

Development of 3-stage i-VTEC VCM Engine for CIVIC Hybrid

Shigeo OKUI*
Naohiro ISHIKAWA*

Tsutomu KISHI*
Kohei HANADA*

ABSTRACT

A 1.3 L 3-stage i-VTEC VCM engine, which satisfies both low fuel consumption and low emission requirements, was developed for the 2006 CIVIC Hybrid. In the development of this engine, friction was greatly reduced and volumetric efficiency was increased. In addition, VTEC technology was evolved to realize a 3-stage i-VTEC VCM that enables 3-stage valve motion switchover at low and high engine speeds and during cylinder idling. With the increased motor output, it is possible to run the automobile on the motor alone over a wider range of driving conditions, and to realize a further reduction in fuel consumption. The newly developed engine, higher power motor and more efficient CVT transmission enable the 2006 CIVIC Hybrid to achieve better vehicle dynamic performance and a fuel consumption of 31.0 km/L in the 10-15 mode. In addition, the performance of the high density 2-bed, 3-way catalyst has been increased, realizing low emissions equal to 75% of the low emissions standard for fiscal 2005.

1. Introduction

The necessity of protecting the global environment and conserving resources is increasing demands for greater automotive fuel economy and reduced exhaust emissions. Responding to those demands, Honda has continued to research and develop Variable Valve Timing and Lift Electronic Control (VTEC)-equipped next-generation engines^{(1),(2)}. Honda has also developed a proprietary Integrated Motor Assist (IMA) system, a hybrid powertrain combining an electric motor and an engine that was first used in the ultra-high fuel economy 1999 Insight⁽³⁾. The IMA system was also used to enhance fuel economy in the CIVIC Hybrid⁽⁴⁾, a hybrid small sedan marketed in 2001.

A new powertrain has been developed for the 2006 CIVIC Hybrid, using the LDA-MF3 engine⁽⁴⁾ from the 2001 model as the base engine. Friction has been reduced and volumetric efficiency enhanced in the new LDA-MF5 engine. In addition, the engine has been provided with a 3-stage i-VTEC Variable Cylinder Management (VCM) mechanism, enabling switching between three stages of valve operation: Low engine speeds, high engine speeds, and cylinder idling (valve deactivation). The power of the motor and the torque capacity and transmission efficiency of the CVT have also been enhanced, increasing the efficiency of the powertrain as a whole.

This paper will discuss the new technologies used in the LDA-MF5 engine, with a focus on the 3-stage i-VTEC VCM mechanism.

* Automobile R&D Center

2. Development Goals

The IMA system used in the 2001 CIVIC Hybrid enabled the vehicle to achieve the world's top level of fuel economy for a small 5-passenger sedan.

In the new development, all aspects of the hybrid powertrain were enhanced, and development goals were set for achieving enhanced driving performance and fuel economy as well as greater passenger comfort, all in a more compact package.

The specific targets were as follows:

- (1) Fuel economy of 31.0 km/L in domestic 10-15 mode
- (2) Acceleration performance of 0-100 km/h in 12 seconds
- (3) An emissions level 75% lower than the FY2005 low emissions standards
- (4) High responsiveness and a natural drivability equivalent to that of a gasoline vehicle, offering exhilarating driving in all ranges

3. Hybrid System

The new system uses a thin DC brushless motor, which is positioned between the engine and the CVT and is directly connected to the engine crankshaft. An integrated power unit (IPU), containing the high-voltage components (the inverter unit that drives the motor, a high-voltage Ni-MH battery pack, etc.) and a cooling system, is located in the trunk behind the rear seat. The power cable connecting the motor and the IPU runs underneath the floor

