

Study on Variable Valve Timing System Using Electromagnetic Mechanism

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ABSTRACT

The elimination of the throttle has recently attracted attention as a means of improving fuel economy through the reduction of pumping loss. The research described in this paper concerns fuel economy, noise, vibration performance and wide-open throttle performance in an engine equipped with an electromagnetic variable valve timing mechanism. This mechanism enables the throttle to be eliminated.

A high-efficiency mechanism equipped with a low voltage drive method from considerations of practical use and constant voltage opening and closing control that has realized short and stable valve contact speed were developed. In comparison with a conventional cam-driven valvetrain, this new valve mechanism has achieved a simulation-based improvement of 7% in fuel economy in the 10.15 mode and a roughly 20% increase in torque at low to mid engine speeds through optimization of valve timing and scavenging effectiveness. In addition, the combination of compact type-integrated hydraulic tappet, dual over-excitation constant voltage control and resin engine cover, has enabled the engine to record the same noise level when idling as an engine with a conventional valvetrain.

1. Introduction

Many attempts are being made to reduce pumping losses in a 4-stroke engine by eliminating the throttle to improve the fuel economy of the engine. Methods of doing this include an inlet air regulation method in which the inlet valve opening and closing timings are varied⁽¹⁾⁻⁽⁶⁾, a hydraulic drive valve method in which hydraulic pressure between the cam and inlet valve is released during the valve lift and the inlet valve closing timing is changed⁽⁷⁾, and a mass-produced mechanical method employing an intermediate lever and an eccentric camshaft in which the valve lift is varied by changing the contact part of the operating curve between the base of the intermediate lever and the roller follower. However, these methods necessitated an increase in the number of parts due to environmental compatibility and the complexity of the mechanism. In order to overcome this issue, research was carried out concerning the mechanism and control of an electromagnetic valve that was simple and whose valve timing had a high degree of freedom resulting in improved engine performance.

2. Basic Principle and Operating Mode of an Electromagnetic Valve

As shown in Fig. 1, the basic principle of operation of an electromagnetic valve is free vibration of a spring and a kinetic system. The friction and structural attenuation parts

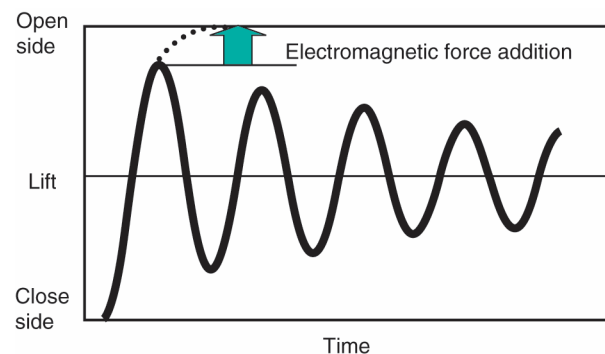


Fig. 1 Basic principle of electromagnetic valve

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are drawn in and held by an electromagnet. As shown in Fig. 2, compared to the conventional valve profile the behavior of an electromagnetic valve is controlled by the timing of energization of the electromagnet, and the lift time is constant irrespective of the rotational speed. Consequently, the profile with respect to the crank angle is a rectangular wave in the low to mid range speed, enabling the volumetric efficiency to be increased. Also, the valve open and close timing can be made fully variable, aiming to optimize the intake and exhaust pulsations and reducing pumping loss.

Figure 3 shows the operating mode. In the initial state (center part of the diagram), there is equilibrium between the upper and lower springs, so the valve and armature are stationary at a point midway along the valve lift. When the signal for putting the engine into an operating condition is sent, electric current flows alternately through the upper and lower coils at a fixed period, causing the armature to be drawn in while vibrating, until the valve is fully closed (left part of the diagram). After this, the valve operates continuously (right part of the diagram), and when the signal for putting the engine into a deactivated condition is sent, all valves cease operation at once, and return to the neutral position (center part of the diagram).

