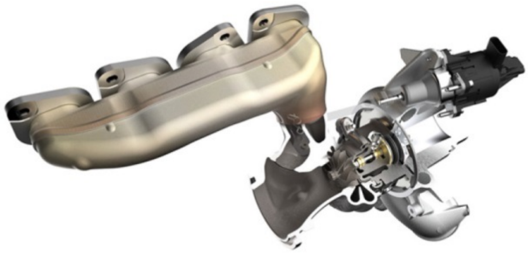
Development of High-Performance Turbocharger Turbine under Exhaust Pulsation for Next-Generation Hybrid Vehicles



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While passenger vehicle engines are evolving in line with the electrifications of powertrains, more efficient turbochargers are needed than ever before to comply with stricter fuel efficiency regulations and to improve engine performance. In this report, focusing on the fact that turbochargers mounted on engines are driven under exhaust pulsation, we developed a new turbine scroll shape that effectively utilizes the unsteadiness of exhaust pulsation, and measured its effect on the engine bench. As a result, we found hysteresis characteristics of instantaneous turbine performance with respect to the turbine pressure ratio through unsteady turbine performance measurements under exhaust pulsation and large-scale unsteady flow analysis, and a non-linear A/R scroll with reduced scroll volume while maintaining its steady-state flow characteristics was developed, thereby achieving an improvement in the fuel efficiency performance of the engine.

1. Introduction

As countries around the world work toward decarbonization, electrifications of automotive powertrains have been promoted in recent years, especially in environmentally advanced countries. On the other hand, emerging countries are facing issues such as the development of charging infrastructures, and it is considered necessary to reduce fuel consumption of hybrid vehicles by 2030. As strict fuel efficiency regulations are imposed on passenger car engines, technologies to reduce fuel consumption and emissions in actual driving conditions are being applied to gasoline engines. Applicable technologies for improving the thermal efficiency of gasoline engines include the Miller cycle with variable valves and exhaust gas recirculation (EGR). However, to improve the thermal efficiency while maintaining the torque, further improvement of the turbocharger efficiency is required.

Focusing on the fact that turbochargers mounted on engines are driven under exhaust pulsation, Mitsubishi Heavy Industries, Ltd. Group (MHI Group) has been working to improve turbine performance by elucidating flow phenomena using unsteady performance measurements and numerical flow analysis to understand turbine performance characteristics under exhaust pulsation. As a result, we have clarified that the absolute exit flow angle of the turbine scroll exit changes due to pulsation, and proposed the application of a mixed-flow turbine to suppress turbine leading edge loss [(1)]. **Figure 1** shows the turbine internal flow structure of one pitch of the rotor and indicates that higher losses are generated at high pressure ratios than at low pressure ratios under pulsation conditions. To propose an optimal turbocharger matching for each customer's engine, we are also working to develop an engine 1D simulation method using an unsteady low-dimensional model to evaluate transient behaviors of a turbocharger [(2)]. This report describes our initiative to develop a new turbine scroll shape that effectively utilizes the unsteadiness of exhaust pulsation and to measure its effect on an engine bench.

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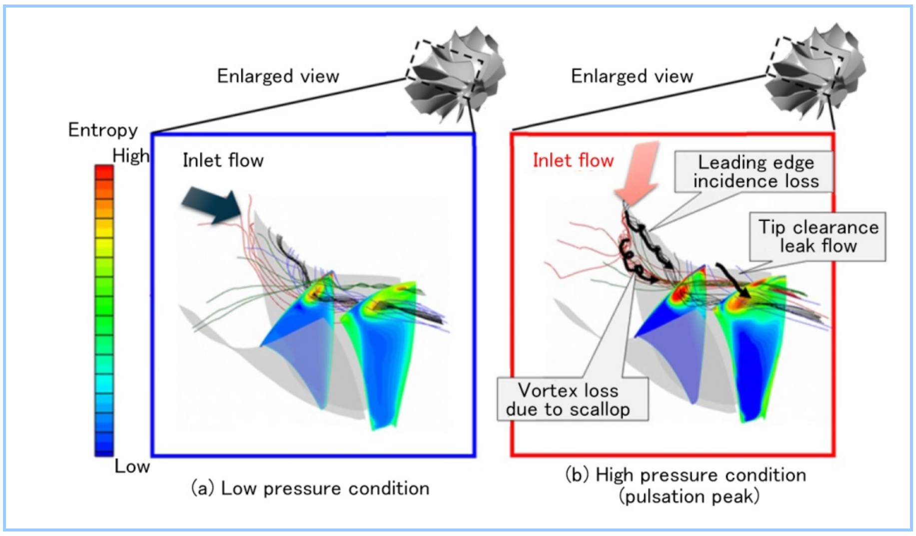

Figure 1 Turbine internal flow structure under pulsating condition

2. Improving turbine efficiency under exhaust pulsation

This chapter summarizes the design concept of a non-linear A/R turbine scroll that utilizes the unsteadiness of exhaust pulsation effectively.