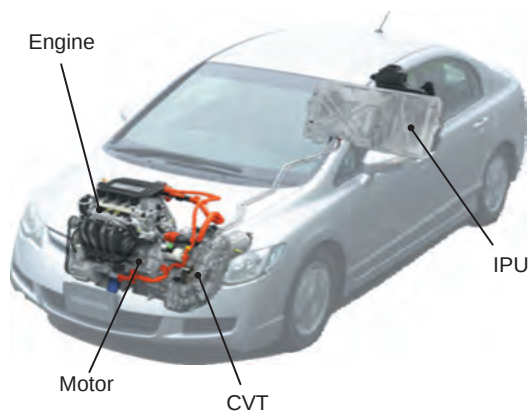


Fig. 1 IMA system construction

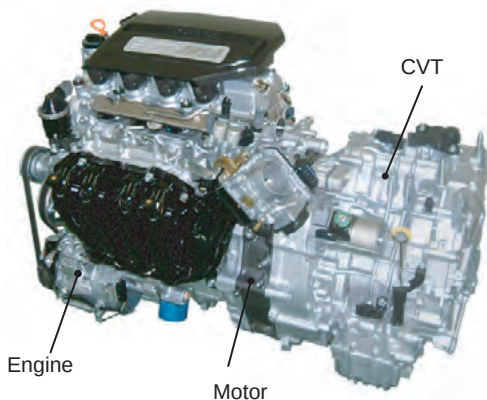


Fig. 2 View of newly developed hybrid powertrain

Table 1 Engine specifications

Engine code	LDA-MF5	LDA-MF3
Cylinder configuration	In-line 4-cylinder	In-line 4-cylinder
Bore × stroke (mm)	73 × 80	73 × 80
Displacement (cm ³)	1339	1339
Compression ratio	10.8 : 1	10.8 : 1
Valve train	SOHC 3-stage VTEC	SOHC 2-stage VTEC
Number of valves	2 per cylinder	2 per cylinder
Valve diameter (mm)		
Inlet	35	32
Exhaust	30	28
Fuel supply system	Programmed fuel injection	Programmed fuel injection
Ignition system	Dual point sequential ignition	Dual point sequential ignition
Intake manifold Diameter × length (mm)	34 × 340	30 × 200
Exhaust manifold	Integrated cylinder head	Conventional
Gasoline	Regular (RON91)	Regular (RON91)
Max. power (kW/rpm)	70/6000	63/5700
Max. torque (Nm/rpm)	123/4600	119/3300

of the cabin. Figure 1 shows the configuration of the components in the vehicle. Figure 2 shows an external view of the hybrid powertrain.

With the engine as the main power source and the motor functioning as a supplementary power source, it was possible to make the overall system simple and lightweight.

4. Overview of Engine and Main Specifications

Table 1 shows a comparison of the major specifications of the LDA-MF5 engine and the LDA-MF3 engine used in the 2001 CIVIC Hybrid. In the newly developed engine, the diameter of the inlet and exhaust valves has been increased, the shape of the inlet and exhaust ports has been optimized and a long, large-diameter intake manifold with a plastic resonator has been used. This resulted in increased volumetric efficiency and an 11% increase in power. A variety of measures were taken to reduce friction, including integrating the exhaust manifold and cylinder head to enable rapid heating of the cooling water. In addition, the new 3-stage i-VTEC VCM mechanism enables the system to switch between low and high engine speed valve timing and deactivate the valves to balance fuel economy and power.

Figure 3 shows a cross section of the intake manifold with attached plastic resonator. The optimum pipe length and diameter ($\phi 34 \times 340$ mm) for power at high engine speeds were used. This resulted in an increase of approximately 5% in volumetric efficiency at 4500 rpm and above compared to the intake manifold used in the LDA-MF3 engine. Positioning the resonator over the chamber synchronized resonating frequencies, resulting in increased volumetric efficiency in the medium engine speed range. As Fig. 4 shows, when the resonator is in operation, the intake port pressure directly before closure of the intake valve is higher, resulting in increased air intake. Figure 5 shows the effect of the resonator on the power characteristic. The resonator increases power between 3000 and 4000 rpm, resulting in the achievement of an excellent torque characteristic.

Figure 6 shows an external view of the exhaust manifold integrated cylinder head, and the configuration of the water jacket. This configuration ensures that exhaust gas concentrates in the cylinder head. Heat from the exhaust gas heats the cooling water, reducing the time required to warm up the engine. Also, eliminating the steel exhaust manifold decreased the weight of the engine.

Figure 7 shows a diagram of the cooling water circulation channels. The cooling water flows first to the cylinder head, enabling rapid warming using the heat of the exhaust gas. A bypass channel located in the cylinder block channel rising from the water pump to the cylinder head increases the coolant flow over the upper section of the cylinder block, suppressing engine knocking.

