

Development of V10 500-HP Engine

– Technologies for High-performance and Low-emission Clean Powertrain –

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ABSTRACT

This article introduces environmental support technologies for the V10 500-HP engine that was developed for use in super sports cars. A new valve assembly was developed that adds a cylinder deactivation function to the high engine performance DOHC i-VTEC mechanism in order to achieve a balance between high engine performance and fuel economy. In order to achieve a balance between high engine performance and low emissions, the exhaust manifold was made a long type, a two-bed closed couple (CC) catalyst (CAT) and an under-floor (UF) catalyst were configured as the exhaust emissions control system, and a secondary air system was adopted. Misfire detection was supported by the adoption of a cylinder pressure sensor system. These various technologies enabled achievement of a balance between high output performance at the top of its class among competing cars and high environmental performance that responds to the demands of the times.

1. Introduction

The V10 500-HP engine was developed starting in late 2004, and was slated to be mounted in the successor to the NSX. Under the impact of the worldwide economic downturn that followed upon the Lehman Brothers Shock, however, development was canceled at the end of 2008. Principle technologies in this engine, for which development had largely been completed, are now being introduced in two parts⁽¹⁾. This article presents an overview of the engine and describes the technology that addresses the era's demand for environmental performance.

2. Development Goals and Objectives

2.1. Development Goals

The first goal of this engine was to serve as the core of commercial product appeal for the super sports car that would be the successor to the NSX, satisfying the user with its overwhelming engine performance. On the other hand,

it was also considered necessary for this to serve as the flagship engine that is situated at the very peak of Honda's engine lineup, and as such, it would have to fulfill Honda's corporate responsibility to provide the environmental support demanded by the times. Given this perspective, it was decided to pursue development of this engine under the aim of achieving a balance between power performance that creates acceleration reaching into a whole different dimension, and environmental performance that addresses the demands of the times.

2.2. Development Objectives

The objectives first defined for development are shown below. Figure 1 shows their placement.

- (1) Power: 500 HP or more
- (2) Fuel economy: Clear the US Gas Guzzler Tax regulations
- (3) Emissions: Comply with California State LEV2-ULEV regulations

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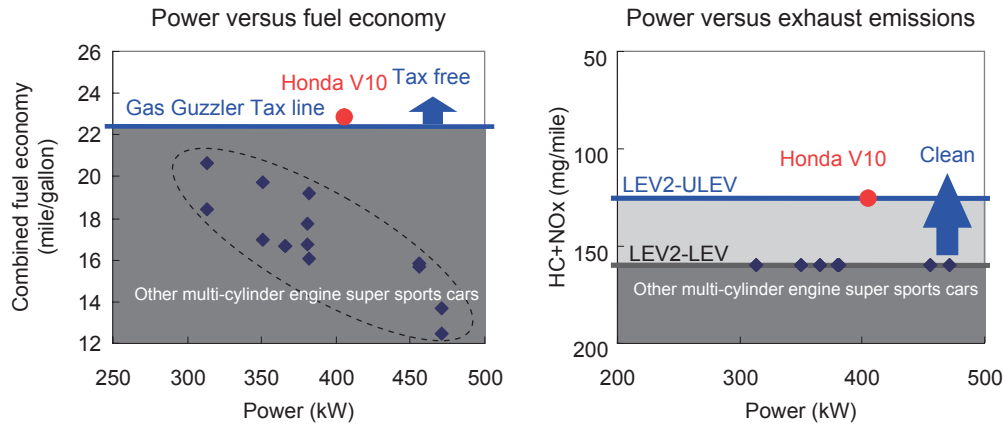


Fig. 1 Competitiveness of power, fuel economy and exhaust emissions

Table 1 Engine specifications

Cylinder configuration	V10
Bank angle	90°
Firing interval	90°-54°(uneven firing)
Bore pitch / offset	102 / 20
Bore × Stroke (mm)	90 × 78.5
Displacement (cm ³)	4993
Compression ratio	12.3 : 1
Valve train	DOHC i-VTEC VCM
Number of valves	4 per cylinder
Valve diameter IN / EX (mm)	37 / 31.5
Gasoline	Premium (RON95)
Max. power (kW/rpm)	405 / 8200
Max. torque (Nm/rpm)	513 / 7000
Idle / Fuel cut (rpm)	850 / 8500
Fuel economy City / Hwy label (mpg)	16 / 21
Unadjusted Combined (mpg)	22.8
Emissions	LEV2-ULEV

3. Overview of Engine Frame

The number of cylinders and the air intake system were determined so as to be appropriate to the engine's position as a flagship model for Honda. It was therefore given the 10-cylinder V configuration (V10) typical in the lineage of Honda F1 engines, and natural air (NA) intake. The displacement per cylinder was set at 500 cm³ for a superior balance between horsepower and torque in a high-performance NA engine, with a total engine displacement of 5.0 L. The maximum displacement for the engine frame was set at 5.5 L, in consideration of future development possibilities. The bank angle was determined in light of engine balance, the feeling of a step in noise and vibration (NV) when switching back and forth between all-cylinder operation and cylinder-deactivated operation, the engine room package, common points with the V8 in terms of a production machine, and so on. For superior performance in all these factors, a 90° angle with unequal interval ignition (no crank pin offset) was adopted.