(1) Design concept

To improve turbine performance, it is important to understand the flow phenomena under highly unsteady exhaust pulsating conditions. Therefore, we investigated the phenomena via validated numerical and analytical model of a sector scroll shown in **Figure 2** [(3)]. Equation (1) shows the mass conservation law in this model, where $\frac{dm}{dt}$ is time variation of mass flow rate variation within the sector region, C_θ is a tangential component of the velocity, C_r is a radial component of the velocity, A is the scroll cross-sectional area, R_c is a centroid radius of the scroll, b is an axial width of the scroll outlet and ρ is fluid density. The change in mass flow rate with respect to the control volume is expressed by Equation (2), and Equation (3) holds based on the law of conservation of angular momentum. By combining Equation (1) to Equation (3) with the ideal gas law, the absolute scroll exit flow angle α is derived as shown in Equation (4), where $\frac{d\left(\frac{A}{R_c}\right)}{d\theta}$ is the local gradient of A/R and $\frac{d\left(\frac{P}{T}\right)}{dt}$ is the time variation of the ratio of pressure and temperature. This equation represents the relationship between the scroll shape and pressure pulsation conditions and the absolute scroll exit flow angle. The first term on the right side of the equation indicates that scroll A/R affects the exit flow angle at a particular circumferential position. The second term on the right side of the equation indicates that the slope of the ratio of pressure to temperature affects the absolute exit flow angle and that the higher the frequency and amplitude of the pulsation and the more the unsteadiness, the greater its effect on the exit flow angle. **Figure 3** shows the effects of scroll A/R on the absolute scroll exit flow angle under pulsating conditions. These are one of the factors that make the unsteadiness inside the rotor stronger as the frequency and amplitude of the pulsation increases, and close examination of the unsteady term suggests that the unsteady effect of the pulsation on the flow distribution inside the scroll resulted from instantaneous mass imbalance in the sector region. To understand the performance characteristics of the turbine under exhaust pulsation, MHI conducted an unsteady performance test in collaboration with Imperial College London (ICL). **Figure 4** shows an example of the performance measurement results. In Figure 4(a), which summarizes the relationship between the mass flow parameter and pressure ratio, the unsteady flow characteristic has a hysteresis loop surrounding the steady flow characteristic. In the first half of the pulsation, the flow rate increases first, and then the pressure increases as the scroll is filled (Filling). Conversely, in the second half of the pulsation, the flow rate decreases first, and then the pressure decreases as the scroll empties (Empty). This results in a hysteresis loop. Figure 4(b), which summarizes the relationship between turbine torque and pressure ratio, also shows a similar considerable fluctuation. It was previously thought that the time scale of exhaust pulsation was much larger than the time scale of flow inside the turbine, and that the performance of the turbine rotor blade would be quasi-steady, but in fact it was found that the performance deviated from quasi-steady because of Filling & Empty and the propagation of pressure waves in the scroll and piping.

As such, while the circumferential variation of scroll A/R was conventionally linearly reduced with respect to scroll A/R at the scroll inlet, we developed a non-linear A/R scroll with a reduced scroll volume to suppress the hysteresis characteristics of the instantaneous turbine flow relative to the pressure ratio while maintaining the steady-state turbine flow characteristics. **Figure 5** shows the scroll A/R distribution of the new designed turbine.

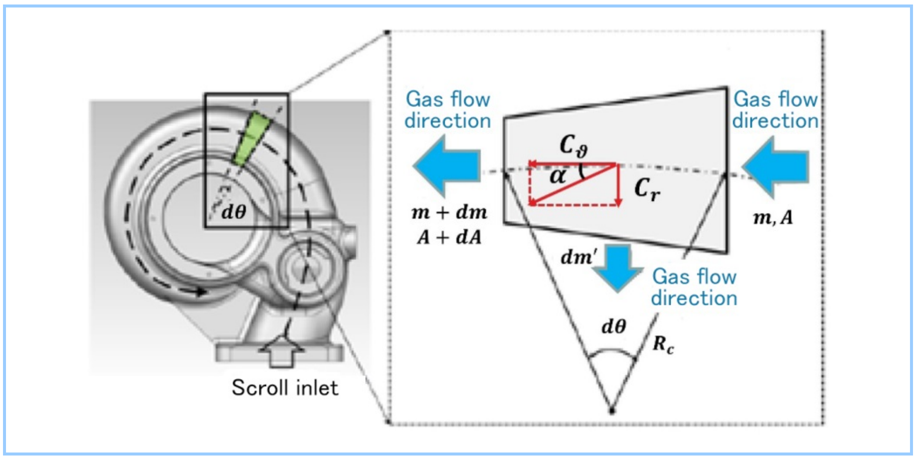

Figure 2 One-dimensional scroll sector model

$$\frac{dm}{dt} = \rho(C_\theta + dC_\theta)(A + dA) + bC_r R_c \rho d\theta - \rho C_\theta A$$
Equation (1) Mass conservation law

$$\frac{dm}{dt} = R_c A d\theta \frac{d\rho}{dt}$$
Equation (2) Variation of mass flow rate with respect to control volume

$$C_\theta R_c = K(const)$$
Equation (3) Law of conservation of angular momentum

$$\tan\alpha = -\frac{K}{b}\frac{d\left(\frac{A}{R_c}\right)}{d\theta} + \frac{AR_c}{Rb}\frac{d\left(\frac{P}{T}\right)}{dt}$$
Equation (4) Absolute scroll exit flow angle