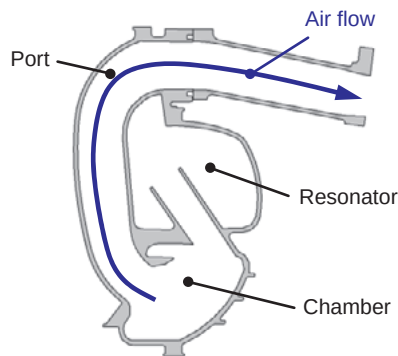


Fig. 3 Structure of intake manifold

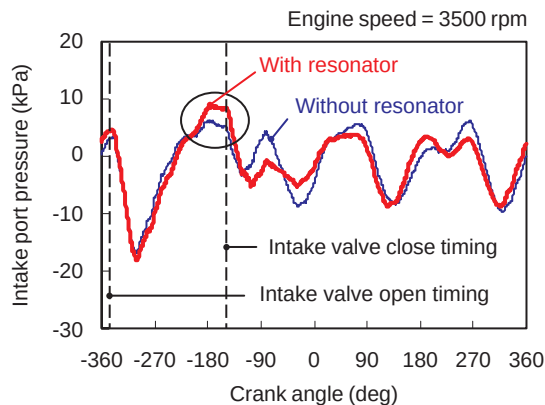


Fig. 4 Characteristics of intake manifold pressure

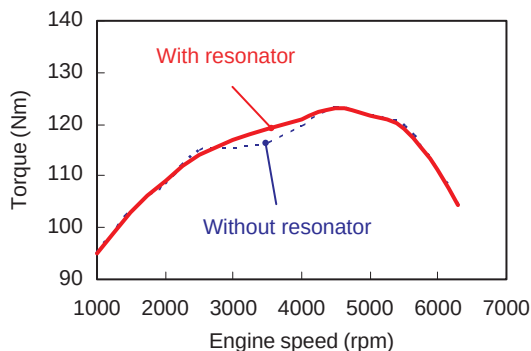


Fig. 5 Effect of intake manifold resonator

Figure 8 shows the effect of the bypass channel on ignition timing for knocking. The use of the bypass channel reduced knocking at 2000 rpm and above by approximately 2 deg.

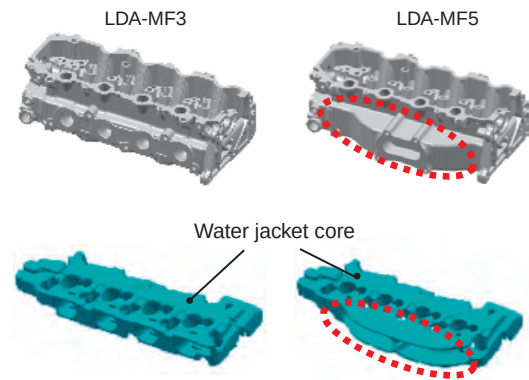


Fig. 6 View of exhaust manifold integrated cylinder head

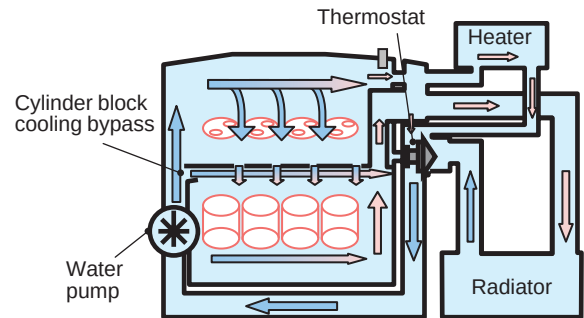


Fig. 7 View of cooling system

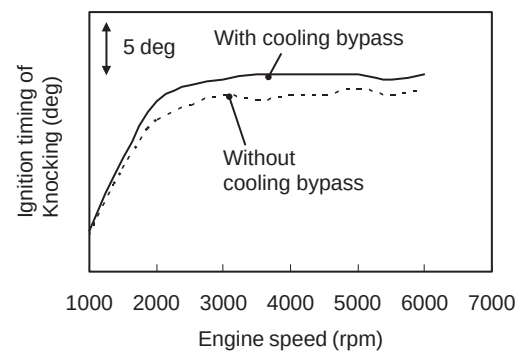


Fig. 8 Effect of newly developed cooling system

5. Power Performance

Figure 9 shows the output performance of the IMA system. The LDA-MF5 system displays superior power to the LDA-MF3 system across the entire driving range, reflecting the enhanced performance of both the engine and the motor. The high torque generated by the motor assist system at low engine speeds gives the system superior performance at 3000 rpm and below compared to a 1.8L i-VTEC (R18A) engine⁽⁵⁾ fitted in an identical vehicle.

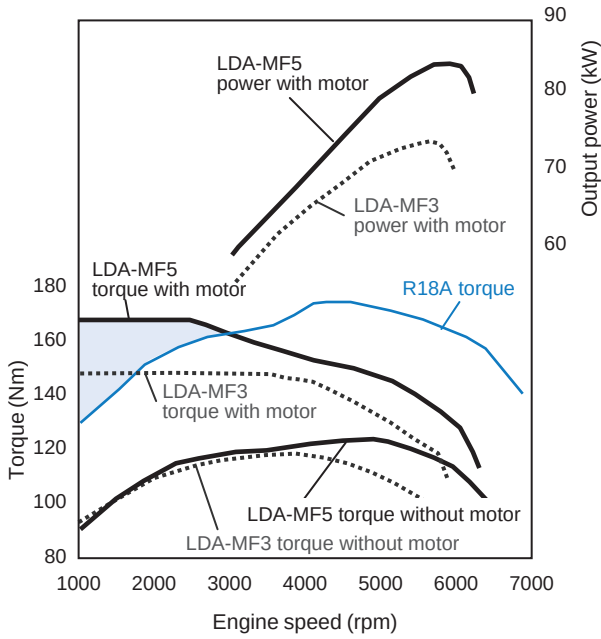


Fig. 9 Output performance of IMA system

6. 3-Stage i-VTEC VCM

6.1. Structure and Principle

The cylinder idling VTEC system used in the LDA-MF3 system provided 2-stage inlet and exhaust valve control: valve operation and cylinder idling. The LDA-MF5 system offers 3-stage control, enabling switching between different valve timing at low engine speeds, high engine speeds and during cylinder deactivation. This provides excellent fuel economy and torque at low speeds and high power at high speeds.