Table 1 shows the main specifications of this engine.

4. Technology for Balancing High Engine Performance with Fuel Economy

Various steps were taken to achieve a balance between high power performance and enhanced fuel economy. Change to a higher compression ratio for enhanced combustion efficiency was combined with the use of lighter-weight component parts, typified by the adoption of titanium conrods, for reduction of mechanical loss. A variable cylinder management system (VCM) was also adopted, and a three-stage VTEC valve assembly mechanism that incorporates cylinder deactivated operation (three-stage VTEC VCM mechanism) was newly developed. This achieved a level of fuel economy that rises as high as 22.8 mpg, above the line defined by the US Gas Guzzler Tax regulations.

4.1. Three-stage VTEC VCM Mechanism

A new DOHC four-valve mechanism that switches valve timing and lift between three stages of low speed, high speed, and cylinder deactivation was developed. Table 2 shows the major specifications in comparison with production models.

(1) Basic structure

Figure 2 shows the rocker arm structure. Bank 1, which operates with normal combustion without performing cylinder deactivation, is a two-stage mechanism similar to previously existing high-performance DOHC VTEC implementations. Bank 2 adds two rocker arms and synchronized pistons for cylinder deactivation switching to the VTEC mechanism found in Bank 1, making it a mechanism capable of cylinder deactivation. A two-loop hydraulic switching system that performs coupling and decoupling hydraulically was adopted to implement valve operation and deactivation switching so as to place an emphasis on switching responsiveness at low speeds.

Figure 3 shows the configuration of components in the three-stage VTEC VCM mechanism. To the conventional VTEC mechanism, Bank 2 has added two hydraulic passages for low speed and deactivation and a three-way

Table 2 Valve train specifications

Engine code		–	J35Z2	F20C	LDA-MF5
Cylinder configuration		V10	V6	L4	L4
Valve train		DOHC	SOHC	DOHC	SOHC
		3-stage VTEC VCM	VCM	VTEC	3-stage VTEC VCM
Number of valves per cylinder		4	4	4	4
VCM	Running	○	○	–	–
	Deceleration	○	○	–	○
	Idle	○	–	–	–
VTEC	In	○	–	○	○
	Ex	○	–	○	–
VTC		○	–	○	–
Max. engine speed (rpm)		8500	6900	9000	6500

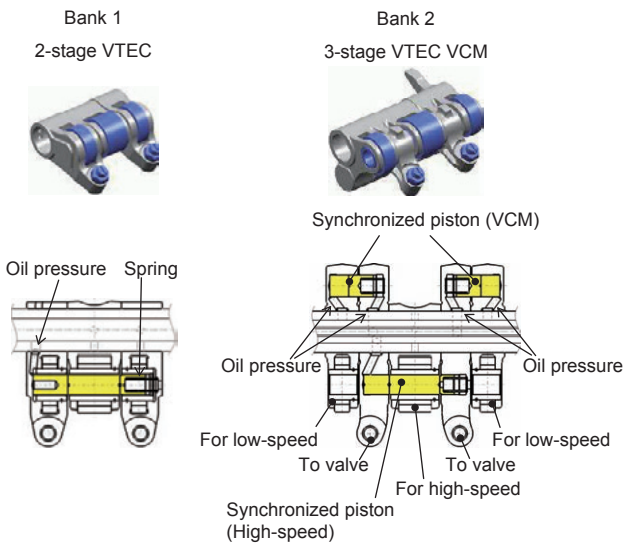


Fig. 2 Components of rocker arm

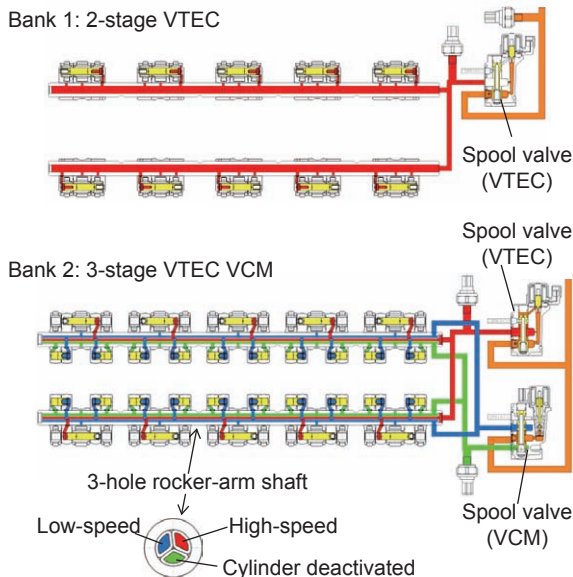


Fig. 3 Components of 3-stage VTEC VCM

spool valve to carry out the hydraulic switching.