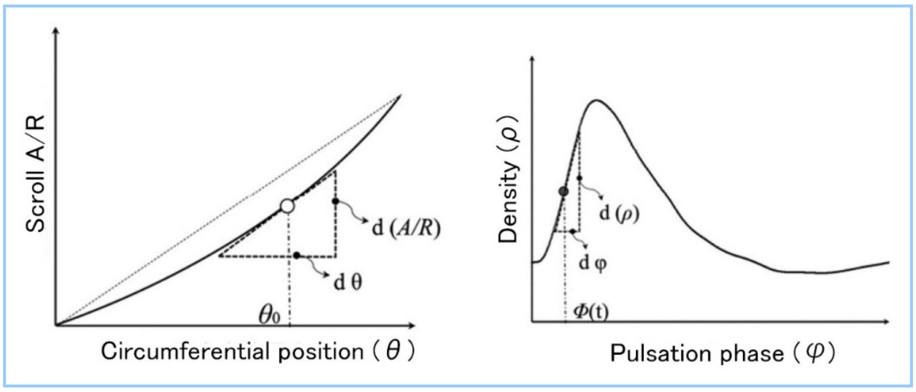

Figure 3 Effect of scroll A/R on absolute scroll exit angle under pulsation conditions

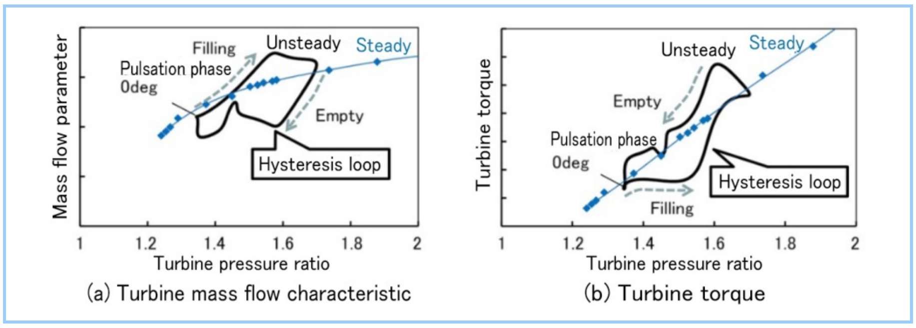

Figure 4 Unsteady turbine performance (Measurement results by Imperial College London)

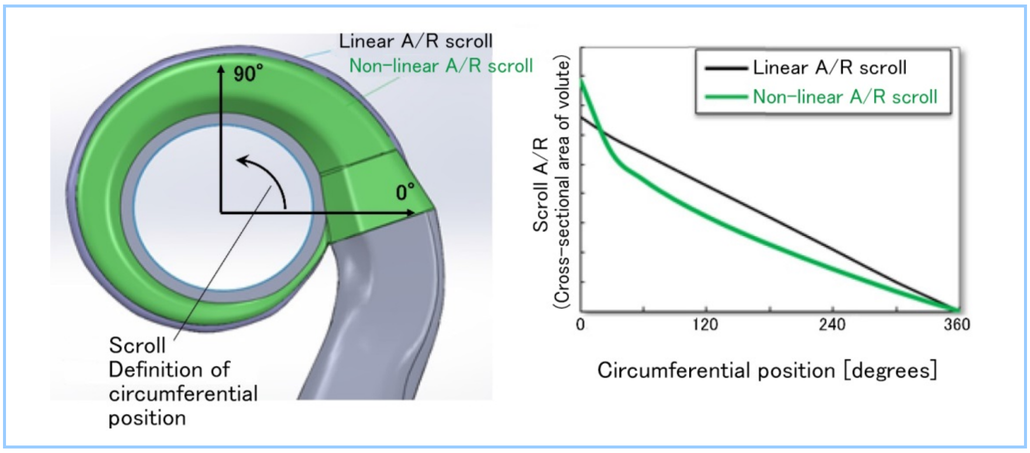

Figure 5 Comparison of linear A/R scroll and non-linear A/R scroll

(2) Unsteady flow simulation

This time, to confirm the effect of non-linear A/R scroll on performance improvement under exhaust pulsation, we used unsteady flow simulation to represent the exhaust pulsation and analyze the flow inside the turbine. **Figure 6** shows the analysis model. The inlet piping, turbine scroll, and turbine rotor were included as computational domains. **Table 1** shows the CFD conditions. Based on the test conditions, the total pressure and total temperature at the inlet boundary were given directly from the measured time series data under pulsation.