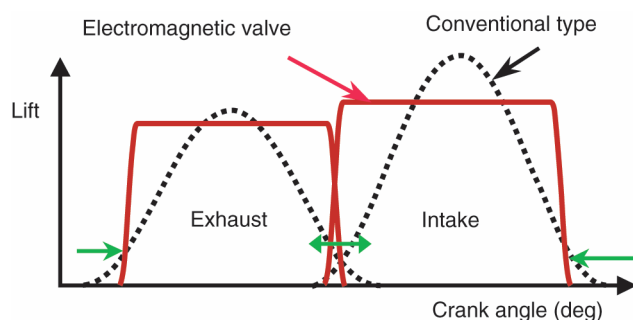


Fig. 2 Comparison of electromagnetic valve profile and conventional valvetrain profile

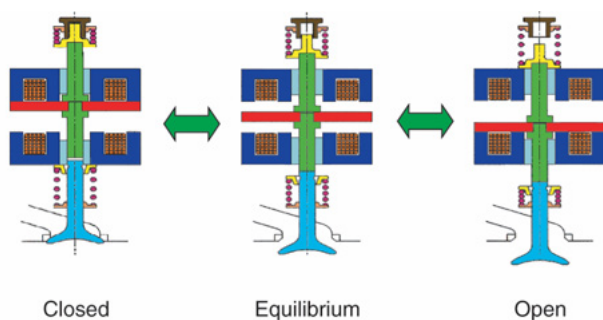


Fig. 3 Motion of electromagnetic valve

3. Outline of Structure and System

Figure 4 and Table 1 show the main structure and specifications of the electromagnetic valve used in this research, and Fig. 5 shows the system.

Concerning the structure, shafts which are supported by springs above and below are fixed to square-shaped armature disks. At the end of the upper shaft is a lift sensor, and between the lower shaft and the valve is a compact-type integrated hydraulic tappet which is used as a valve buffer mechanism. In consideration of wear and thermal expansion of each part, there is a separation mechanism which ensures that the valve makes contact first and then the armature is

Table 1 Valvetrain specifications

Valve diameter (IN/EX) (mm)	30/24
Valve lift (IN/EX) (mm)	7/6
IN maximum spring force (N)	480
EX maximum spring force (N)	550