(2) Operating mechanism

Figure 4(a) shows the operational state of the hydraulics and synchronized pistons when starting and at low speeds. The hydraulic state shown in blue causes the deactivation switching synchronized pistons to move so that the rocker arm on the valve stem is coupled with a rocker arm that is driven by a low-speed cam, and the valve is driven by the low-speed cam.

When the hydraulics shown in red are added to this state, the high-speed synchronized piston is made to move, as shown in Fig. 4(b). The rocker arm on the valve stem is coupled with a rocker arm that is driven by a high-speed cam, and the valve is driven by the high-speed cam, which has a higher lift.

When the hydraulic state shown in blue in Fig. 4(a) switches over to the hydraulic state shown in green, the deactivation switching synchronized piston moves so that the rocker arm on the valve stem and the rocker arm driven by a low-speed cam are decoupled. This results in the state of cylinder deactivation shown in Fig. 4(c).

4.2. VCM Operating Conditions

The engine's VCM operates primarily on the basis of throttle opening information to determine whether the vehicle is in a cruise, deceleration, or idle state from the vehicle speed, engine speed, engine oil temperature, gear

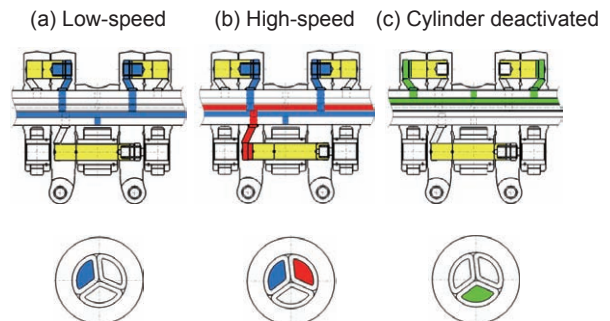


Fig. 4 Operating principle of 3-stage VTEC VCM

speed, and the like. Then, as shown in Fig. 5, it deactivates one bank of cylinders and switches over to five-cylinder operation. At the same time, out of environmental concern, it also determines whether the catalyzer temperature and other such factors in the exhaust emissions reduction system are in a state appropriate for switching over.

Measures have also been taken to ameliorate the reduction in drivability resulting from torque level differences when switching occurs. The accuracy of switch-over response in the VTEC mechanism has already been increased, as in the V6 VCM, and ignition control^{(2), (3)} has already been applied. Moreover, intake air volume control by cylinder bank was applied this time so that switching over can take place smoothly and without torque level differences.

4.3. Fuel Economy Enhancement Effect of VCM

When this engine is running under cylinder deactivation,

all the valves on the deactivated side are stopped in their seated state. This reduces pumping loss and valve drive loss. On the operating cylinder bank side, the throttle opening is larger, and this also reduces pumping loss.

Taking advantage of the characteristics of the multiple-cylinder engine, the idle speed can also be configured for cylinder deactivation. Since the displacement is so large, the engine power can be maintained to a high level even when running with cylinders deactivated, and this allows operation with cylinder deactivation across a wide range of speeds from idle to approximately 100 mph (160 km/h).

The pink area in Fig. 6 shows the operating range of the engine with cylinders deactivated in EPA LA-4 and highway modes. The frequency of cylinder deactivation in LA-4 mode was 68% and in highway mode it was 91%. The enhancement effect on combined mode fuel economy was 13% (relative to having all cylinders active).

