

Development of High-performance Diesel Engine Compliant with Euro-V

Ryuta MATSUI* Kazuaki SHIMOYAMA* Isao CHIBA*
Shoshi HIDAKA* Shigeji NONAKA*

ABSTRACT

Honda has developed a 2.2 L 4-cylinder turbocharged diesel engine that has achieved high power, low fuel consumption, and ultra low emissions. This is a second-generation diesel engine, following Honda's first diesel power plant for automobiles launched in 2004. The newly developed engine has realized larger reductions in exhaust emissions, enabling compliance with Euro-V standards, as well as enhancements in output and in noise and vibration (NV) reduction, while also maintaining fuel economy equivalent to that of the previous engine. A 180 MPa common-rail system was adopted and the shape of the combustion chamber was optimized for even lower exhaust emission performance. A recently developed, highly efficient variable nozzle turbine (VNT) was adopted and intake and exhaust system performance has been upgraded for enhanced output. Where the maximum output and torque of the previous model engine were 103 kW/340 Nm, these figures have been raised to 132 kW/380 Nm, signifying a larger increase. NV performance has become a concern for diesel-powered passenger vehicles. The structural response of the cylinder block has been bettered by optimizing the cylinder block structure, and a new chain drive-line layout and chain cover structure capable of reducing vibration and noise have been developed. As a result, the NV performance of this engine is better than that of previous diesel engines.

1. Introduction

Within the context of growing worldwide concern for environmental issues, the demand for diesel engines that have a large impact in CO₂ reduction and high power performance has been expanding rapidly, particularly in Europe. Diesel power performance has been rising to that on par with gasoline engines. Meanwhile, however, the European exhaust emissions standards that are scheduled to take effect in 2009 (EURO-V) will be much more rigorous than the current EURO-IV standards.

The first diesel engine Honda developed to be manufactured in-house was developed for use in the ACCORD in 2003, and it complied with EURO-IV at that time, before those standards were enforced.^{(1) - (3)} This model subsequently saw wider use in the CR-V, CIVIC, and FR-V, as well, and was well received by the market. During that time, a diesel particulate filter (DPF) system capable of reducing emissions of particulate matter (PM) to lower levels was also developed and put into use.⁽⁶⁾ Following those developments, Honda has developed a second-generation diesel engine that achieves greatly

enhanced power performance and reduced exhaust emissions as well as reduced noise and vibration. This paper reports on the development concept, the achieved performance, and the technology that was applied to that end.

2. Development Concept

The concept for the present engine was to maintain the fuel economy characteristics of previous models while also achieving top-class power performance and EURO-V compliance. Controls on exhaust emissions have become particularly rigorous in recent years, and the new standards will require NO_x approximately 28% lower and PM 80% lower than EURO-IV. Achieving these levels called for the development of NO_x reduction technology using highly precise combustion control as well as the enhancement of PM reduction technology through use of the DPF developed in 2005. Figure 1 shows recent trends in exhaust emission regulations. Previous models had already earned good reputations for their handling of the noise and vibration typical of diesel engines, and the goal

* Automobile R&D Center

for this model was to attain performance that was still one rank higher. One of the issues was combustion noise, which had to be reduced in balance with the reduction in exhaust emissions. This necessitated still more advanced control technology. In structural systems, vibration control and noise prevention also became necessary in the cylinder block and chain case in particular.

The following three items were pursued as the core technologies for achieving the above objectives.