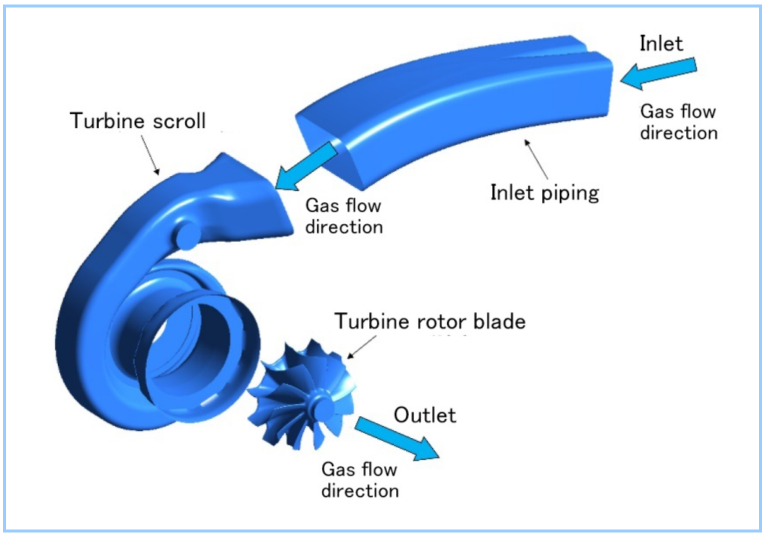

Figure 6 CFD model overview

Table 1 Summary of CFD conditions

	Parameter
CFD code	ANSYS CFX
Turbulence model	SST
Rotational speed	50krpm
Pulsation frequency	60Hz
Inlet boundary condition	Total pressure, total temperature
Outlet boundary condition	Static pressure
Mesh number	Scroll & inlet piping: 1,240,000 Rotor blade: 660,000
Time step	77 steps / Rotation

Figure 7 shows the unsteady CFD results comparison between the linear A/R scroll and the non-linear A/R scroll. The CFD results indicate that the non-linear A/R scroll maintains the same turbine flow characteristics, but the hysteresis characteristics of the instantaneous turbine mass flow under exhaust pulsating conditions are suppressed by changing the scroll cross-sectional area, resulting in improved turbine torque over a wide operating range. A comparison of cycle-averaged efficiencies under the pulsating conditions shown in Equation (5) indicates that the non-linear A/R scroll improved the efficiency by 1.3%, mainly due to turbine torque increase.

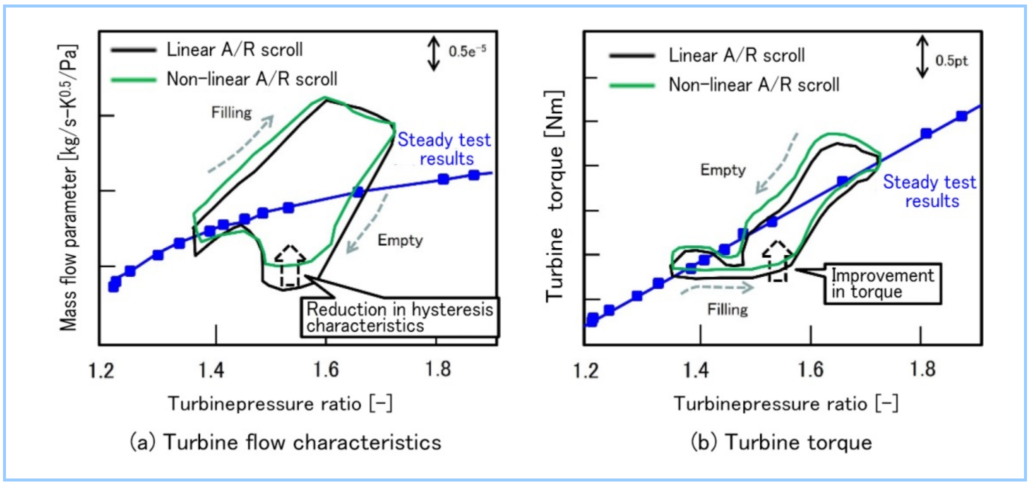

Figure 7 Comparison of turbine unsteady performance

$$\eta = \frac{\int_0^T (\tau \cdot \omega) dt}{\int_0^T \left\{ \dot{m} \cdot Cp \cdot T_0 \cdot \left(1 - \pi^{\frac{\kappa - 1}{\kappa}}\right) \right\} dt}$$

Equation (5) Turbine efficiency under exhaust pulsation

3. Engine test equipment

Next, we conducted an engine test in collaboration with Universiti Teknologi Malaysia (UTM) to confirm the effect of non-linear A/R scroll on engine performance. ICL and UTM have jointly established Low Carbon Transport in cooperation with Imperial College London (LoCARtic), a research organization at UTM to develop low-carbon technologies for transportation equipment, including turbocharger technology. LoCARtic has an engine test bench and can conduct various verification tests. This time, measurements of the pulsation pressure in turbine as well as the engine performance were conducted. To ensure a fair evaluation of each turbocharger, the settings of the measurement devices were matched as much as possible.

(1) Engine and turbocharger

This test used a UTM-owned 1.6-liter turbocharged gasoline engine for passenger vehicles. **Table 2** shows the manufacturer specification of the engine used in this test, and **Table 3** shows the testing turbocharger specifications. A waste gate turbocharger was used to match the engine displacement.