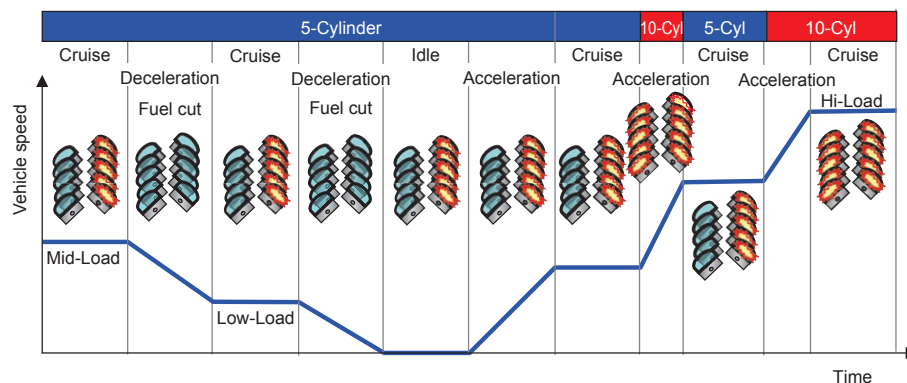


Fig. 5 Operation of VCM

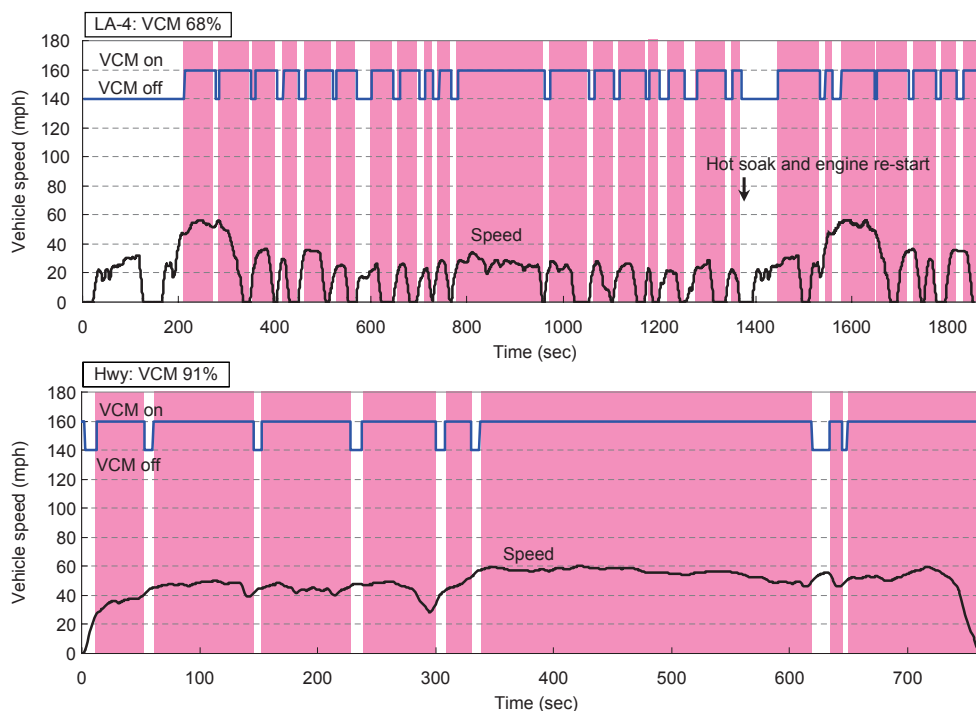


Fig. 6 Operation of VCM in LA-4/Hwy mode

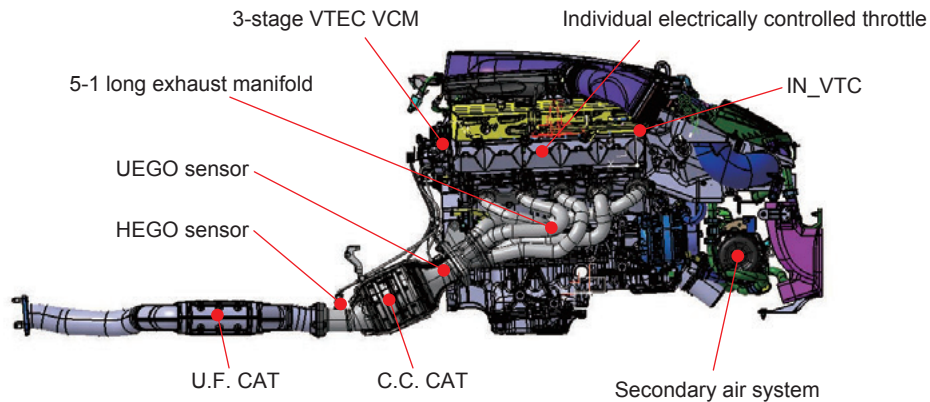


Fig. 7 Configuration of emissions control system

5. Technology for Achieving a Balance of High Power Performance and Low Emissions

Seeking to achieve a balance of high power performance and low emissions first involved work on the engine alone. The combustion chamber shape was optimized to reduce unburned gases, and retard control at startup using valve timing control (VTC) together with optimization of the fuel injection method were used to reduce feed emissions.