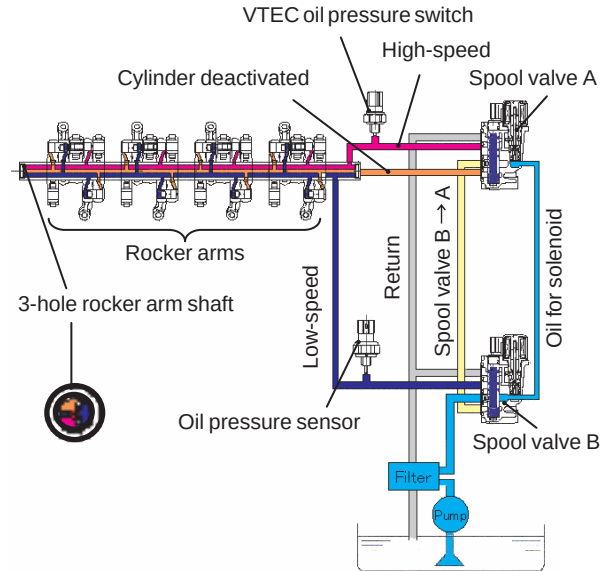
Figure 10 shows the component configuration of the 3-stage i-VTEC VCM mechanism. As in previous VTEC mechanisms, hydraulic pressure controls spool valves and synchro pistons built into the rocker arms, allowing the amount of lift of the intake and exhaust valves to be varied. The new system adds an extra spool valve to the single valve used in the LDA-MF3, and the hydraulic channel for use in cylinder idling has been made independent. These modifications have increased the reliability of start-up from cylinder idling, enabling all four cylinders to be idled, as compared to the three-cylinder idling used in the LDA-MF3.

Figure 11 shows the configuration of the rocker arms. Five rocker arms, which are composed of synchro pistons and return springs, are provided for each cylinder: three on the inlet side and two on the exhaust side. As in the LDA-MF3, a hydraulic/hydraulic switching mechanism that uses hydraulic pressure for connection and disconnection of the rocker arms was used for switching between low-speed valve timing and lift and cylinder idling. This ensures that it is possible to switch at low speeds of around 1000 rpm, when hydraulic pressure is low. A simple hydraulic/spring mechanism, in which the rocker arms are connected by hydraulic pressure and disconnected by the pressure of a spring, was used for switching between low-speed valve timing and lift and high-speed valve timing and lift.

Figure 11(a) shows valve operation at low speeds. Hydraulic pressure acts on the deactivation rocker arm, connecting it to the

low-speed rocker arm. The connected rocker arms drive the valves according to the low-speed cam profile.

Figure 11(b) shows valve operation at high speeds. The connection between the low-speed rocker arm and the deactivation rocker arm is maintained by the return spring. At the same time, hydraulic pressure acts on the hydraulic channel of the deactivation rocker arm on the high-speed rocker arm side. The operation of the



	Spool valve A	Spool valve B
Low-speed	OFF	OFF
High-speed	OFF	ON
Cylinder deactivated	ON	ON

Fig. 10 3-stage i-VTEC VCM valve train and hydraulic passage

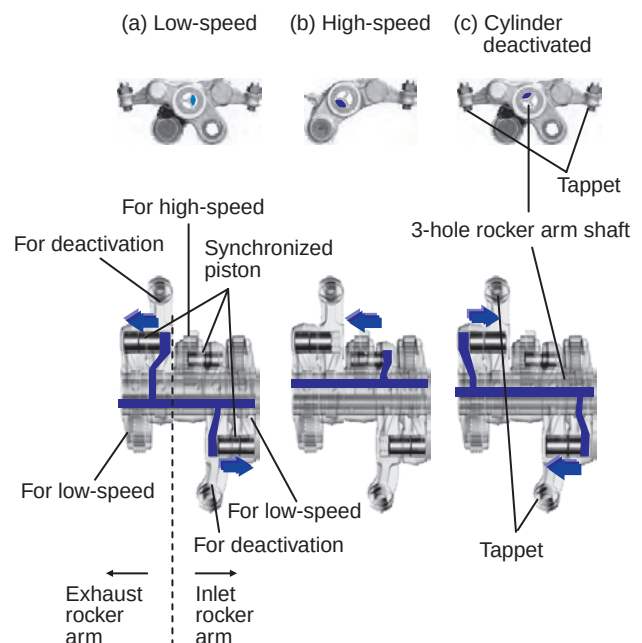


Fig. 11 3-stage i-VTEC VCM rocker arm and rocker arm shaft construction

synchro piston connects the deactivation rocker arm and the high-speed rocker arm. The valves are driven by the connected rocker arms according to the high-speed cam profile. On the exhaust side, only one type of cam is used, and therefore there is no cam switching.

