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Valve timing and valve lift control mechanism for engines

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Abstract

A new type engine valve control system has been presented, in which both the valve lift and valve timing are controlled directly by electric motors. A mechanism of the valve timing control system is made of planetary gears. The outer gear is the timing pulley which has a timing belt driven by the crankshaft of an engine. Two planetary gears are inside of the pulley. The gears engage with the inner gear of the pulley. The center of the disc, which has centers of the planetary gear, is connected to the camshaft. Then, the crank rotation is transmitted to the camshaft, and rotations of sun gear are added to the rotations of camshaft. This means that when rotation angle of the sun gear is controlled, the phase between the inlet valve and the exhaust valve can be controlled. The lift control system is made of linear slider and ball screw. The cam shape of this system is three-dimensional. The height of the cam varies along the axis of the shaft. When the ball screw rotates, the camshaft slides in the axial direction, so that the lift of the cam varies. The control method is presented for the mechanism, in which valve phase and the lift are controlled continuously. Experimental tests have been carried out for the system.

Keywords: Control; Valve; Engine; Phase; Lift; Variable lift; Variable phase; Driven valve system

1. Introduction

Variable valve timing (VVT) is used in spark ignition automotive engines to improve fuel economy, reduce NO_x gas, and increase peak torque and power. A number of papers have been reported for the effects when variable timing cam is used [1–9]. A survey of the problems were written in [1,2], in [3,4], influences of the variable valve timing on the combustion were discussed, and its mechanism and designs were reported in [5–8], in which oil pressure controls were applied. The switchable twin cam was also developed in [9]. In order to have complete VVT system, camless engine valve trains were discussed [10–25], in which the valve motion was completely independent of the piston motion by using electromechanical actuators. In those papers, the authors discussed mechanisms of new type camless engines [10,11], benefits of it in vehicle operation [12], robust unthrottled operation [13], and dynamic model [14]. The control method was also developed in [16,17,21] for its modeling and control. The analysis has also been made in [17]. For the camless engine, the biggest control difficulty comes from the valve seating velocity. It should be very slow to avoid acoustical noise and wear. Solving this problem, a method of soft landing of electromechanical valve actuator has been presented in [18,20]. To make the feedback control, the system requires velocity sensors, and a sensing device was discussed in [22]. To have cheaper control system, sensorless valve actuators were also reported [15,23].

The variable valve lift also makes an important role to the performance of the engine [19,24,25]. The variable lift controls were performed by fluid or switchable cam. It was shown that the combination of variable valve lift and exhaust turbo-charging offers a considerable potential to further improve both low-end-torque and maximum power in the papers. Therefore, the engine with variable timing and variable valve lift control are desirable. However, the actuator that controls both the lift and timing has not been developed. The camless engine has advantages as just

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mentioned, but it has also disadvantages as mentioned below: it needs large electric power, and complex and expensive control systems. After solving those problems, the electromechanical actuator, which controls both lift and timing in practical engine, will be developed in a near future.

Although the mechanical valve (valve–cam system) has disadvantages for controlling valve timings as mentioned in the previous works, it has also some advantages when the continuous valve timing control can be performed. The advantages are as follows: the cam lift follows the cam profile when appropriate springs are used [26]. This means that, by using the appropriate cam profile, the precise valve motion is possible without control, which is also important in engine performance [19]. The maximum cam lift can be set at large values (5–9 mm) because the motion of the valve is restricted by the cam profile, the noise level is in practical use, and the valve movement is stable. From this situation, the present article provides a new-type valve timing and valve lift control system using a conventional valve–cam system. It has advantages of valve–cam system as just mentioned. In addition, the valve timing and valve lift are controlled continuously by using DC motors. The control system is simple, and although there is a friction loss, it requires no large electric power source for the control. To have precise continuous valve timing control, the present article gives a new continuous valve timing control system using planetary gear mechanism. In our system, since an electric motor controls the valve timings directly, it does not require fluid pressure pumps and electromagnetic valves [1–9]. The present article also provides a new variable valve lift mechanism controlled by an electric motor, which is different from the system in [24,25]. The valve lift system is combined to the valve timing control system. Hence, the present system can control both valve lifts and valve timing by electric motors directly.

2. Mechanism of valve control system

The driving mechanism of the valve is essentially the same as that in a customary engine with valves and cams, but the present system has phase and lift control mechanisms. The present valve control system consists of two parts, one of which is the valve timing control mechanism, and the other is the variable valve lift mechanism.