In order to enhance purification performance of feed emissions using the catalyzer, it is important that the catalyst be made to heat up quickly during cold starts. When the objective is low emissions, the heat mass of the exhaust manifold located upstream from the catalyzer needs to be minimized by designing the manifold to be as small and light as possible. Since the emphasis with this engine is on power performance, however, it needs to have a large, long exhaust manifold of the 5-1 type. The exhaust emissions control system, as shown in Fig. 7, consists of a closed couple (CC) catalyzer placed at the exhaust manifold using a three-way catalyzer of the two-bed type (Fig. 8), and an under-floor (UF) catalyzer using a three-way catalyzer of the one-bed type, as well as a secondary air system adopted to raise the catalyst temperature.

5.1. Feed Emissions Purification Technology

In order to reduce the heat mass of the exhaust manifold, the fabrication method was changed from welding together

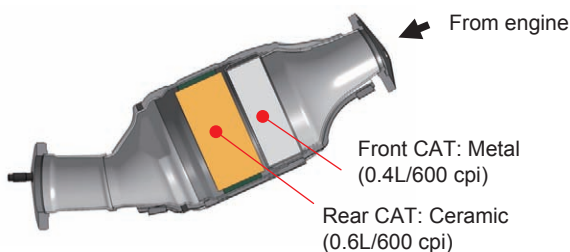


Fig. 8 Layout of C.C. CAT

a number of curved pipes to hydroforming by bending thin-sheet pipe. The number of parts and the weight were reduced.

For the front bed of the closed couple (CC) catalyzer, a metal catalyst support that heats up quickly was adopted.

These measures yielded the results shown in Figs. 9 and 10. The catalyst temperature at the initial stage of LA-4 mode had risen to 250°C within 20 seconds after engine startup. This is on a par with LEV2-ULEV vehicles with V6 engines.

5.2. Technology to Achieve Balance with Fuel Economy Enhancement

When the engine is operated with cylinders deactivated for a long period in order to enhance fuel economy, the temperature of the catalyst on the deactivated bank side will decline. Achieving emissions purification performance equal to that when operating with all cylinders requires that the catalyst on the deactivated bank side maintain its light-off condition. When the catalyst temperature declines rapidly, the time to deactivation of the catalyst will be reduced, the time spent with cylinders deactivated will be limited, and the rate of fuel economy enhancement will decline.