Cylinder idling is shown in Figure 11(c). Hydraulic pressure acts on the low-speed rocker arm, and the operation of the synchro piston disconnects the deactivation and low-speed rocker arms. The valves are deactivated by the deactivation rocker arm (zero cam lift).

6.2. Effects

Figure 12 shows the output characteristic at low-speed and high-speed valve timing and lift. Switching between the low-speed and high-speed rocker arms at around 4800 rpm ensures an excellent power characteristic from low speeds to high speeds. In addition, the use of low-speed valve timing and lift provides excellent combustion at low speeds and low loads, resulting in superior fuel economy and emissions performance.

When the vehicle is decelerating and fuel is not being injected, the idling of the intake and exhaust valves reduces pumping loss. This friction reduction is captured by the motor as regenerated energy. Figure 13 shows engine friction during deceleration (fully closed throttle). Compared to deactivation of three cylinders, which reduces engine friction against full valve operation by a maximum of approximately 50%, deactivation of all four cylinders reduces pumping loss to virtually zero and reduces engine friction by a maximum of approximately 66% against full valve operation. This has increased the ratio of regenerated energy to braking energy from 57% to 64%, providing increased motor assist during

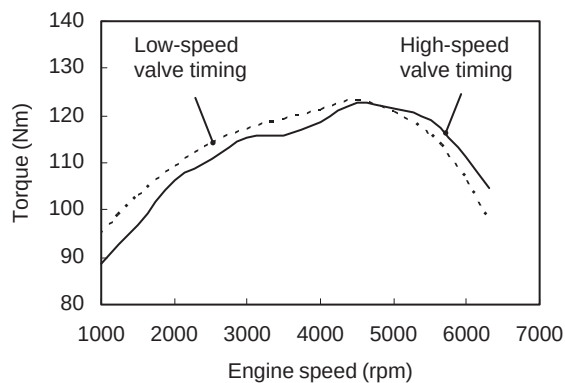


Fig. 12 Effect of valve timing and lift on torque

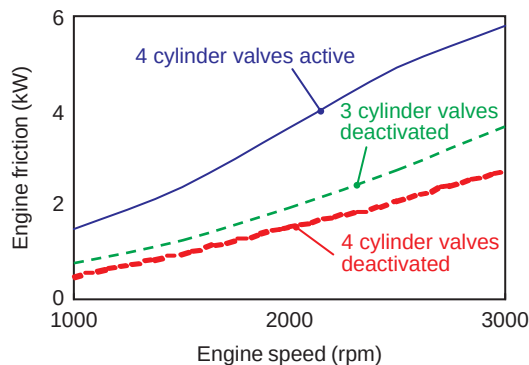


Fig. 13 Effect of VCM on reduction of engine friction

acceleration. In combination with increased motor power, this allows vehicle operation by the motor alone during low-speed cruising, resulting in increased fuel economy.

6.3. System Control

Figure 14 shows a diagram of the operation of the 3-stage i-VTEC VCM and the motor. When the vehicle becomes stationary, the engine automatically stops; the engine is restarted by the motor when the brakes are released. Low-speed valve timing and lift at take-off and at low vehicle speeds provides excellent fuel economy and torque. The motor generates drive power in response to the magnitude of torque required. The vehicle operates on motor power alone at low speeds and low loads. At this time, all the cylinders are deactivated and no fuel is injected. When the vehicle rapidly accelerates, the system switches to high-speed valve timing and lift at around 4800 rpm and above in order to generate high power. During deceleration, fuel injection is suspended and all the cylinders are deactivated, reducing pumping loss and increasing regenerated energy.

Switching between stages in the 3-stage i-VTEC VCM system is conducted based on a number of vehicle parameters, including engine speed, hydraulic pressure, water temperature, vehicle speed and remaining charge in the high-voltage batteries. This provides natural drivability and an acceleration and deceleration feel equivalent to those offered by a standard gasoline vehicle.

The system uses torque management control, a cooperative control involving drive by wire (DBW) and cylinder idling, to generate drive force. The target torque for the end of the crankshaft is decided from the degree of opening of the accelerator pedal and engine speed. The necessary allocation of engine and motor torque to realize this target torque is determined with consideration of energy management (remaining battery charge, etc.).