2.1. Valve timing control mechanism

The phase of one of the cams is variable in this article. Fig. 1 shows the geometry of the present valve timing mechanism. Rotations of a crankshaft of engine are transmitted to both inlet and exhaust cams by using a timing belt and timing pulleys. In this experiment, an inverter motor is used instead of engine as shown in Fig. 1. In the camless engine, combustions affect the performance of valve motion [24], because the valve motion is directly controlled by electromechanical actuator [10–25]. In the valve–cam engine, since, to prevent jumps and bounces, the spring is set with an appropriate initial displacement (x_0). The restoring force is $F = k(x_0 + x)$, where k is the valve spring constant and x, the displacement of the spring under the cam rotation. The force should be greater than the inertia force of the valve, and it is decided with a certain safety factor. The effects of combustion of the engine on the valve motion can be neglected because it will be in the safety factor. This means that the valve motion follows the cam profile in customary engines [26]. Therefore, the motor will be applicable instead of an engine for checking the control performance.

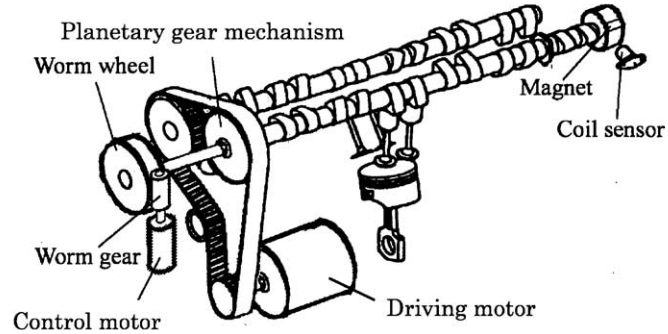

Fig. 1. Geometry of present valve timing control mechanism.

In our system, the timing pulley has planetary gear mechanism inside, and the rotation of the timing pulley is transmitted to the camshaft passing through the planetary gears. Since a shaft of the sun gear is connected to a control motor using a worm gear mechanism, the control motor can rotate the sun gear, but the torque from the cam to the control motor is locked by the worm. The control motor is connected to the engine frame. Since the control motor can vary the rotation angle of the cam, the angles between the inlet valve and the exhaust valve (phase between the inlet valve and the exhaust valve) can be controlled.

A compact mechanism is desirable for engines. The present article provides a compact valve timing control pulley unit as shown in Fig. 2 that has the above-mentioned planetary mechanism. In the pulley, two planetary gears engage with the inner gear of the pulley. The shafts of the planetary gears are connected to a side plate with a shaft (output shaft in Fig. 2), and the output shaft is connected to the camshaft. The rotation of the timing pulley is transmitted to the camshaft with a certain gear ratio. The inside of planet gear engages with a sun gear. The sun gear has a shaft with worm wheel gear teeth. The worm wheel gear engages with a worm whose shaft (input shaft in Fig. 2) has a control motor connected to a frame (of engine in the practical use). Hence, when the control motor rotates, the rotation is transmitted to the sun gear passing through the worm wheel. The rotation of the sun gear is added to that of the pulley. Then, the phase between the inlet valve and the exhaust valve can be varied. In the system, when the control motor does not rotate, the worm and worm wheel mechanism lock the sun gear. In such case, the rotation of

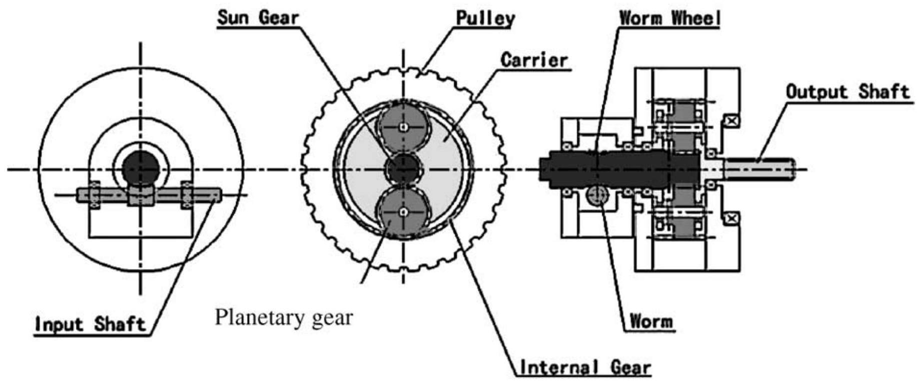

Fig. 2. Present pulley with planetary gears mechanism.

the crankshaft is transmitted to the camshaft directly. When the phase control is required, the control motor is driven, and so the valve timing can be controlled.

Table 1 depicts the dimensions of the planetary gears, where Z_a is the number of gear teeth of sun gear A, Z_b the number of planetary gear B, and Z_c the number of internal gear C. When the sun gear is fixed, the gear ratio between the inner gear and the carrier is

$$i_1 = 1/(Z_a/Z_c + 1) = 0.8$$

The camshaft rotates 0.8 revolutions when the timing pulley rotates one revolution. The ratio between the camshaft speed and the crankshaft speed should be 1/2 in the engine, and the number of timing pulley of the driving motor is 30. Since our system has compact planetary gear reduction mechanism as just mentioned, the size is small in comparison with conventional engines.