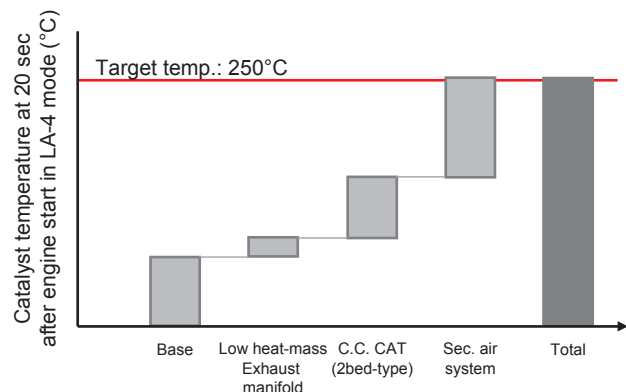


Fig. 9 Catalyst temperature after engine start

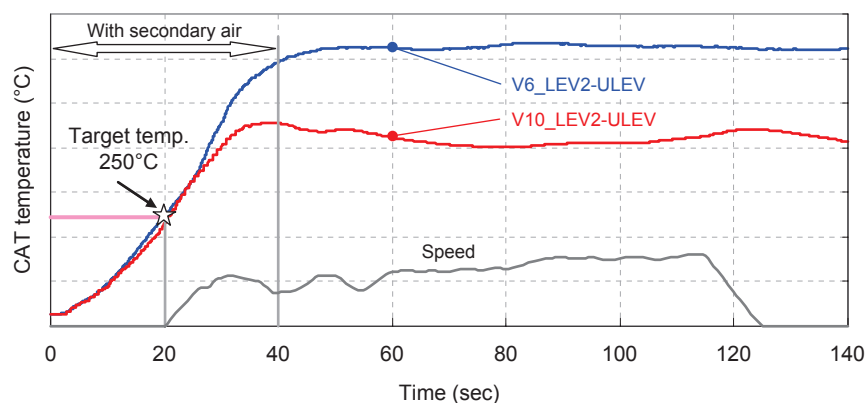


Fig. 10 Catalyst temperature after engine start in LA-4 mode

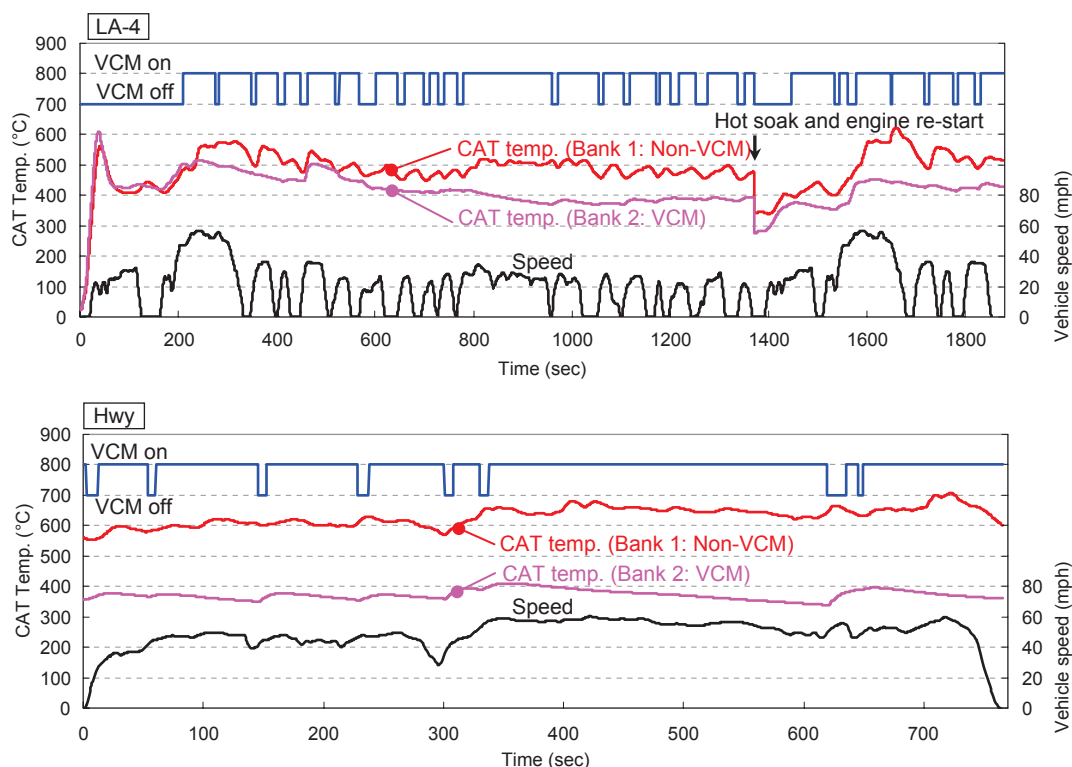


Fig. 11 Relationship between VCM and catalyst temperature

Therefore, a ceramic catalyst support with superior heat retention was adopted for the rear bed of the closed couple (CC) catalyzer. This limits the drop in catalyst temperature and enables maintaining the light-off temperature of approximately 320°C over a long time. This served to achieve a balance with fuel economy enhancement.

Figure 11 shows how the catalyst temperature on the deactivated bank side maintains the light-off state in LA-4 and highway modes.

6. Misfire Detection Technology

Support for misfire detection is a prerequisite to taking environmental measures for all destinations. However, to

deal with determination of multiple misfires in 10 cylinders by means of the total pattern using the conventional method of detecting fluctuations in crank angle speed would require enormous software development. For this engine, therefore, the characteristics of a cylinder pressure sensor system⁽⁴⁾ employing adaptive calculation were used to advantage in a system capable of knocking detection as well as misfire detection.

6.1. System Configuration

As shown in Fig. 12, the system is configured with cylinder pressure sensors and a cylinder pressure unit. The system is set up to transfer data to the engine control unit (ECU) by means of the controller area network (CAN).

Inside the cylinder pressure unit, signals from the sensors are converted into voltages and then into digital signals by an AD converter, and fed into the central processing unit (CPU). Inside the CPU, the cylinder pressure for each crank angle is also computed using crank pulses and cylinder pulses. One 100-MHz CPU is used for each five cylinders (one per bank), and the AD converters are configured for sampling at 50 kHz. The result is that cylinder pressure can be measured for each degree of crank angle at speeds up to 8000 rpm or more.

Misfire detection and knocking detection require different frequency filtering for their respective waveform acquisition. Digital filtering is therefore performed within the CPU and the optimal pressure waveforms are subjected to computation.

6.2. Structure of Cylinder Pressure Sensors

The cylinder pressure sensors are placed to minimize their effect on the valve assembly and valve layout. As shown in Fig. 13, therefore, they were installed between the spark plugs and cylinder heads, sharing the fitting with the plugs.