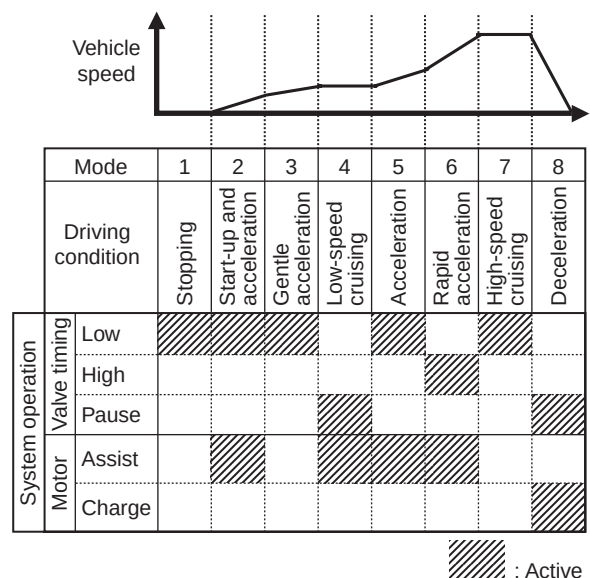


Fig. 14 3-stage i-VTEC+IMA operation

Table 2 Engine friction reduction technology

Engine code	LDA-MF5	LDA-MF3
Roller rocker arm	○	○
Off-set cylinder arrangement	○	○
Low-tension piston ring	○	○
Streak crank bearing	○	○
MoS ₂ processing of piston skirt	○	○
Cam shaft chain drive system	○	○
Low-viscosity engine oil	○	○
Cylinder sleeve plateau honing	○	○
Mirror surface treatment cam journal	○	—
Aluminum diecast piston	○	—
Ion-plate piston ring	○	—
Manifold-integrated cylinder head	○	—
Air conditioner belt-auto tensioner	○	—

7. Reduction of Engine Friction

Table 2 shows the main technologies used in the reduction of engine friction. In addition to the numerous friction reduction technologies previously used in the LDA-MF3, the new engine also features high-strength die-cast pistons⁽⁶⁾, an exhaust manifold integrated cylinder head, mirror surface treatment of the cam journals and an auto-tensioner for the accessories belt, among other new technologies that reduce friction.

Figure 15 shows the characteristics of the materials used in the high-strength die-cast pistons. The material used in the new pistons has a lower rate of thermal expansion than the previous material, controlling increases in friction generated by temperature changes. CAE was used in three-dimensional behavioral calculations to achieve uniform stiffness and optimize the shape of the pistons, in order to maximize friction reduction while ensuring durability and reliability.

Figure 16 shows a graph of engine friction against total displacement for existing Honda engines at an engine speed of 1500 rpm and an intake pressure of -53 kPa. In addition to new friction reduction technologies, the achievement of weight savings in the valve springs and piston rings and the reduction of contact area in the LDA-MF5 engine reduced friction by 8% against the

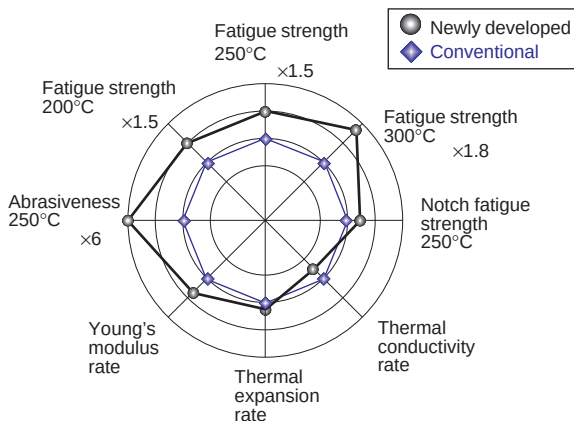


Fig. 15 Characteristics of piston materials

Engine speed = 1500 rpm, Intake pressure = -53 kPa

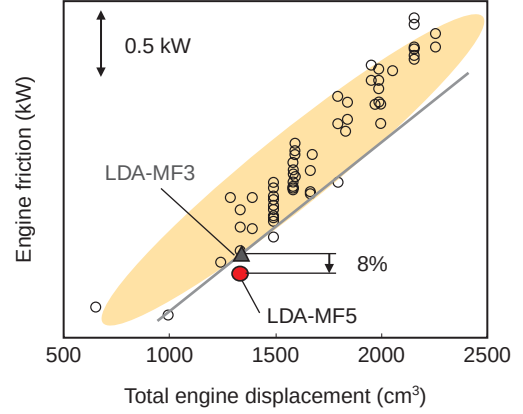


Fig. 16 Enhancement of engine friction

LDA-MF3 engine. This is the lowest figure for engine friction yet achieved by Honda in an engine of this displacement.

