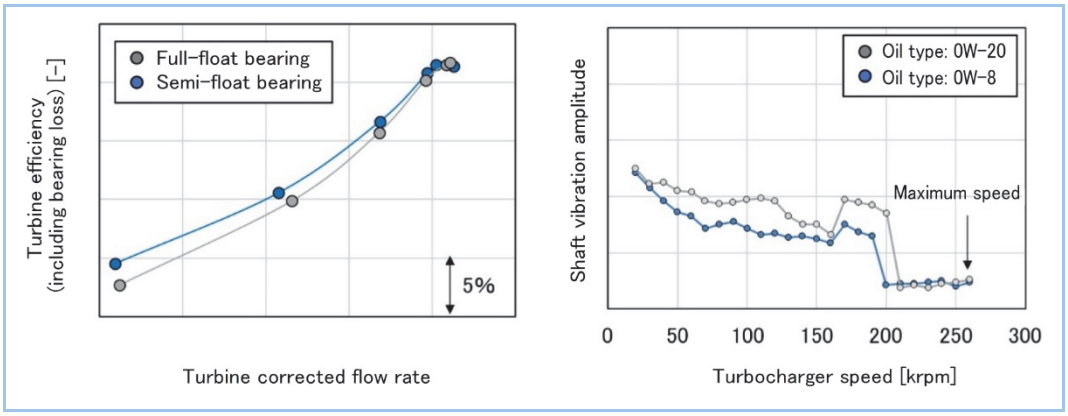

Figure 10 Performance test results and shaft vibration test results of semi-float bearing

6. Effectiveness verification of improvements

To analyze the effect of the turbocharger incorporating the elemental improvements described in chapters 4 and 5 on the engine performance, we conducted an engine simulation. **Figure 11** shows the changes in the turbine and compressor efficiencies and fuel consumption at engine operating points. Compared to the conventional turbocharger, the overall efficiency of the newly designed turbocharger was improved by 2.4 ppt in one engine cycle, and the fuel consumption was improved by 1.1 g/kW-h by revising the engine settings accordingly. The improvement in the overall efficiency was broken down into the following two: improvement in the average turbine efficiency under exhaust pulsation by 1.5 ppt due to improved aerodynamic efficiency of the turbine at design points 1 and 2 and reduced bearing loss thanks to semi-float bearings, and improvement in the compressor efficiency by 2.0 ppt due to reduced aerodynamic loss in the compressor. As shown in Figure 8, the aerodynamic efficiency of the turbine at design points 1 and 2 was improved, but the improvement in the average turbine efficiency under exhaust pulsation became smaller because the efficiency in the low expansion ratio region shown in Figure 4 decreased. As such, by improving the aerodynamic efficiency in this region, further improvement in the turbocharger efficiency can be expected.

The turbocharger efficiency was improved at all operating points: by 0.5 ppt at the low-speed torque point and by 1.0 ppt at the maximum output point, etc. The above results indicate that the efficiency of the newly designed turbocharger in terms of power characteristics of engines for PHEVs is improved over the conventional turbocharger in all operating ranges, and can be expected to contribute to the improvement in the engine performance. We are planning to verify the effects on the fuel consumption and thermal efficiency of the engine on the engine bench in the future.

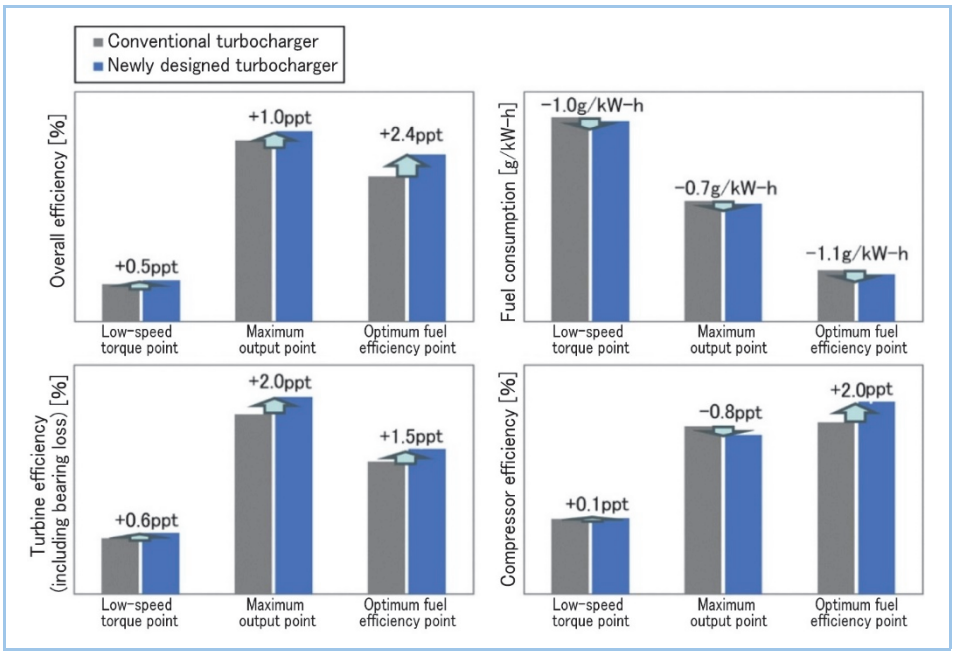

Figure 11 Result of engine and turbocharger performance evaluation in engine simulation

7. Conclusion

To contribute to improving the thermal efficiency of engines for PHEVs at the optimum fuel efficiency point, we worked to improve the elements that contribute to performance (matching, aerodynamic performance, and bearing mechanical loss), aiming to enhance the efficiency of turbochargers. With regard to the matching, we analyzed operating points under exhaust pulsation and considered the operating U/C_0 and the efficiency characteristics of the turbine rotor blade to set the optimum D_c/D_t, with which the turbine efficiency can be expected to improve. With regard to the compressor, we optimized the blade geometry to reduce the loss near the optimum fuel efficiency point, resulting in an improvement in the efficiency at the optimum fuel efficiency point by 2.0 ppt. With regard to the turbine, we reduced the leakage flow at the blade tip clearance as well as optimized the blade geometry to improve the flow at the exhaust diffuser, resulting in an improvement in the efficiency at design point 1 by 2.0 ppt and at design point 2 by 4.2 ppt. With regard to the bearings, we adopted semi-float bearings to reduce the shaft diameter by 10%, which resulted in the reduction of the bearing loss, leading to an improvement in the turbine efficiency by 1.0 ppt.

With these improved elements applied, we evaluated their effects on engine performance. As a result, an improvement in the fuel efficiency by 1.1 g/kW-h at the optimum fuel efficiency point was expected. We are planning to apply the development process described in this report to engines that can be used with new fuels, for which we expect to receive inquiries from customers, to further increase orders.