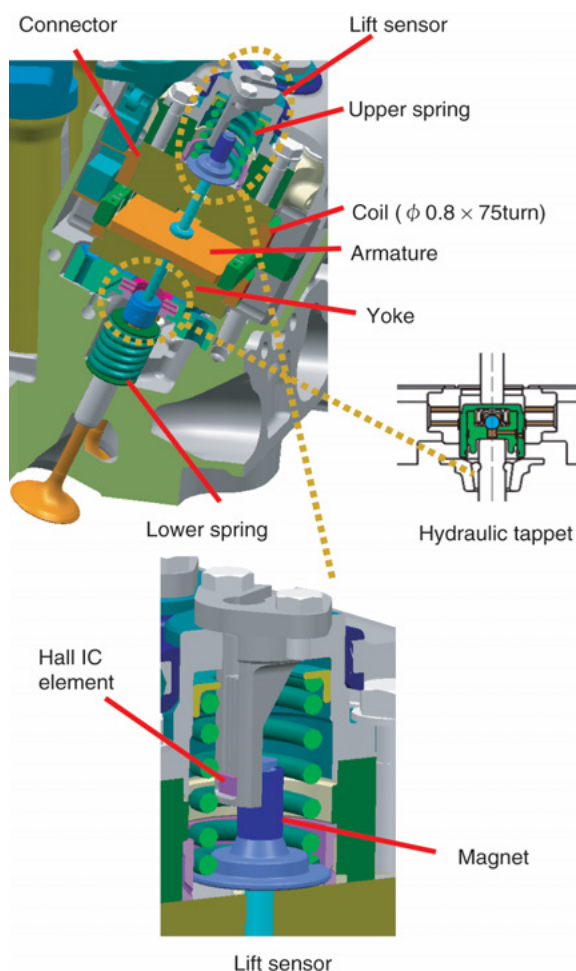


Fig. 4 Structure and hydraulic tappet and lift sensor

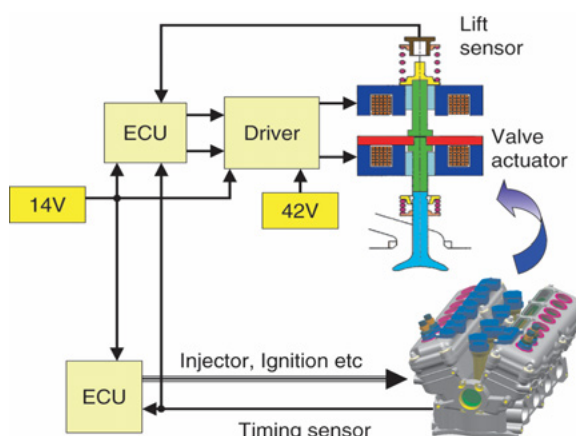


Fig. 5 Electromagnetic valve management system

drawn in on the fully closed side. This is equivalent to the tappet clearance in the conventional cam-driven valvetrain. In order to minimize the effect of pressure inside the cylinder, the spring load on the exhaust side is made higher than that on the intake side. The yoke is made of laminated silicon steel sheets in order to reduce eddy current loss and reduce

cost. It contains a resin bobbin around which is wound a coil. The electromagnetic valve system shares only the timing sensor. The ECU and driver are dedicated parts which have been added to the existing ECU. Each valve is driven by a low voltage of 42 V in consideration of mounting in an actual engine, and is controlled independently of the others by a signal from the lift sensor.

4. Study of High Efficiency by Simulation

When the amount of intake air is controlled by using variable valve timing in order to eliminate the throttle and improve fuel economy, the electric power consumption performance exerts a large effect on the fuel economy. Generally, methods used to reduce the consumption of electric power include improved attraction force by means of increased magnetic path area, reduced leakage magnetic flux, improved material characteristics, reduced eddy current loss by means of lamination, and coil cooling.

The B (magnetic flux density) - H (magnetic field) characteristics of the silicon steel used in this research are shown in Fig. 6. It can be seen that the magnetic flux density is saturated in places where the magnetic field is strong. Based on this fact, static magnetic field simulation was used to analyze the attraction force. In the simulation of the electric and mechanical compound, the mechanism of the actual behavior of the electromagnetic valve in which the application of a voltage causes current to flow, generating magnetic flux, which in turn causes the armature to be drawn in, was analyzed. Eddy current loss generated by an abrupt change in the magnetic flux when the armature is drawn in was also analyzed, several patterns were calculated, enabling a low power consumption laminated structure and drive method to be devised.

Figure 7 shows a comparison between the attraction force simulation and the measured results when the displacement distance is minute. Although there are differences in saturated areas, good accuracy is obtained.

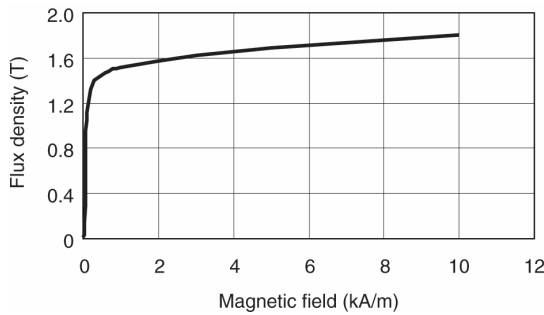


Fig. 6 Magnetic flux and magnetic field characteristics

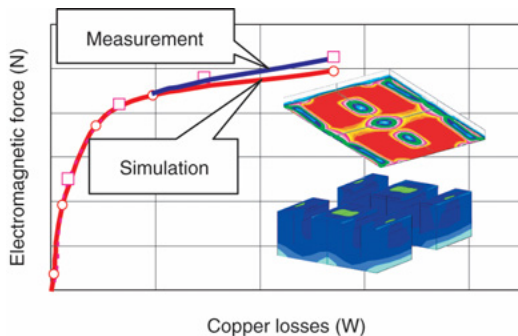


Fig. 7 Static magnetic field simulation

Figure 8 shows the transformer model for the electrical and mechanical compound simulation, and the results of simulation. Equations (1), (3) and (4) apply to the circuit on the left side, and Eq. (2) applies to the circuit on the right side. Both the self induction and mutual inductance are factors of time. This is because the B-H characteristics are non-linear, the magnetic permeability varies, and also the magnetic resistance changes along with the displacement of the armature.

Consequently, not only the product of L_1 and $\frac{dI_1}{dt}$, but also the product of I_1 and $\frac{dL_1}{dt}$ contribute to the generation of an induced electromotive force accompanying current I_1 .