8. Reduction of Fuel Consumption through Enhanced Combustion

A new intake port that enhances turbulence at the end of the compression stroke (directly before ignition) by means of increased air intake and the generation of increased swirl (horizontal vortices) and tumble (vertical vortices) was developed. This new port reduces fuel consumption by enhancing combustion while at the same time increasing volumetric efficiency. Figure 17 shows the shape of the intake port, and Figs. 18 and 19 show CAE analyses of in-cylinder turbulence. The use of a restriction inside the port close to the valves in addition to a jumping spot increased the directionality of swirl and tumble during the intake stroke, resulting in the achievement of strong turbulence at 10 deg BTDC, directly before the completion of the compression stroke.

Figure 20 shows the relationship between the intake speed coefficient, M_i , defined by Eq. (1), and vortex strength, V_i , defined by Eq. (2). Vortex strength has been increased by approximately 25% against the previous model.

$$\text{Intake speed coefficient } M_i = (U_p/a_i) \cdot (A_p/Z_{MEI}) \quad (1)$$

U_p : Average piston speed (m/s)

a_i : Speed of sound passing the intake valves (m/s)

A_p : Cross-sectional area of piston (m²)

Z_{MEI} : Average effective open area of intake valve (m²)

According to C. F. Taylor⁽⁷⁾, the major determinant of volumetric efficiency during the intake stroke is the pressure drop of the intake valves. The pressure drop can be considered as a Mach number function of the intake valves, and defined as the intake speed coefficient, M_i .

$$\text{Vortex speed } V_i = (S_r^2 + T_r^2)^{0.5} \quad (2)$$

S_r : Swirl ratio

T_r : Tumble ratio

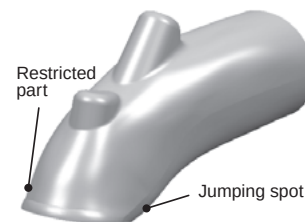


Fig. 17 View of intake head port

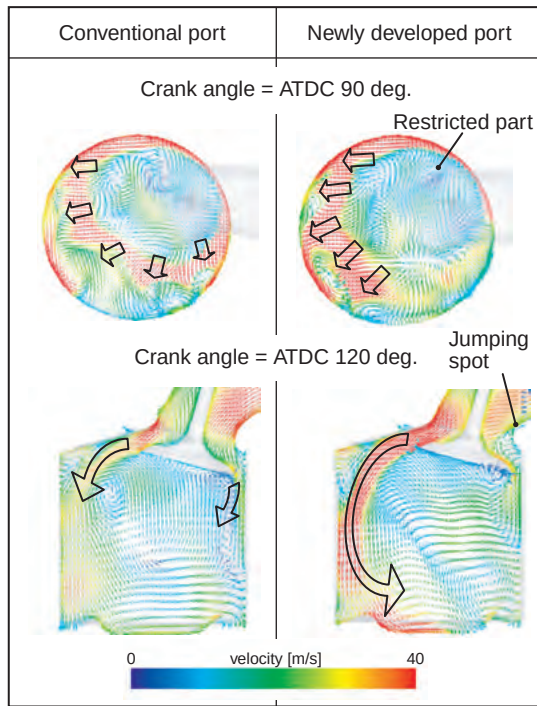


Fig. 18 Comparison of swirl and tumble flow

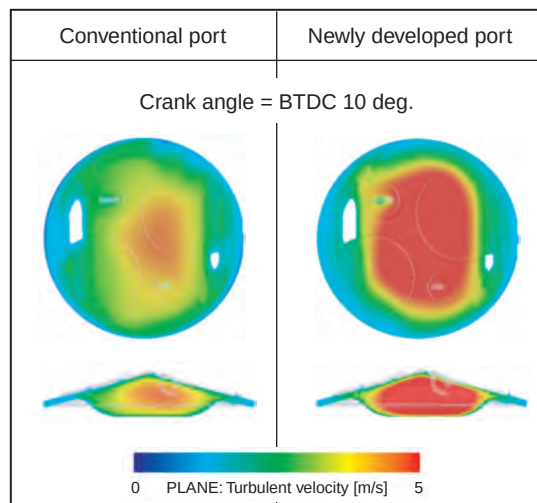


Fig. 19 Comparison of turbulence intensity

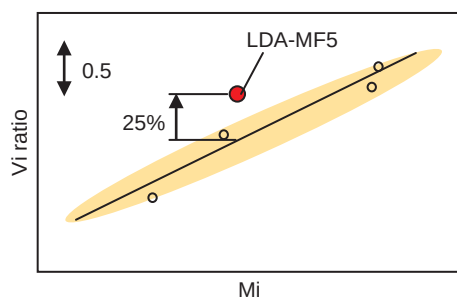


Fig. 20 Enhancement of Vi ratio

Figure 21 shows BSFC, Nox emissions and the co-variation of IMEP against EGR rate. Combustion is stable even at EGR rates of over 25%, enabling mass EGR to be used. As a result, NOx emissions have been reduced and a reduction of 5% in BSFC has been achieved.