When the inner gear of the pulley is fixed, the rotation ratio between the sun gear and the carrier is

$$i_2 = 1/(Z_c/Z_a + 1) = 1/5$$

A compact motor is desirable in engines, and the motion from the planetary gear should be locked at the control motor. The gear ratio of the worm and the worm wheel is chosen to be 1/30 with consideration of the conditions as just mentioned and the control speed. When the control axis connected to the sun gear rotates 150 revolutions, the camshaft rotates one revolution.

2.2. Variable valve lift mechanism

A cam with slope in the axial direction is presented as shown in Fig. 3. Using the cam, the valve lift is varied when the camshaft moves in the axial direction. To demonstrate this mechanism, a model of the cam was made (see Fig. 4), in which the camshaft is consisting of shaft A and B. The output shaft of the above mentioned valve timing mechanism is connected to the right end of shaft A by a screw. The rotary motion of the crankshaft of the engine is transmitted to shaft A passing through the above mentioned valve timing mechanism. Shaft B has the cam, and so the rotation of shaft A is transmitted to shaft B, because shaft A is connected to shaft B by using splines, but shaft B moves in the axial direction independently. Shaft B has

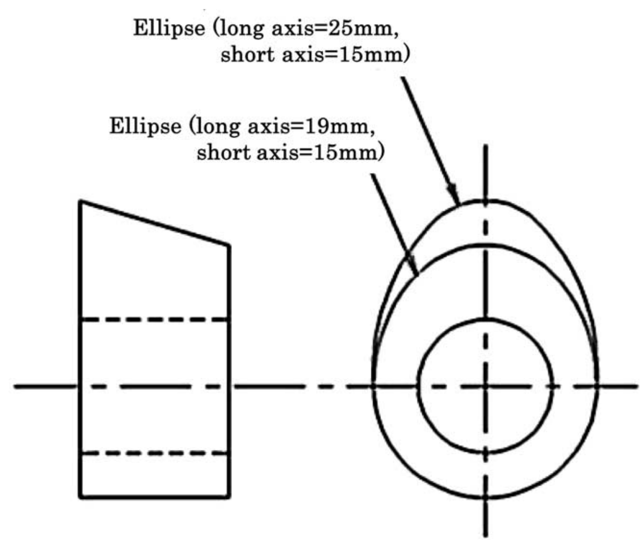

Fig. 3. Cam profile (B in Fig. 4).

Table 1
Dimensions of planetary gears

	Sun gear A, Z_a	Planet gear B, Z_b	Internal gear C, Z_c	Pulley
Gear type	Regular	Regular	Regular	XL type
Module	1	1	1	
Pressure angle (°)	20	20	20	
Number of teeth	16	24	64	48
Pitch circle diameter (mm)	16	24	64	77.62

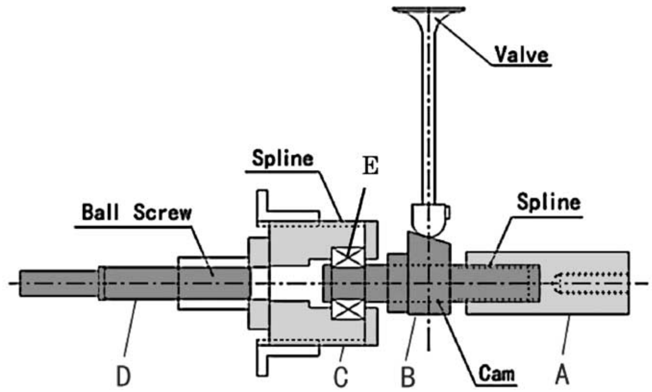

Fig. 4. Present variable valve lift system.

bearing E at the end of shaft C which has a splines around the outer surface, and its rotation is restricted, because the splines engaging with that of shaft C is fixed to the frame. Hence, the rotation of shaft B does not transmit to shaft C. Shaft C has a ball screw at another end that engages with the ball nut. The ball nut is connected to an end of shaft D, and has a control motor at the another end. Then, when a rotation is added to shaft D by using the motor, shaft C slides along the splines in the axial direction. Shaft C and B also slide when shaft C slides. Then, the cam connected to shaft B moves in the axial direction with rotations given by shaft A. Since the cam has a slope, the valve lift varies when the cam moves in the axial direction. Since the gear ratio of the ball screw is large, a compact DC motor can control the axial movement directly. In the experiment, the pitch of the ball screw is 3 mm, and the range of the cam lift is 4 mm through 10 mm that will be enough in practical engines.