- (1) Lightweight, highly rigid, quiet engine frame
- (2) Highly precise combustion control
- (3) Highly efficient exhaust processing system

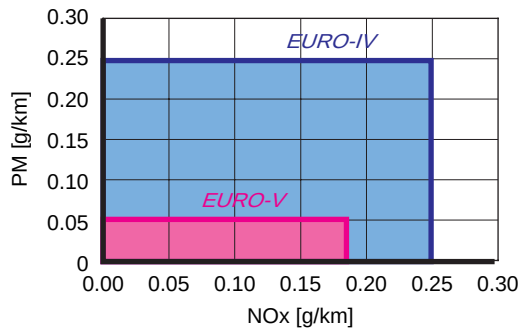


Fig. 1 Exhaust emission regulations

3. Overview of Engine

3.1. Overview of Engine and Major Specifications

The maximum power and maximum torque of this engine have been increased to 132 kW and 380 Nm, compared to 103 kW and 340 Nm in the previous model. The increased maximum combustion pressure that accompanied the upgraded power output was handled by reinforcing the strength of the cylinder block, the cylinder head, and other engine frame parts.

A third-generation common-rail system, manufactured by Bosch, that has a piezoelectric injector with a maximum injection pressure of 180 MPa were adopted for the fuel injection system in order to balance the requirements of increased power output and compliance with EURO-V regulations.

The DPF system developed and put on the market in 2005 was further enhanced and included as standard equipment to make the exhaust after-treatment system comply with EURO-V regulations. A layout was adopted that places the DPF directly under the turbocharger with the oxidation catalyst. This enabled enhancement of DPF regeneration performance. The engine also incorporates a new front exhaust with a view to packaging, including for installation on other vehicle models. An external view of the engine is shown in Fig. 2, and the main specifications are in Table 1.

Table 1 Main specifications of i-DTEC diesel engine

Engine	Developed model	Previous model
Cylinder configuration	In-line 4-cylinder	In-line 4-cylinder
Bore × stroke (mm)	85 × 96.8	85 × 97.1
Displacement (cm ³)	2197	2204
Compression ratio	16.3	16.7
Valve Train	DOHC 4 valves	DOHC 4 valves
Fuel injection system	180 MPa common rail	160 MPa common rail
Maximum power [kW/rpm]	132/4000	103/4000
Maximum torque [Nm/rpm]	380/2000	340/2000

3.2. Main Elements of Engine Structure

The same advanced semisolid casting technology (ASCT) used to fabricate the cylinder block for the previous model was adopted and closed-deck block structure for the offset cylinder layout was realized in this engine. The rise in combustion pressure from the higher power was handled by developing cylinder head gaskets with a new structure and upgrading the strength of the area around the bearing caps.

The basic design for the cylinder heads is like the previous model in that it has a layout of in-line valves and center injection. As shown in Fig. 3, it was also made lighter and more compact by lowering the height of the cylinder head while also enhancing productivity and assuring strength. In order to support the increased combustion pressure, the thickness of the gasket was increased and particular efforts were made to assure that

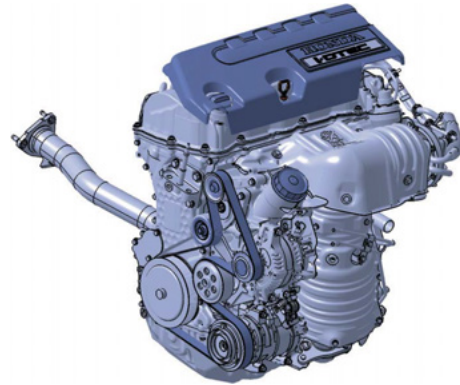


Fig. 2 External view of i-DTEC diesel engine

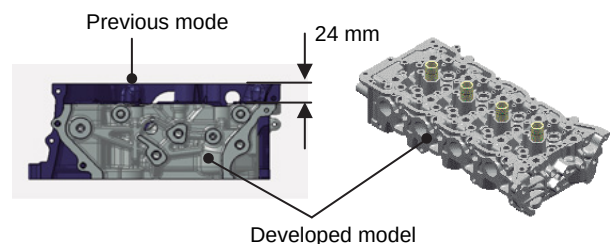


Fig. 3 Comparison of cylinder head configuration

the interior structure of the water jacket would have adequate strength to sustain high power output by conducting structural analysis using computer-aided engineering (CAE) to find ways of reducing stresses.