Lean combustion was used in the LDA-MF3 to reduce fuel consumption, but not in the LDA-MF5. This is because motor operation takes place in the range in which lean combustion was previously used.

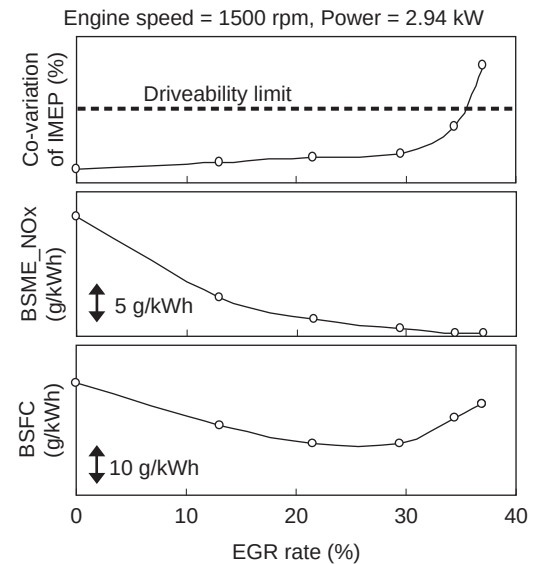


Fig. 21 Characteristics of EGR

9. Vehicle Fuel Economy and Dynamic Performance

The use of the 3-stage i-VTEC VCM mechanism, increased motor power, increased transmission efficiency in the CVT, and vehicle technologies including cooperative control of braking regeneration, have resulted in a fuel consumption of 31.0 km/L in 10-15 mode, a 5% increase against the previous vehicle. In terms of dynamic performance, increased engine and motor power have enabled 0-100 km/h acceleration in 12.1 sec. Figure 22 shows the positioning of the vehicle in terms of 0-100 km/h acceleration and 10-15 mode fuel economy.

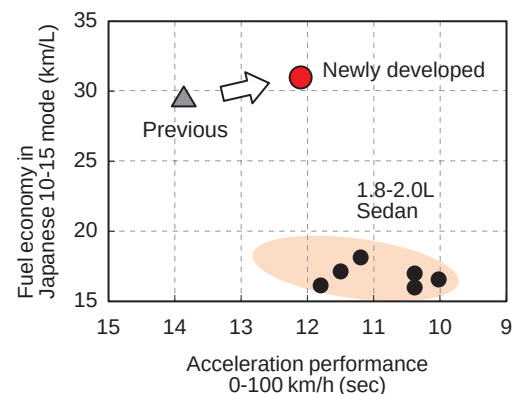


Fig. 22 0-100 km/h acceleration performance and fuel economy

10. Emissions Reduction Technologies

The catalyst used in the vehicle is a high-density, two-bed, three-way, close-coupled model. The enhancement of the catalytic converter⁽⁸⁾ has resulted in excellent purification performance, enabling the precious metals loading to be reduced. The exhaust manifold integrated cylinder head has eliminated the need for the exhaust manifold, thereby reducing the area radiating exhaust heat, thus enabling more rapid activation of the catalyst. Other emissions reduction technologies include a 6-hole injector and electronic EGR valves. The use of these technologies in addition to high-precision engine control has enabled the achievement of the emissions target, an emissions level 75% lower than the FY2005 low emissions standards.

11. Conclusion

A new engine, the LDA-MF5, has been developed for the 2006 CIVIC Hybrid. The following are the salient points of this development:

- (1) A 3-stage i-VTEC VCM mechanism has been developed that enables switching between low and high speed engine valve timing and cylinder idling, thus achieving a balance between excellent fuel economy and torque at low and medium engine speeds and high power at high engine speeds.
- (2) Deactivation of all four cylinders has reduced pumping loss to almost zero, resulting in increased regenerated energy and enabling operation by the motor alone.
- (3) In combination with vehicle technologies, the newly developed hybrid powertrain has enabled the achievement of a fuel economy of 31.0 km/L in 10-15 mode and 0-100 km/h acceleration in 12.1 sec.
- (4) The use of a high-density, 2-bed, 3-way catalyst and an exhaust manifold integrated cylinder head, in addition to high-precision engine control, has resulted in the achievement of an emissions level 75% lower than the FY2005 low emissions standards.

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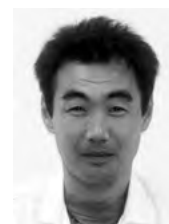
■ Authors ■



Shigeo OKUI



Tsutomu KISHI



Naohiro ISHIKAWA



Kohei HANADA