2.3. Sensors

2.3.1. Cam rotation angle sensor

The above-mentioned system requires a rotary angle-measuring sensor in the control. In this article, a cheap coil sensor with a magnet chip is developed. A permanent magnet chip is pasted at the surface of the camshaft, and a fixed coil sensor lies on the shaft surface with a small air gap as shown in Fig. 1. In the sensor, when the shaft rotates, electric voltages are induced when the magnet chip passes through the coil. The induced voltage is input to a control computer, and rotation angles and phase between the inlet valve and the exhaust valve are calculated. The dimensions of the coil used in this experiment are as follows: outer radius of the coil = 20 mm, inner radius of the coil = 6 mm, length = 20 mm, electric resistance = 1 Ω, coil turn = 500, and air gap between the coil and the shaft = 1 mm.

Fig. 5 shows the coil voltage versus time when the coil sensor is used. The phase between the inlet valve and the exhaust valve is obtained by measuring the time between the peaks of both curves.

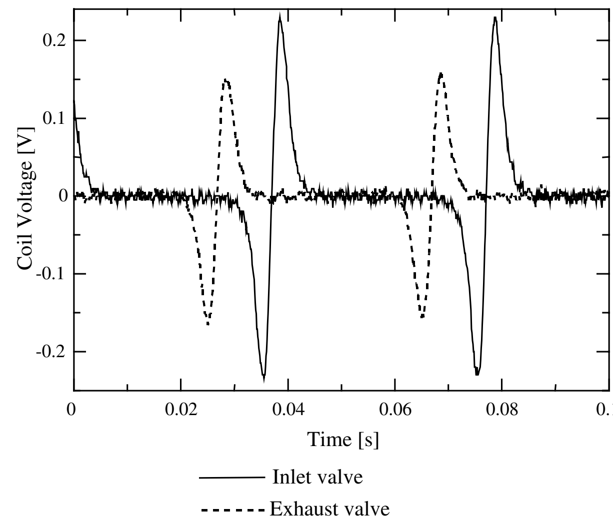

Fig. 5. Response of sensor coil (phase = 90°).

2.3.2. Valve lift sensor

It is difficult to stack the valve displacement sensor in an engine, but the displacement sensor can be set outside the engine head for the movement in the axial direction. Using the displacement of shaft D in the axial direction without using the valve displacement sensor performs the control of the valve lift. Since the cam profile in this system is three-dimensional and the profile has production errors, it is complicated to calculate the exact relation between the valve lift and the displacement of shaft D in the axial direction. Hence, the relation between the valve lift and the displacement of shaft in the axial direction was measured. A laser gap sensor measured the displacement of the valve, and the shaft movement was measured by eddy current type sensor. Fig. 6 shows the relation between the induced voltages V in the eddy current sensor and the valve lifts L (mm) in one rotation. The curve is written in the following form by using the least square's method:

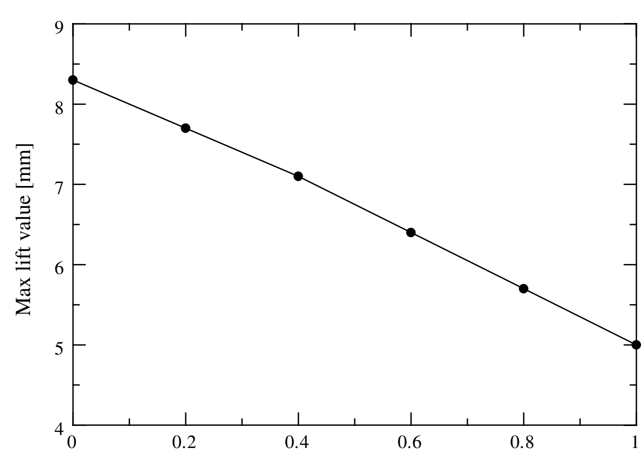

Fig. 6. Maximum valve lift in one rotation versus eddy current sensor voltage.

$$L = -0.37V^2 - 2.93V + 8.30 \quad (1)$$

By using Eq. (1), the control can be performed by using the eddy current sensor only.

3. Valve timing and valve lift controls

Fig. 7 shows a photo of our experimental apparatus. An inverter motor with power of 15 kW is used instead of an engine. The motor drives pulley of our valve timing mechanism by using a timing belt, and so the above-mentioned camshaft for the inlet valve is rotated. The motor also drives the cam for the exhaust valve without the mechanism at the same time by using a timing belt. A magnetic chip is pasted at each camshaft for detecting rotary angles. A valve of a customary engine is used whose mass is 48 g and valve spring constant is 12.3 N/mm.

As for the valve lift control system, a DC motor is used whose dimensions are as follows: the rating voltage = 12 V, power = 150 W, rating rotating speed = 6440 rpm, and rating torque = 2030 mN m. The dimensions of the motor for the valve timing control are as follows: the rating voltage = 48 V, power = 140 W, rating speed = 7160 rpm, and rating torque = 2640 mN m.