During the lifting operation, the attraction force does not rise immediately, even when the current rises, but exhibits abrupt characteristics when the distance between the armature and coil becomes minute. Also, it can be seen that eddy current loss occurs when the magnetic flux changes abruptly, and does not occur when the armature is held.

$$V_1 = R_1 I_1 + L_1 \frac{dI_1}{dt} + \frac{dL_1}{dt} I_1 + M \frac{dI_2}{dt} + \frac{dM}{dt} I_2 \quad (1)$$

$$0 = R_2 I_2 + L_2 \frac{dI_2}{dt} + \frac{dL_2}{dt} I_2 + M \frac{dI_1}{dt} + \frac{dM}{dt} I_1 \quad (2)$$

$$L_1 = \frac{N_1^2 A}{\frac{1}{\mu} + \frac{2x}{\mu_0}} \quad (3)$$

$$\frac{dL_1}{dt} = - \frac{N_1^2 A}{\left[\frac{1}{\mu} - \frac{2x}{\mu_0} \right]^2} \left\{ \frac{1}{\mu_0} \times \frac{d\mu}{dB} \times \frac{dB}{dt} + \frac{2}{\mu_0} \times \frac{dx}{dt} \right\} \quad (4)$$

M in the above equation is the mutual inductance, μ is the magnetic permeability of the magnetic material, μ_0 is the magnetic permeability of air, I is the effective length of the magnetic path, A is the effective cross-sectional area of the magnetic path, N is the number of coil turns, and x is the armature lift.

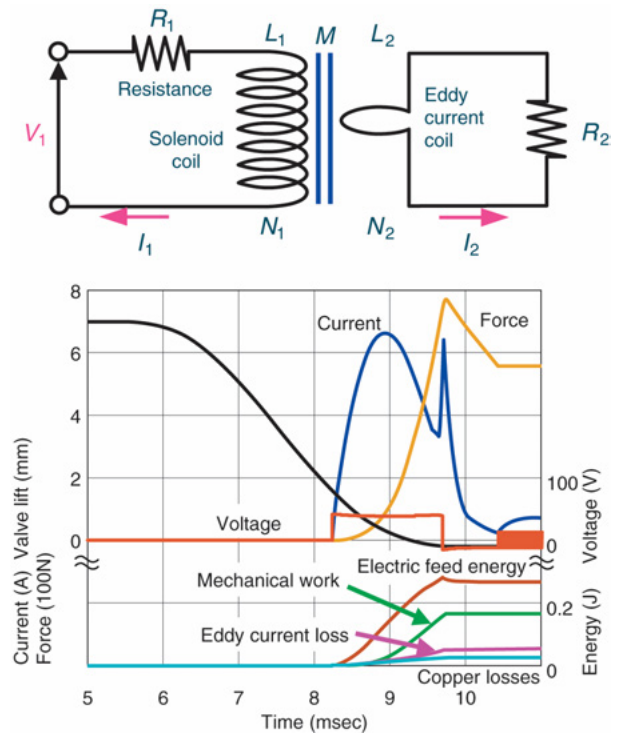


Fig. 8 Electric/mechanical compound simulation

5. Power Consumption Performance

Based on the above simulation results, a 4-cylinder engine on which were mounted electromagnetic valves having a high efficiency laminated structure was fabricated, and the power consumption between the coil terminals was measured using the actual engine. The results of measurement are shown in Fig. 9. A performance of about 150 W was attained at 1 500 rpm when one each of the inlet and exhaust valves were deactivated, and a performance of about 300 W, equivalent to slipper-type valvetrain, was obtained for 16-valve operation.