Figure 4 shows this engine valve assembly layout and vacuum pump location, compared to the previous model. As will be explained below, this design seeks to reduce chain meshing noise and achieve greater compactness by adopting a two-axis layout for the valve drive assembly in which the vacuum pump is driven by an Oldham coupling from the transmission end of the exhaust cam shaft, instead of the three-axis layout for the vacuum pump drive in the previous engine.

3.3. Fuel Injection System

The fuel injection system uses a piezo-electric injector with a maximum injection pressure of 180 MPa in order to reduce exhaust emissions by achieving a balance between enhancement of spray characteristics and greater power output. The injector body contains an integrated actuator formed by alternating layers of piezo-electric elements and electrodes. The moving parts that operate during injection are therefore more compact than in a solenoid type injector, enabling reduction of the total height of the cylinder head. Figure 5 shows a general view of the piezo-electric injector.

The higher responsivity of the actuator is reflected

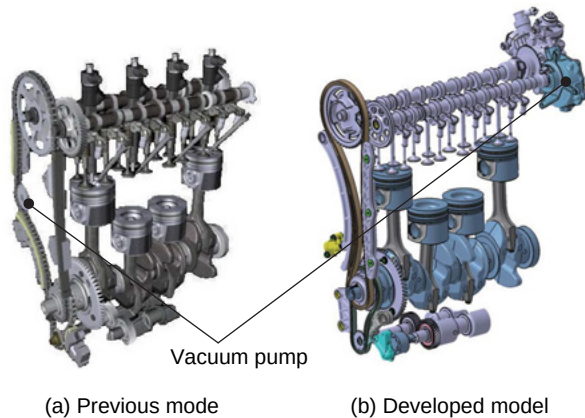


Fig. 4 Schematic diagram of drive train system

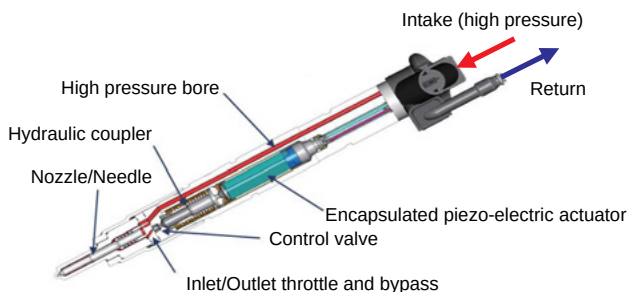


Fig. 5 Drawing of Bosch piezo-electric injector

more efficiently in the injection characteristics, yielding a nearly rectangular injection rate waveform. The time needed to activate the actuator and reach maximum injection volume has been shortened approximately 40% compared to the previous model. This has increased the possible range for microinjection fuel volume and interval settings during multiple injection, which is important for the reduction of both exhaust emissions and NV. These measures have enabled higher precision combustion control.

4. Main Technical Details

4.1. Combustion Technology

Figure 6 shows an overview of the exhaust emissions objectives achieved.

The EURO-V regulations apply more rigorous controls, particularly on PM and NOx emissions. Reduction of PM calls for the air utilization rate to be enhanced, and reducing NOx emissions calls for combustion temperatures to be lowered. In order to reduce PM emissions, therefore, the combustion chamber was made the reentrant type, which has a shallower, more dish-like shape than the previous model.^{(4),(5)} This is intended to achieve a uniform air-fuel mixture by spreading the fuel spray, and to limit the dispersion of fuel outside the combustion chamber might cause by the longer period of fuel injection occasioned by higher power output. A balance between higher power output and NOx reduction was also sought by reducing the compression ratio to 16.3 from 16.7 for the previous model and by lowering the combustion temperature. Figure 7 shows the shape of the combustion chamber.