3.1. Valve timing control

Varying rotary phases between the inlet cam and the exhaust cam, the valve timing control is performed. The exhaust cam rotates with a constant phase, but the phase of inlet cam varies in this system. The control is needed to vary the phase only, and the control of valve response is not necessary, because the cam creates valve motions. The control has to be corresponding to driver's action of acceleration or reduction of speed of the engine. Since the action speed is somewhat slow, the control speed is relatively small. Since the rigidity of the valve timing mechanism using the planetary gear and the worm is large, vibrations are small. However, the system has large frictions. Since the friction force varies with the movement of valves and the camshaft, the equation of motion of the system is nonlinear, and it is difficult to have theoretical dynamics. For the system, the PID control is applicable, because it does not require system dynamics when appropriate feedback gains are chosen. Since system parameters do not vary, the same gains are applicable in engines. Performing a few experiments or using PID tuner, the gains are obtained easily. To have the set value, the integration control (I-control) is valid, but it often affects the control stability and requires a large amplifier. In the present control, since the friction (damping) is large, the overshoot will be significantly small, and the stable zone is large. This means that the control is possible using P-control for the position as mentioned below. In such case, a large gain of P-control is applicable which is corresponding to the power amplifier. Therefore, the PD feedback control is performed for having the set position (P-control) and absorbing vibrations (D-control).

The voltages induced in the coil sensors are input to a digital signal processor (DSP). In the experiment, the computer (DSP) makes samplings of the induced voltages in the coil sensors, and finds the maximum value of each coil in one cycle. The count number n_2 from peak to peak in the inlet cam means the total count number in one rotation. Let the count number between the peak of the inlet cam and the exhaust cam be n_1. The phase angle (°) between the inlet cam and the exhaust cam is $\gamma = (n_1/n_2) \times 360$. When the sampling in one cycle is finished, the counter is set to be zero, then the next counting starts. The rotating frequency (rps) is given by $f = f_s/n_1$, where f_s is the sampling frequency.

The subtraction of the objective phase and the measured phase is input to the control motor after multiplying an appropriate feedback gains:

$$V_{d1} = k_1\{g_1(f) - \gamma\} + k_2 \frac{d}{dt}\{g_1(f) - \gamma\} \quad (2)$$

where V_{d1} is the motor input voltage, k_1 and k_2 are the feedback gains, f is the rotating frequency, and $g_1(f)$ is the objective phase.

The phase should be large at low and high engine speeds, but small at middle speeds. Making this control,

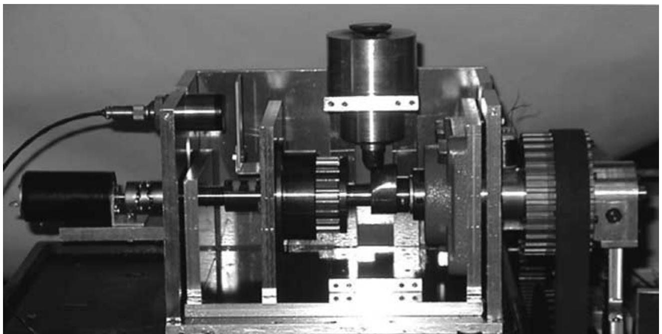

Fig. 7. Variable valve timing and lift system.

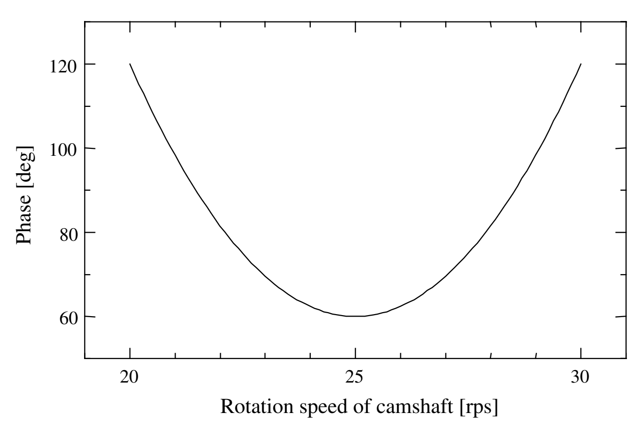

Fig. 8. Objective values for the phase.

energy efficiencies increase, and NO_x in exhaust gas decreases. Hence, the objective phase is assumed to be the curve in Fig. 8. Using the measured cam speed, the objective phase is calculated from Fig. 8.