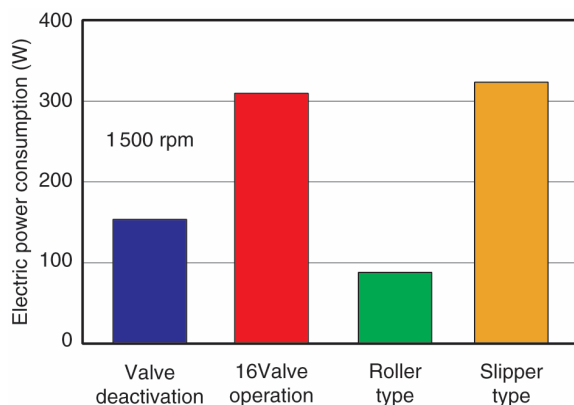


Fig. 9 Comparison of electric power consumption

6. Control System

Figure 10 shows the basic principle of control. During valve lift, constant voltage control takes place, and when the valve is in a held state, constant current control takes place. In the case of the more generally known constant current control, if the valve is subjected to an external disturbance such as friction while lifting, the attained distance of free vibration will be small, and changes in the inductance of the actuator will be more sluggish, causing current to flow more readily. However, because the current is constant, the voltage is reduced, causing the attraction force to be reduced. In contrast, constant voltage control is used in this system, so the current increases, causing the attraction force to increase, thus enabling stable behavior to be realized. The constant voltage control method used controls the energization timing based on a comparison of the actual displacement of each valve detected by the lift sensor with the target value. Energization start control is intended to realize both stable operation of the valve and reduction of contact speed.

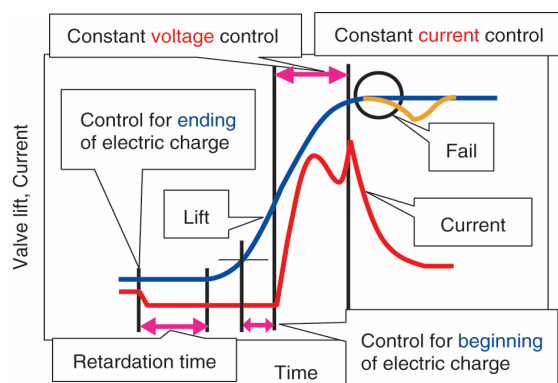


Fig. 10 Control principle

Because the contact speed is determined by the energization start timing, this method measures the valve displacement time, compares it with the target value, and determines the energization start timing of the next cycle.

Energization end control is used to determine the valve timing using the energization end timing. For this reason, it corrects random variations in the delay time caused by the effect of residual magnetic flux, and measures the period from the end of energization to a lift of 1 mm in order to correct the delay time for the next cycle. In addition, this control system uses a contact judgment detection system. When a failure occurs and the valve reaches the neutral position, the engine performance is largely affected, so the armature is attracted to the closed valve side or the open valve side depending upon the timing of the occurrence of the failure.

7. Noise and Vibration Characteristics

A conventional valvetrain mechanism has a buffer curve to control impact noise generated when the valve makes contact and also durability. However, an electromagnetic valve has no buffer curve, and its attraction force characteristics become increasingly abrupt with decreasing distance between the armature and the coil. For this reason, impact noise when the valve and armature make contact becomes a concern.

The contribution of the valvetrain noise to mechanical noise is highest when the engine is idling, so an evaluation of proximity noise above the cylinder head during idling was carried out in a simple anechoic chamber. The results are shown in Fig. 11. The sound pressure level of the electromagnetic valve was about 19 dB worse than that of the conventional cam-driven valvetrain.

In contrast, as shown in Figs. 12 and 13, by employing dual overexcitation for constant voltage overexcitation control, the abrupt attraction force characteristics in the vicinity of contact were reduced, and the armature contact speed was reduced from 0.45 to 0.1 m/sec, causing the impact acceleration on the yoke to be reduced to no more than 1/4. In addition, by using compact-type integrated hydraulic tappet shown in Figs. 14 and 15, it was possible to obtain a reduction of 15 dB, and also by using a resin engine cover and reduced idling speed to obtain the same noise reduction performance as a conventional cam-driven valvetrain.