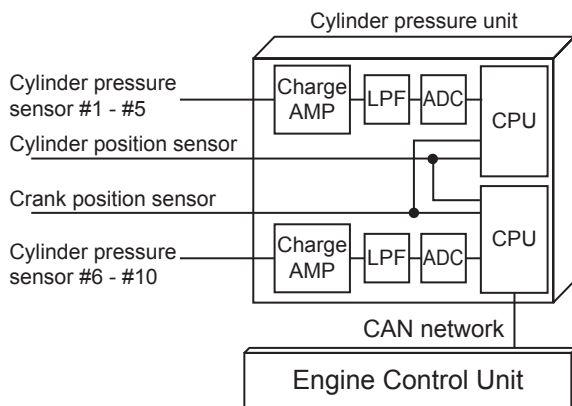


Fig. 12 Cylinder pressure unit configuration

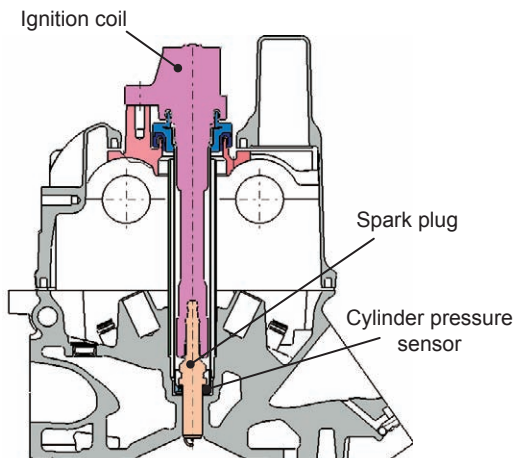


Fig. 13 Installation of cylinder pressure sensor

Figure 14 shows the structure of the sensors. They are basically configured with a piezoelectric element fitted inside a cylindrical housing in a simple washer-like structure that senses strain between the cylinder head and the spark plug. Lead titanate (PbTiO_3) was used for the piezoelectric elements.

6.3. Sensor Output Compensation by Adaptive Calculation

It is widely known that one of the basic properties of lead titanate (PbTiO_3) is that its piezoelectric constant changes greatly with the temperature. In order to use this substance as a cylinder pressure sensor in an automobile engine, that and various other property changes should be addressed.

The varying rate of sensor properties under the environmental conditions in which this engine is used is large, ranging from 120% to -80%. The sensor output cannot be used just as it is, so output compensation is performed by adaptive calculation within the cylinder pressure unit. The method used is outlined below.

- (1) The motoring pressure is estimated by calculation from the operational state.
- (2) The motoring pressure obtained by calculation and the actual measured motoring pressure are made to agree by mapping, and that value is stored in the ECU as the standard pressure.
- (3) The cylinder pressure during the compression cycle is largely determined by the intake air volume, and is not influenced by subsequent misfiring or combustion. The sensor signal is therefore corrected at each cycle so as to agree with the standard motoring pressure obtained in (2), and a stable estimated cylinder pressure is thus obtained for each crank angle.

6.4. Misfire Detection

The cylinder pressure waveform following correction shows the pressure rising with combustion when normal combustion occurs, but when misfiring occurs, it will agree with the motoring pressure computed within the

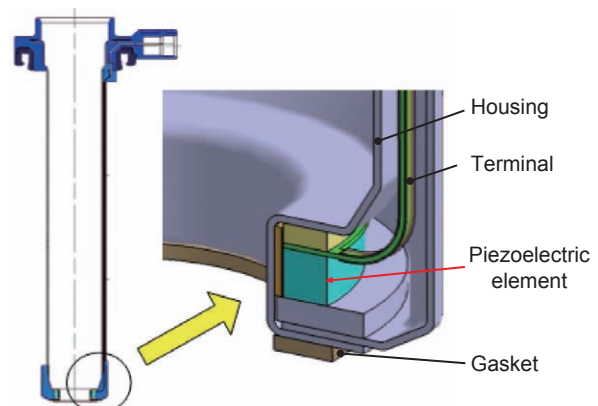


Fig. 14 Cylinder pressure sensor structure

unit. Making use of this characteristic, the ratio between the cylinder pressure waveform during combustion and the motoring pressure waveform is determined, which allows determination of whether or not energy was generated by combustion, or, in other words, determination of a misfire state.

Figure 15 shows the waveforms for combustion and misfire in the identical operational state. As a result of these innovations, 100% misfire detection performance can be achieved in a V10 engine over the entire range of speeds and under all conditions of the environment of use.

Figure 16 shows an example of detection performance when misfires occur continuously in a single cylinder of an actual engine. The red portion shows normal combustion, and the blue shows continuous misfiring in a single cylinder, indicating how the determination of misfiring can be made.

6.5. Knocking Detection

Sensors to measure cylinder pressure are placed in every cylinder. These can therefore also be used to advantage to detect knocking. Figure 17 shows a comparison of the

layout of conventional knocking sensors and of cylinder pressure sensors.