Table 2 Manufacturer specification of the testing engine

	Parameter
Displacement volume	1,561cc
Stroke	88mm
Bore	76mm
Compression ratio	9.5 : 1
Number of valves	4
Firing order	1-3-4-2
Fuel injection type	Common-rail port injection
Rated max. output	103kW @5,000rpm
Rated max. torque	205Nm @2,000-4,000rpm
Fuel type	Petrol RON95

Table 3 Testing turbocharger specifications

Turbine scroll	Linear A/R	Non-linear A/R
Turbine rotor	43 mm, 11 blades	
Compressor	51 mm, 6+6 blades	

(2) Measuring equipment

Figure 8 shows the schematic diagram of engine testing instrumentations. As shown in this figure, engine torque, speed, flow rate, pressure, temperature etc. were measured.

The engine crankshaft output is mechanically connected to the engine dynamometer via a coupling. In this test, a 260-kW AC dynamometer was used to not only load the engine but also drive it with the motor to realize the driving cycle test described below.

The air flow rate, fuel flow rate, cooling water flow rate, and lubricant flow rate of the engine were measured. The air flow was measured upstream of the turbocharger compressor, and two hot-film mass flowmeters with different capacities were connected in series to maintain measurement resolution to measure flow rate over a wide range from idling to maximum output.

On the intake side, pressure measurements were taken upstream and downstream of the compressor and intercooler. On the exhaust side, pressure measurements were taken at the manifold, turbine inlet, 45° and 135° circumferential locations of the scroll, and turbine outlet to investigate the pressure propagation of the pulsation in detail.

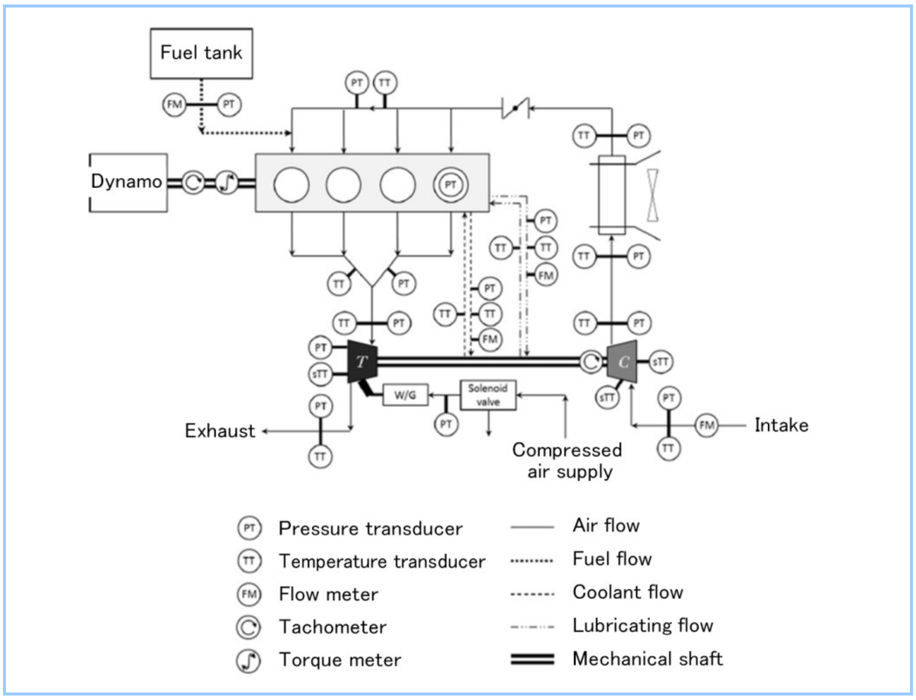

Figure 8 Schematic diagram of engine testing instrumentations

(3) ECU Tuning

In this test, the engine control unit (ECU) was tuned to match with the turbocharger to bring out the potential of the engine performance. The procedure that we followed to adjust the engine ECU is explained next. Stoichiometric condition of air-fuel ratio is ideal under all conditions, but often this is limited by the turbine inlet temperature at high engine speed and high load condition. In this test, the ignition timing was changed to improve combustion efficiency while achieving the target brake output torque with the turbocharger turbine exhaust temperature limited to 950°C or less. To achieve high engine efficiency, combustion with a high compression ratio and optimum ignition timing is required. Advancing the ignition timing to the optimum combustion timing improves the torque and fuel efficiency. If knocking was detected during the ECU tuning, the ignition timing was retarded by 3 degrees for safety reasons. Using the same procedure, the ECU tuning was adopted to each turbine scroll.

Figure 9 compares the results of the engine ignition timing map. It was confirmed that the non-linear A/R scroll allows more advanced ignition timing over a wider range than the linear A/R scroll. The mechanism of how the ignition timing was changed by the change of turbine scroll is discussed in the next chapter.