3.2. Valve lift control

In this system, moving the camshaft in the axial direction, a continuous control can be made. The valve lift is calculated by using the formulae as mentioned above, and the PD feedback control is possible:

$$V_{d2} = \alpha_1\{H(f) - h\} + \alpha_2 \frac{\mathrm{d}}{\mathrm{d}t}\{H(f) - h\} \tag{3}$$

where V_{d2} is the input voltage to the valve lift control motor, α_1 and α_2 the feedback gains, $H(f)$ the objective valve lift with respect to the cam rotation frequency f, and h the maximum valve lift in one rotation of the cam. The variable valve lift system is desirable, which increase with the cam rotating speeds. Then, two objective valve lifts $H(f)$ are considered, one of which increases linearly (see Fig. 9(a)), and the other increases, then saturates as shown in Fig. 9(b). Using the measured cam speed, the objective valve lift is calculated from Fig. 9.

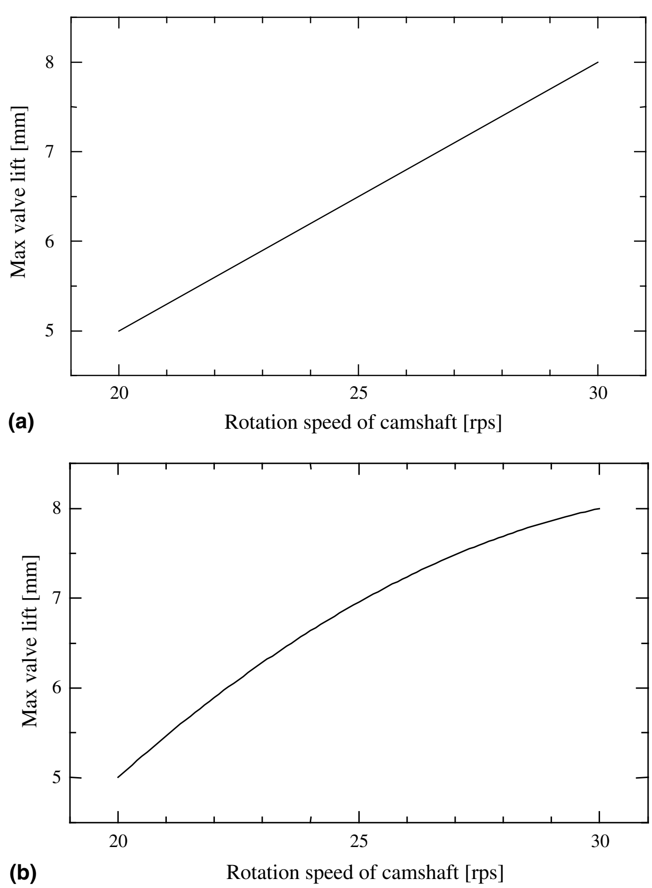

Fig. 9. Objective values for the cam lift.

4. Results under the control

Since drivers make accelerations and reductions of engine speeds, the patterns are different. Then real time controls have to be made according to engine speeds. Consider the control, in which the phase and cam lift correspond to the objective curves as shown in Figs. 8 and 9. The desired values are decided by reference to the objective curves (Figs. 8 and 9) corresponding to the cam rotating speeds. We first investigated the step response for the phase and the lift by using both P- and D-control. The differences between the result in P-control and that in PD control were small in spite of the control current being increased in the PD control. Since frictions are large in this system, and damping is enough, an effect of D-control is small. Hence, P-control is enough for controlling them ($k_2 = \alpha_2 = 0$).

In the control of both the phases and lifts, we consider a normal velocity pattern, in which engine speed increases linearly, becomes flat, then decrease. Fig. 10(a) shows the velocity pattern, which was created by manual operation of a driving motor controller. The desired values for the phase and the lift are calculated by using Figs. 8 and 9(a). Dashed lines in Fig. 10(b) and (c) denote those. The