Figure 18 shows waveform processing being carried out. When knocking occurs, a pressure fluctuation wave caused by the knocking is added to the cylinder pressure waveform. A bandpass filter can then be used to isolate just the frequencies of the pressure fluctuation wave caused by the knocking. This constitutes knocking detection. The sensor placement and waveform processing described above have enabled stable knocking detection.

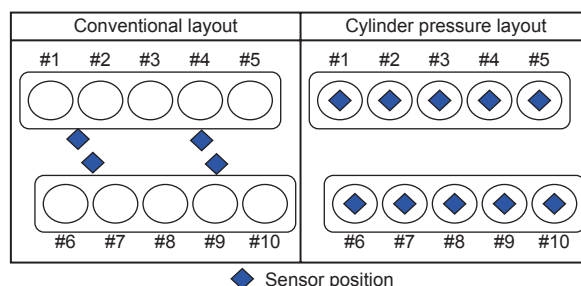


Fig. 17 Sensor layout

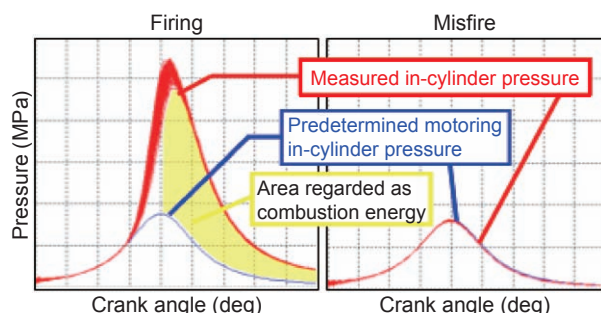


Fig. 15 Difference between firing pressure and misfire pressure

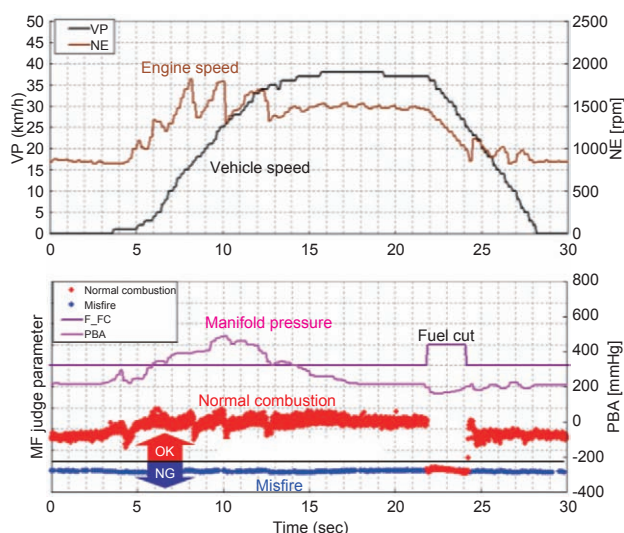


Fig. 16 Single continuous misfire on actual driving pattern

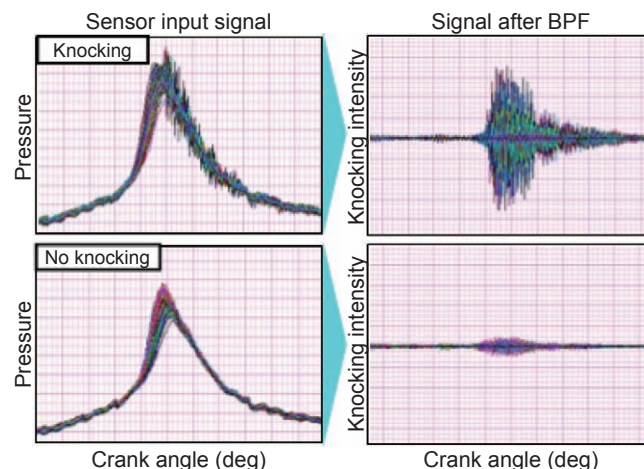


Fig. 18 Knocking signal processing

7. Conclusions

This engine has achieved the below environmental performance objectives in a way that has no precedent among 500-HP class multiple-cylinder engines mounted in super sports cars.

- (1) Fuel economy: Cleared the US Gas Guzzler Tax regulations
- (2) Emissions: Complied with California State LEV2-ULEV regulations

For people who love engines, the NA, high-RPM, multiple-cylinder engine is an endless object of attraction, and it was a joy for the authors to be involved in this development project. The environmental performance

objectives for this engine were set at unprecedentedly high levels out of the strong desire to build an engine that would meet the demands of a new era. The authors hope that this article may serve to advance the future development of such engines.

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