The injector nozzle was positioned at the center of the combustion chamber. The number of nozzle holes was

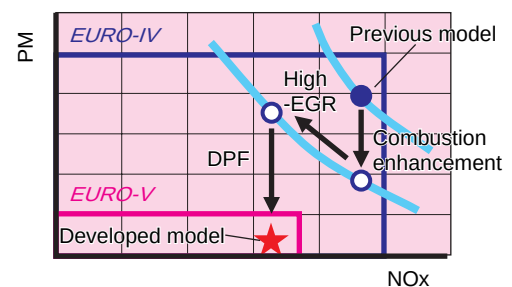


Fig. 6 Enhancement of exhaust emissions

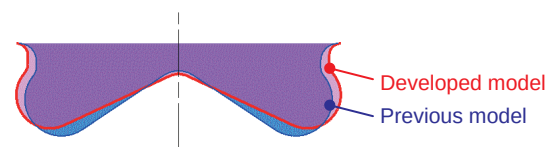


Fig. 7 Shape of combustion chamber

Table 2 Specifications of injection system

Specification	Developed model	Previous model
Injector specification		
Type	Piezo-electric	Solenoid
Max. injection pressure [MPa]	180	160
Number of holes	7	6
Hole Dia. [mm]	$\phi 0.12$	$\phi 0.13$
Spray angle [deg]	156	153
Type of sac	Micro sac	Micro sac
HP-pump specification		
Type	V	Radial
Number of plungers	2	3
Bore $\times$ stroke [mm]	$\phi 6.5 \times 6.0$	$\phi 6.5 \times 6.8$
Type of cam	2-lobe	Eccentric
Driving speed	1/2 crank speed	5/6 crank speed
Flow control	Suction control	Suction control

increased from 6 in the previous model to 7 holes, and the spray cone angle was broadened. This served to enhance the spray atomization and the air utilization rate, achieving reductions in PM and HC emissions. The nozzle hole diameter was decreased while the number of nozzle holes was increased in order to keep the total nozzle hole area generally equivalent to the previous model. This achieved a balance between enhancement of power output and reduction of engine-out exhaust emissions. Table 2 shows the injector nozzle and fuel pump specifications of the developed model in comparison with the previous model.

A key factor in achieving reduction of exhaust emissions and enhancement of fuel consumption, and further in achieving reduction of combustion noise, is setting the optimum in-cylinder flow according to engine operating conditions. The intake manifold has been fitted with a continuously variable swirl control valve (SCV) as in the previous model in order to generate an optimum swirl under various conditions. For the present SCV control system, the vacuum control used previously was changed to electrical control in order to support combustion control with greater response and higher precision.

The exhaust gas recirculation (EGR) system, which is important for NO_x reduction, has been combined with a highly efficient EGR cooler in order to raise the EGR rate. It also employs an EGR cooler bypass system that has a switchover mechanism to realize stable combustion at lower EGR gas temperatures. The adoption of an electrically operated EGR valve and a tournament-type arrangement of ports for EGR gas distribution also support enhanced control response and decreased inter-cylinder variation. The increase in PM emissions brought on by enhancement of the EGR rate was addressed through adoption of the DPF system.

The use of these technologies achieved compliance with the EURO-V exhaust emissions regulations.

The distinctive combustion noise of the diesel engine was addressed using multiple injection, which is the

advantage of the common rail system. This approach varies the number and pattern of pilot injections in accordance with operating conditions and environmental conditions.

Figure 8 shows the engine power curve at full load power. Increasing the intercooler size and placing the radiator at the front enhanced fresh air cooling performance. In combination with the higher injection rate resulting from the increase in fuel injection pressure noted above, this has enabled greater power output. A newly developed VNT was adopted for the exhaust system in order to perform highly efficient conversion to supercharged energy. This realizes high-level supercharging and response while also enabling balanced distribution of EGR volume and optimum fresh air volume according to operating conditions in the partial load range, thus enabling reduction of exhaust emissions. Figure 9 shows a general view of the VNT. The DPF diameter was also increased for the purpose of reducing pressure drop.