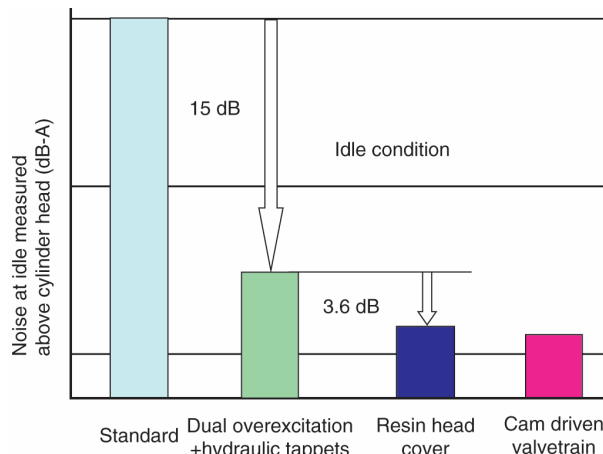


Fig. 11 Controlling methods, structural difference and effects

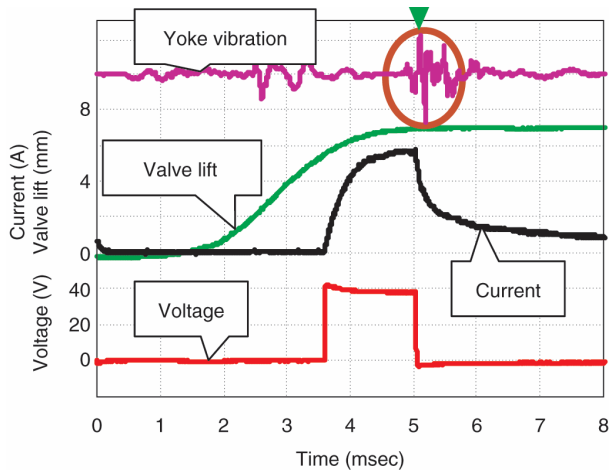


Fig. 12 Overexcitation control under constant voltage condition

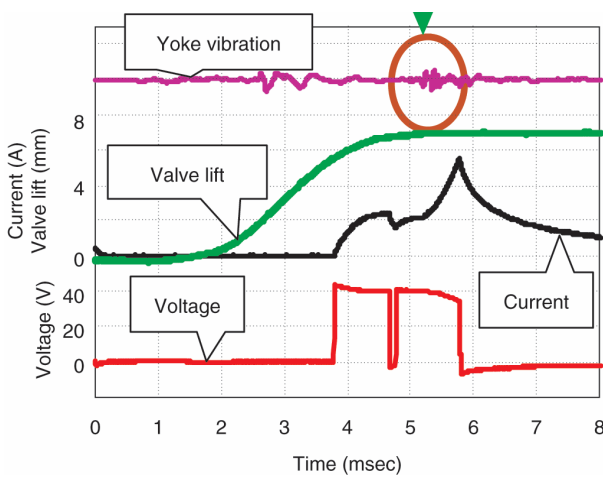


Fig. 13 Dual overexcitation control under constant voltage condition

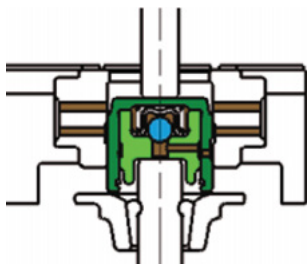


Fig. 14 Hydraulic tappet

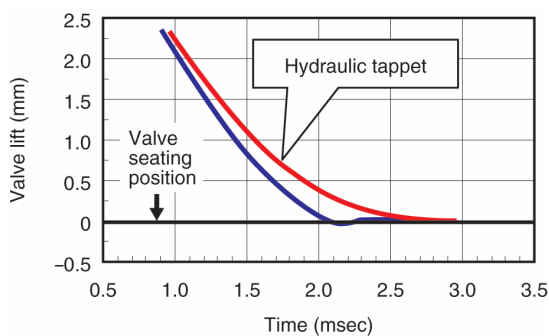


Fig. 15 Hydraulic tappet effect

8. Performance of Actual Engine

Table 2 shows the specifications of the engine used in the performance test, and Fig. 16 shows the results of the actual engine fuel economy performance. It was confirmed that the use of variable valve timing permits the throttle to be eliminated, and the BSFC including electric power consumption was improved by 10% compared to the conventional cam-driven valvetrain owing to delayed intake valve close timing. Figure 17 shows the corresponding PV curves. It can be seen that pumping loss has been reduced as a result of delayed closing. (Output power 2.9 kW at 1 500 rpm, one each of the inlet and exhaust valves deactivated)

In addition, 10.15 mode fuel economy simulation analysis was performed, the simulation result yields a 7% improvement in fuel economy.