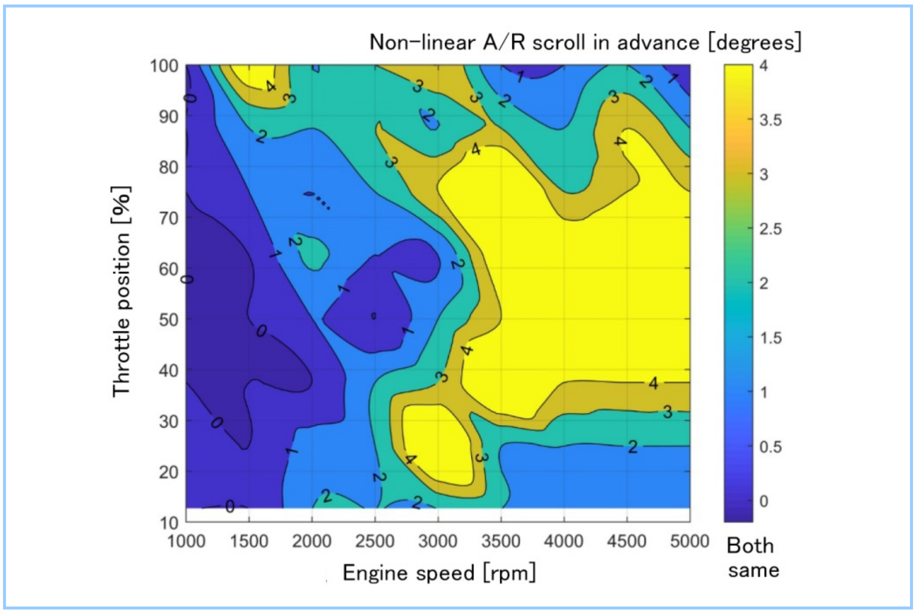

Figure 9 Comparison of ignition timings

4. Engine test results

This chapter reviews the results of the engine test. First, we compared the steady-state performance, and then compared the transient performance in the driving mode.

(1) Steady-state performance test

The measurement of steady-state engine performance was conducted at 1,000 rpm to 5,000 rpm at 500 rpm increments and at 12.5% to 100% throttle positions at 12.5% throttle increments. During the testing, the engine speed and throttle position were set to the target values, and under stationary conditions where all measurement temperature fluctuations were less than 2°C.

Figure 10(a) to Figure 10(c) show the measurement results of the pressure pulsations at the turbine inlet and at the 45° and 135° circumferential locations of the scroll. The amplitude of pressure fluctuation in the case of the non-linear A/R scroll was smaller than that of the linear A/R scroll. This indicates that the fluctuation of the exit flow angle at the turbine scroll outlet is suppressed in the case of the non-linear A/R scroll, and the turbine efficiency is expected to improve due to the reduction in the fluctuation of the exit flow angle. In addition, the maximum pulsating pressure in the case of the non-linear A/R scroll was lower than that of the linear A/R scroll at all crank angles and measurement locations. This indicates that the same engine brake torque was achieved with less exhaust energy. The improvement concept of the non-linear A/R scroll is to suppress torque fluctuation due to the hysteresis characteristics of the instantaneous turbine mass flow under exhaust pulsating conditions, and it is thought that the effect of enabling operation in a more efficient operating range was also obtained on this engine stand due to the weakening of the unsteadiness inside the turbine rotor. The reduction of turbine inlet pressure also affects the reduction of pump loss and knocking improvement in the intake and exhaust stroke of the engine, and as shown in Figure 9, the combustion efficiency in the case of the non-linear A/R scroll is higher because the ignition timing of the engine can be more advanced. **Figure 11** compares the specific fuel consumptions. The fuel consumption in the case of the non-linear A/R scroll was reduced over a wide range except in the low-speed, high-load region near 1,500 rpm, which confirms the effectiveness of the new turbine scroll in improving the thermal efficiency of the engine.