4.2. Exhaust Gas After-treatment Technology

In order to reduce exhaust emissions, it is important to enhance the performance of the exhaust gas after-

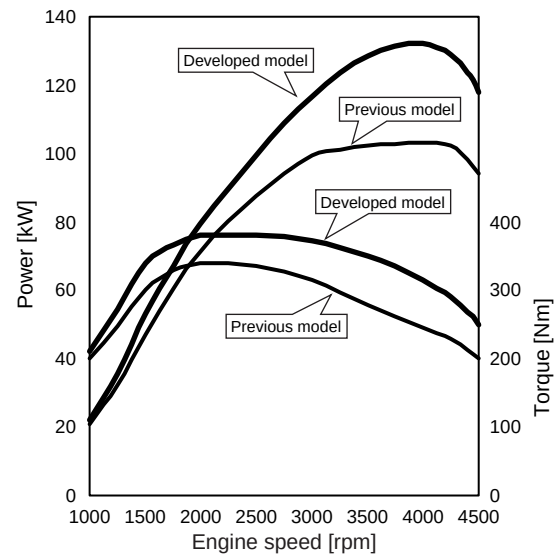


Fig. 8 Power curve of i-DTEC engine

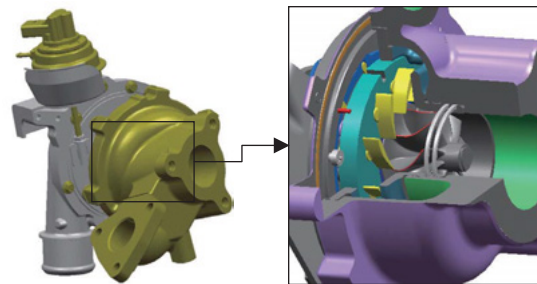


Fig. 9 Variable nozzle turbocharger

treatment system and to do so in conjunction with development of the combustion technology described above. It is important to enhance the PM regeneration performance of the DPF and have faster light-off of the catalyst during cold starts of the diesel engine, which has particularly low exhaust gas temperatures.

The layout of the exhaust after-treatment system for this engine has a diesel oxidation catalyst (DOC) with an air gap in the low heat-mass structure located directly beneath the turbocharger. Immediately behind it is the DPF. This realizes a balance between shortening the time to light-off of the catalyst during the air-warming process and enhancing DPF regeneration performance.

4.2.1. Air gap oxidation catalyst

The oxidation catalyst has a two-layered structure with an air gap in between. This achieves fast, stable catalyst light-off by limiting the drop in catalyst temperature while the air is cool immediately after starting the engine. Figure 10 shows a general view of the air gap structure.

4.2.2. DPF system

Figure 11 shows a layout diagram of the exhaust system.

This engine has the DPF placed immediately behind the DOC so as to limit the cooling of exhaust gases on their way to the DPF during regeneration. This enabled a temperature reduction of nearly 100°C in the DOC with

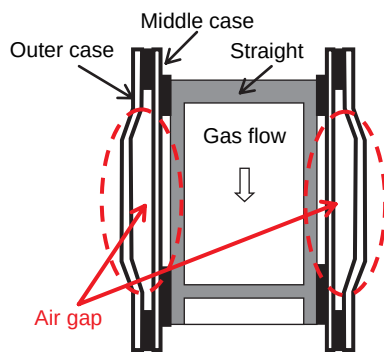


Fig. 10 Close coupled DOC with air gap

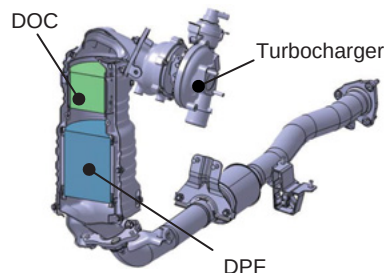


Fig. 11 Close coupled DOC and DPF

the DPF temperature remaining the same. Figure 12 shows the DPF temperature characteristics during regeneration. Taking advantage of the impact of this DOC temperature reduction enabled the DPF temperature to be raised nearly 30°C while limiting the rise in DOC temperature during regeneration. Greater PM combustion speed, reduction in the amount of precious metal, and limitation of deterioration in exhaust gas purification performance have been achieved as a result. Lowering of the exhaust system heat mass before the DPF has also enabled shortening of the warm-up period during regeneration.