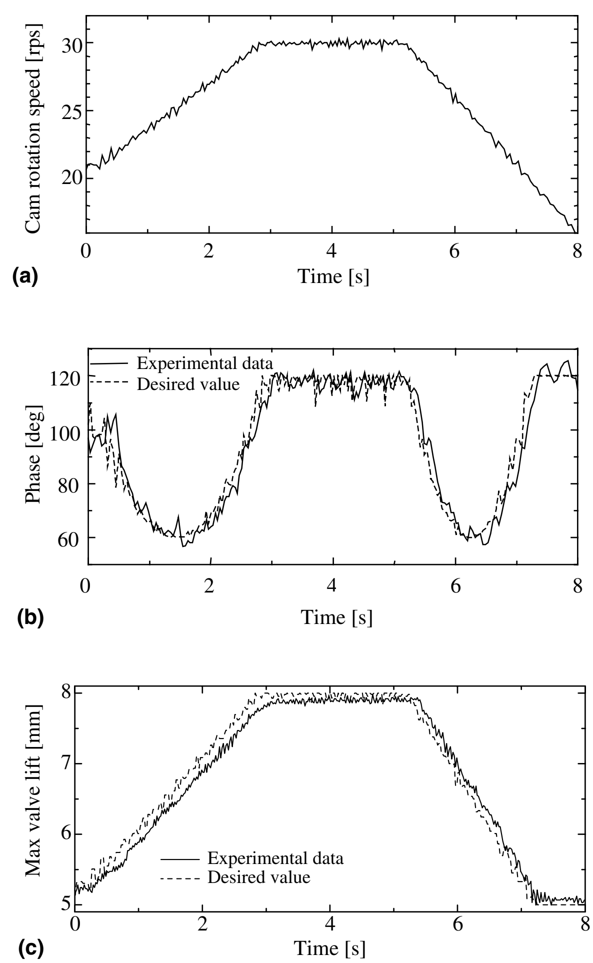

Fig. 10. Results under the phase and lift control: (a) speed of camshaft, (b) phase and (c) max valve lift.

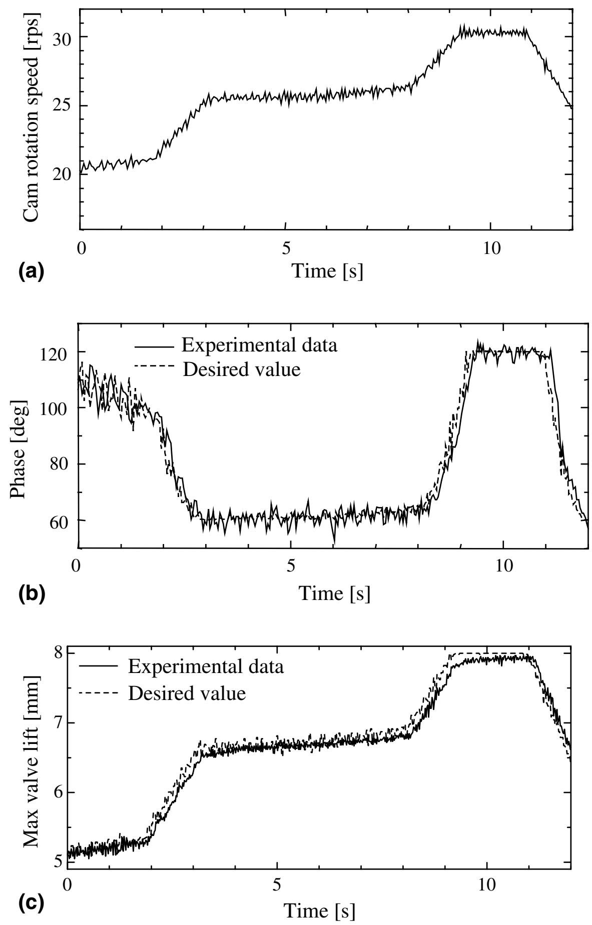

Fig. 11. Results under the phase and lift control: (a) speed of camshaft, (b) phase and (c) max valve lift.

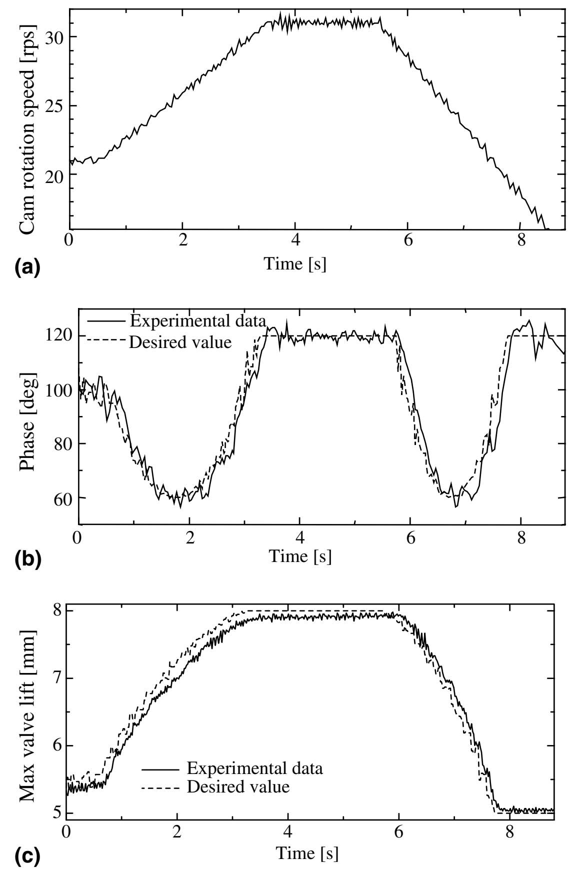

Fig. 12. Results under the phase and lift control: (a) speed of camshaft, (b) phase and (c) max valve lift.

solid lines are the measured values under the control. Although a few control delays are observed (about 0.2 s), the measured values correspond to the desired values for both the phases and the lifts. Fig. 11 shows the results when the velocity curve has steps as shown in Fig. 11(a) for the objective curve in Fig. 9(a).