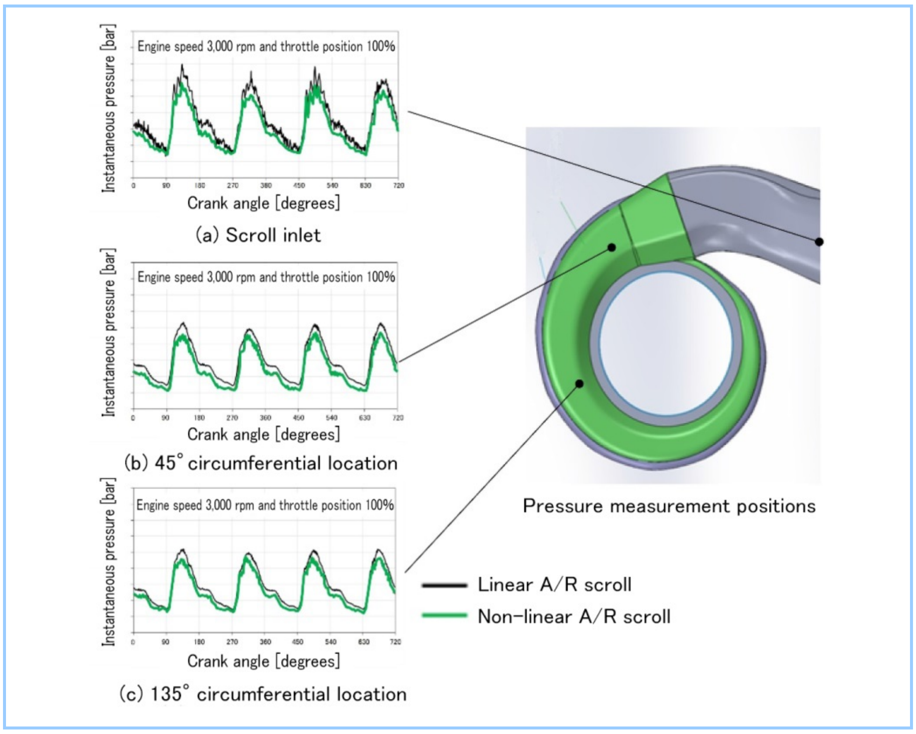

Figure 10 Turbine exhaust pulsation pressure

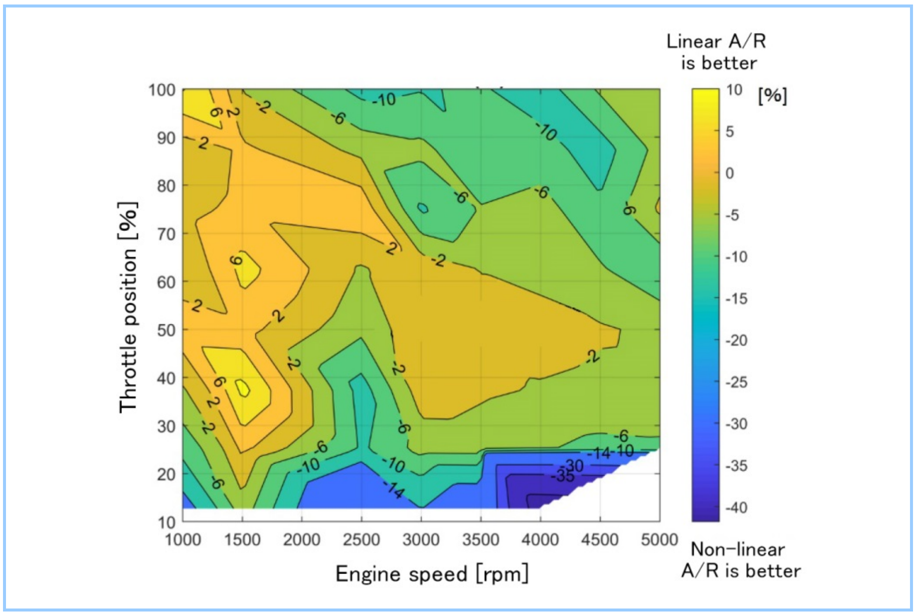

Figure 11 Relative difference of specific fuel consumptions

(2) Performance test in driving mode

Next, the measurement of performance in a driving mode was made. Here, total fuel consumption is compared in the Worldwide harmonized Light duty driving Test Cycle (WLTC). **Figure 12** shows the engine torque and speed for the driving mode. The WLTC driving mode consists of a relatively low-speed phase assuming urban areas affected by traffic signals and traffic congestion, a medium-speed phase assuming suburban areas not so affected by traffic signals and traffic congestion, and a high-speed phase and an extra high-speed phase assuming driving on highways. The higher speed the phase, the higher the engine speed and load, so the frequency and amplitude of the engine pulsation have a greater effect. **Figure 13** compares the specific fuel consumptions and fuel consumptions of the linear A/R scroll and the non-linear A/R scroll over the entire driving mode. The fuel consumption of the non-linear A/R scroll was improved by 0.04 liters (about 4.5%) at high speeds and 0.03 liters (about 3.5%) at extra high speeds compared to the linear A/R scroll, which indicates that the effect is greater in the high-speed phase, in which the frequency and amplitude of the engine pulsation have a greater effect. Comparison across WLTC modes, the fuel consumption was improved by 0.05 liters (about 1.7%) compared to the linear A/R scroll and this indicates the effectiveness of non-linear A/R scroll.