Figure 13 shows the time required for regeneration and the impact of reduction in total post injection quantity. Compared to the previous model, this engine has achieved a 19% shortening of regeneration time and 37% reduction in total post injection quantity.

4.2.3. Enhancement of DPF control

The system utilizes post injection in DPF regeneration. During regeneration, the diesel oil component of the fuel mixes with the engine oil (referred to below as “oil dilution”), may be causing concern about reliable

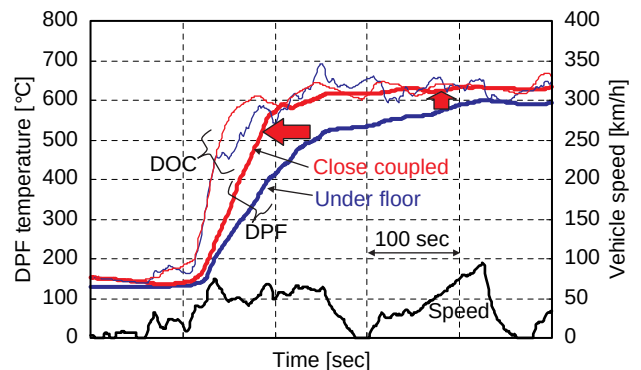


Fig. 12 Effect of close coupled DPF for DOC and DPF temperature

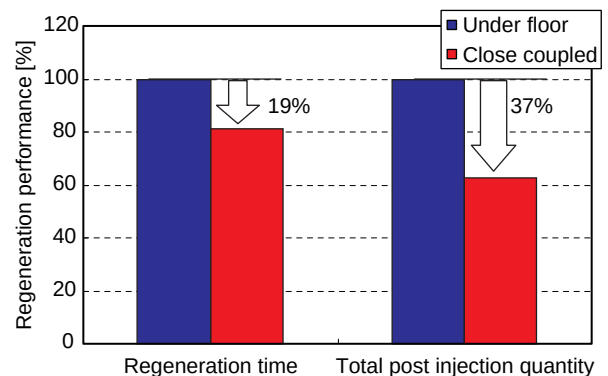


Fig. 13 Effect of close coupled DPF for regeneration performance

durability. With the previous model it was necessary to assume the worst case for conditions of use and limit post injection quantity. With the present engine, however, the cause of dilution and the evaporation mechanism have been understood so that the level of dilution can be computed in the ECU, enabling enhancement of regeneration performance while maintaining reliability. This has yielded regeneration performance in the top class.

4.3. Noise and Vibration (NV) Reduction Technology

With the roller chain generally employed in diesel engines, the reduction of chain meshing noise is important for assuring quietness. Measures taken in the developed engine, including the layout change, have reduced this chain meshing noise. The increase in noise that occurs with increased power output has also been addressed by means of structural systems, as detailed in the following.

4.3.1. Reduction of chain noise

The cam drive chain formerly had a three-axis layout with a sprocket-driven vacuum pump. This was changed to a two-axis layout driven by an Oldham coupling from the exhaust cam shaft. As a result, the large vibrating force generated when the small-diameter sprocket wheel meshed with the chain no longer acted on the vacuum pump shaft, and this reduced the meshing noise from the cam drive chain.

The noise radiating characteristics of the chain case are a major factor influencing the chain noise mechanism. The measures applied to the developed engine include giving the case a dimpled shape and increasing the number of layers in the vibration damper plate in order to enhance its vibration damping performance. This is yielding a reduction effect. Figure 14 shows the shape of the chain case.