Figs. 12 and 13 denote the results in case of the objective curve being Fig. 9(b). Both phases and the lifts correspond to the desired curves. The controlled phase in Fig. 10(b) has a similar shape of the curve in Fig. 12(b). The other curves in Figs. 10 and 11 have also the similar shapes of the corresponding curves in Figs. 12 and 13. Hence, both objective curves in Fig. 9 will be available for this control. There are a few noise in both the desired values and the measured values. This is due to errors of measured rotating speeds. When there are errors in obtaining rotating speeds, the desired value also has errors, but the effects of errors are small. Using I-control can reduce the differences between the controlled results and the desired values. In the figures, however, the differences are small, and their values are in the order of errors in the velocity sensor. In addition, those will be in the range of practical use. Therefore, the P-control is enough for controlling the present system.

As for the valve response in this system, the movement of the valve follows the cam profile, and there is no bounce when the appropriate design is made for the cam profile and the valve spring. This means that the sound noise and the wear of the cams are restricted to within those of customary engines. Since, the cam is connected to the engine crankshaft mechanically by using a timing belt, the timing of the cam perfectly follows to the engine. Hence, when the phase is given between the inlet cam and the exhaust cam by using the planetary gear, the cams for every cylinder have the same phase. This means that our planetary gear and variable lift system can control every cylinder by using two compact DC motors under straightforward control method such as P-control. Hence, the system is cheaper, and its weight is small in comparison with the electromechanical valve system. There is no control loss when the engine speed becomes steady state, because the variations of the phase and valve lift are required in the range of increasing- or decreasing-speed, and they are not required at the constant engine speed. In the small velocity variation range, the control operation is small, or no control is required. This is the advantage of this system in comparison with the camless engine, in which the controls are continuously performed. In our system, however, there is a disadvantage of friction losses like the customary engines of course.

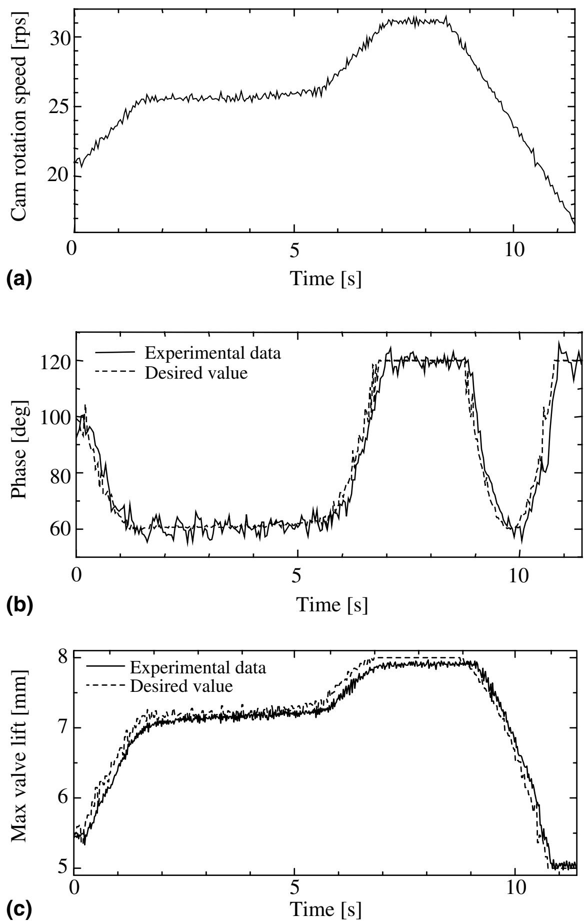

Fig. 13. Results under the phase and lift control: (a) speed of camshaft, (b) phase and (c) max valve lift.

5. Conclusion

A new valve control system is presented for internal combustion engines, in which the valve timing and the lift are continuously controlled. The valve timing control system consists of a planetary gears, worm mechanism and control motor. The valve lift control system consists of the cam having a slope, in which the cam slides in the axial direction by using the control motor. The control method was developed for having appropriate valve timings and valve lifts. To validate it, experimental tests have been carried out for a model made in this article. The obtained results are as follows:

(1) The system presented can control the valve timing and the valve lift continuously.
(2) The controlled results correspond to the objective curves, even when the objective values of the valve timing and the valve lifts vary continuously. The time delay was less than 0.3 s in this case, which will be in practical use.
(3) Although there are friction losses for cams, the present system has some advantages on the valve response stability, sound noise, control energy, prices, weight, and controllability.

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