Table 2 Test engine specifications

Bore × stroke (mm)	75 × 90
Displacement (cm ³)	1 590
Bore spacing (mm)	84
Valve lift (IN/EX) (mm)	7/6
Valve train type	Electromagnetic valve train

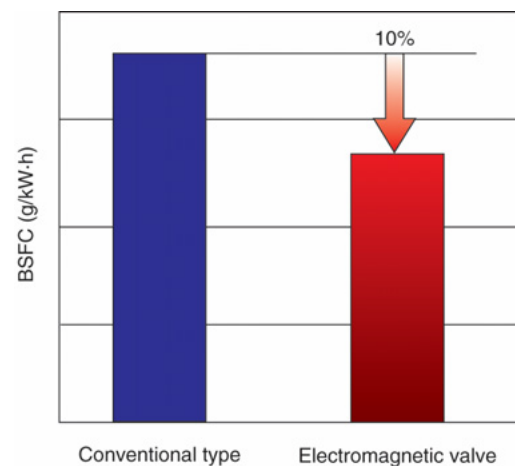


Fig. 16 Comparison of fuel consumption values

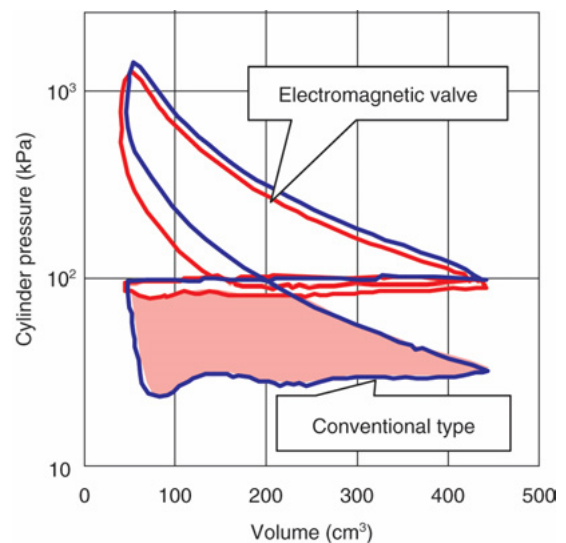


Fig. 17 Pumping loss reduction

Figure 18 shows the actual engine wide-open throttle performance. By setting the closing timing of the intake valve to the bottom dead center, the actual stroke volume was increased, and in addition the improved volumetric efficiency resulting from scavenging utilizing intake and exhaust pulsations realized a torque improvement of about 20% in the low to mid range speeds.

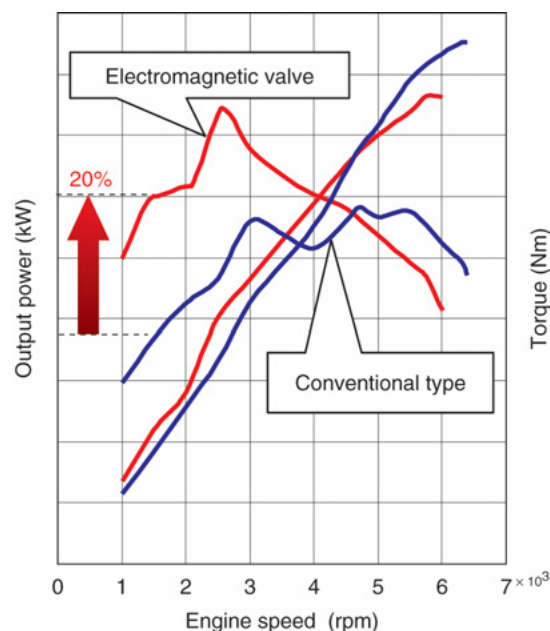


Fig. 18 Wide-open throttle performance

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9. Conclusion

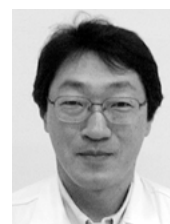
A high efficiency electromagnetic valve mechanism driven by a practical low voltage (42 V) was developed, and the following results were obtained.

- (1) By using the electromagnetic valve to eliminate the throttle, a 10% improvement of BSFC (Output power 2.9 kW at 1 500 rpm) compared to the conventional valvetrain was obtained, and also a 7% improvement was obtained by 10.15 mode fuel economy simulation.
- (2) By utilizing the optimum valve timing and scavenging effect, a torque improvement of roughly 20% was obtained in the low to mid range speeds.
- (3) By using a combination of energization start control and end control, stable valve behavior and low contact speed were attained.
- (4) By using a compact-type integrated hydraulic tappet, dual overexcitation constant voltage control, and a resin engine cover, the noise reduction performance obtained during idling was equivalent to that of a cam-driven valvetrain.
- (5) By combining a static magnetic field simulation and an electrical and mechanical compound simulation of a transformer model, the mechanisms of eddy current loss in operating condition, copper loss, mechanical work, applied energy were analyzed.

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