Implementation of these measures has resulted in a reduction in chain meshing noise, including on the oil pump drive side, compared to the previous model. Figure 15 shows the levels of chain noise achieved.

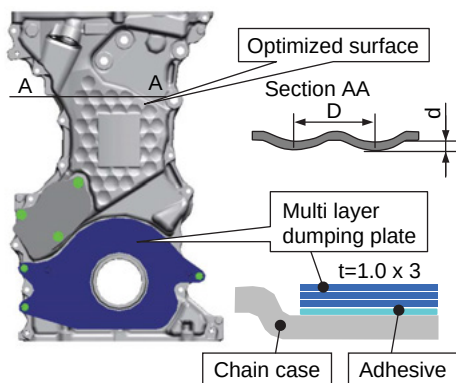


Fig. 14 Optimized chain case

4.3.2. Reduction of noise radiation

The rise in output power is accompanied by increased combustion pressure. This tends to increase combustion excitation force, which is a source of radiant noise, and thus is a factor in worsening noise. These issues were addressed by optimizing the shape of the crankshaft, the cylinder head, the cylinder block, and other such components with the goal of assuring strength and rigidity as well as enhancing structural damping. Measures were also taken, as described above, to optimize the surface shape of the chain case and the oil pan. In combination with the combustion noise reduction effect from multiple injection, these measures achieved noise levels equivalent to those of the previous model even while output power was being raised by 40 Nm. Figure 16 shows the noise radiation levels that were achieved.

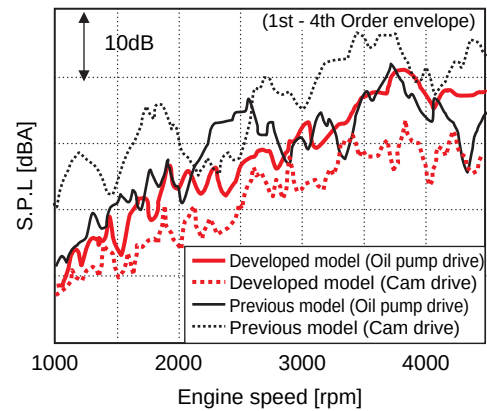


Fig. 15 Effect of developed chain drive system and chain case for chain drive noise reduction

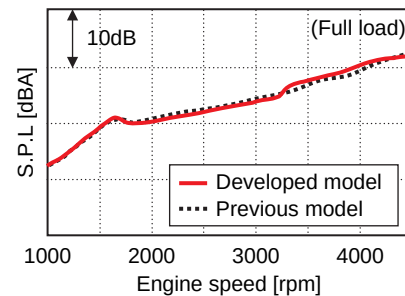


Fig. 16 Comparison of engine radiation noise

5. Conclusion

Honda has developed a second-generation diesel engine that achieves good exhaust emissions performance that both reduces CO₂ emissions and enables compliance with the EURO-V exhaust emissions regulations. In addition to this high level of environmental performance, the engine simultaneously achieves high power

performance and quietness. The developed engine thus is highly capable of providing users with satisfying driving pleasure. Development of this engine yielded the following results:

- (1) A new combustion chamber shape and a 180-MPa common rail system were adopted, and a highly efficient exhaust gas after-treatment system was incorporated. With this combination, the new engine has already achieved compliance with EURO-V emissions standards.
- (2) High power performance has been achieved while reducing exhaust emissions by reducing the compression ratio, employing a highly efficient VNT, and enhancing the exhaust system.
- (3) Performance on the higher level is assured with regard to quietness and fuel consumption.
- (4) Upgraded DPF regeneration performance under cold water and low load operating conditions together with engine oil dilution management have realized an after-treatment system that provides higher performance and higher reliability.

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■ Author ■



Ryuta MATSUI



Kazuaki SHIMOYAMA



Isao CHIBA



Shoshi HIDAKA



Shigeji NONAKA