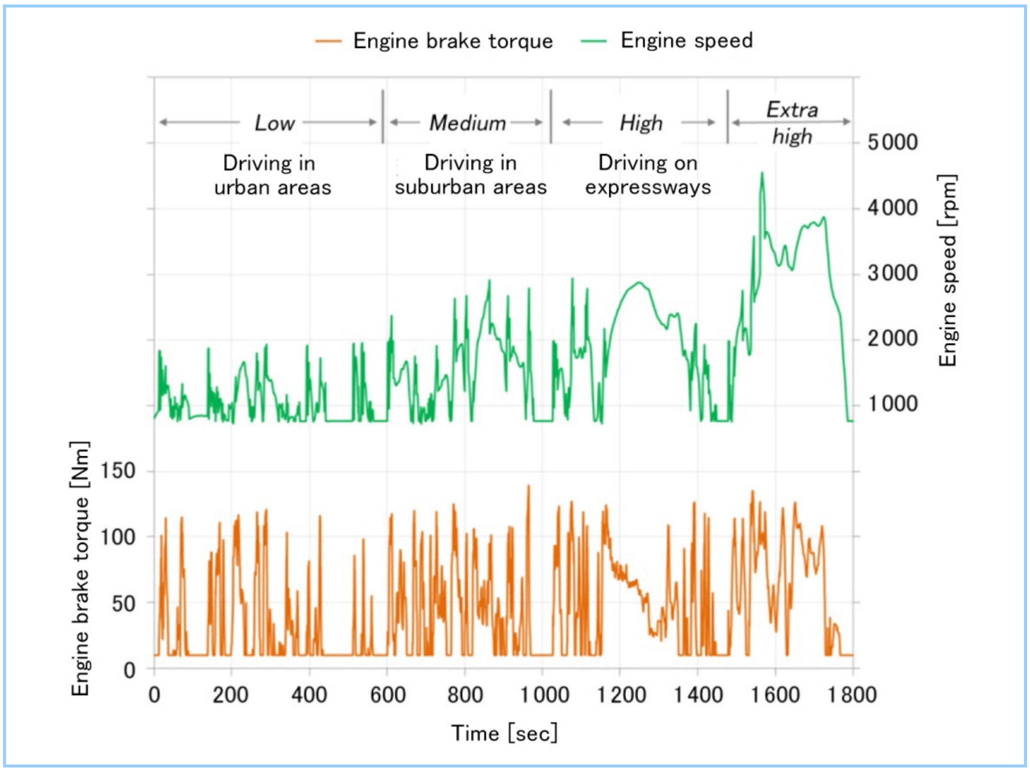

Figure 12 WLTC testing input profile – target engine brake torque and engine speed

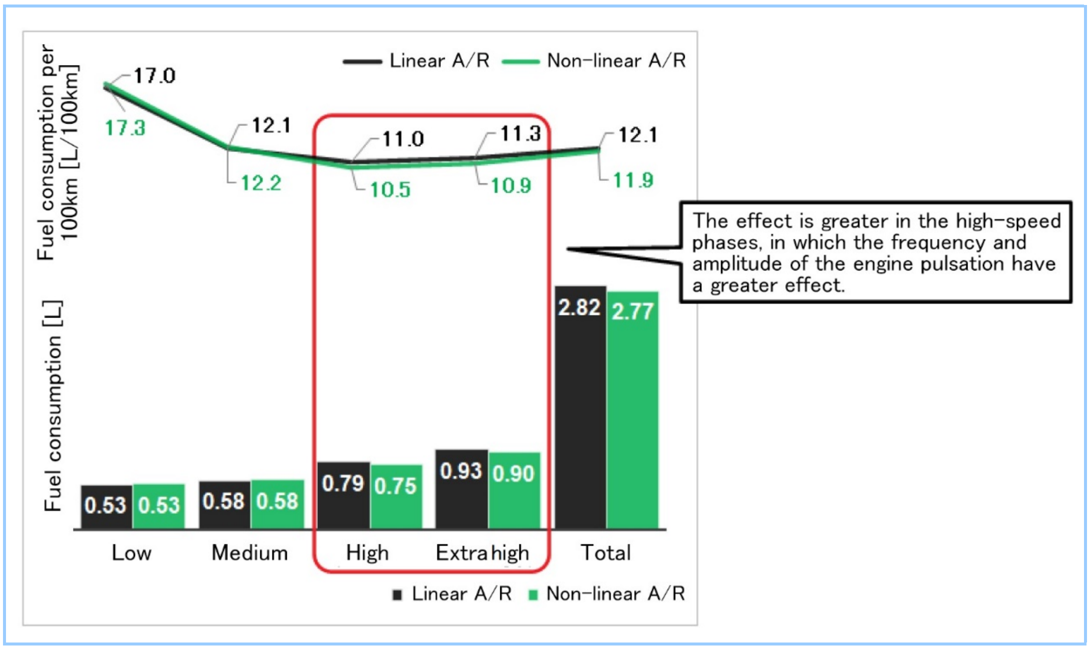

Figure 13 Comparison of specific fuel consumption and fuel consumption in WLTC mode

5. Conclusion

This report presented the development of a new turbine scroll shape that effectively utilizes the unsteadiness of exhaust pulsation and the verification of its effectiveness using a passenger vehicle gasoline engine on a test bench.

As countries around the world work toward decarbonization, passenger vehicle manufacturers are developing various technologies, including electrifications of the powertrain, but there is still abundant room for technological development to improve the efficiency of internal combustion engines to match hybrid vehicles. Turbocharging technology is one of the most effective means, and it is expected that the required turbocharging technology will continue to change in relation to other environmental technologies. The newly developed non-linear A/R turbine scroll, which is effective under exhaust pulsation conditions, is expected to improve fuel efficiency not only at engine full load but also over a wide range of partial loads where high EGR ratio is introduced. Therefore, it is expected to contribute to improving the engine efficiency of hybrid systems. We will continue to develop products that meet our customers' changing needs and contribute to the achievement of a low-carbon society and global environment protection.

Finally, we would like to thank Professor Martinez-Botas of ICL, Professor Rajoo of UTM, and Associate Professor Yang of Shanghai Jiao Tong University for their cooperation in this development through the joint research.

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