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A New Electromagnetic Engine Valve Actuator with Less Energy Consumption for Variable Valve Timing

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Abstract

A variable valve timing (VVT) can improve fuel efficiency, reduce CO2 emissions and increase torque output enabling optimization of these outputs at different engine conditions. To achieve VVT in internal combustion engine, new devices such as mechanical, hydraulic, motor-driven and electromagnetic actuators have been developed in past years to replace the conventional camshaft valve train system used currently. Among these, the electromagnetic actuator using solenoids is the most advanced system to provide the most flexibility to valve timing, but it has critical drawback of high power consumption. In this paper, a new electromagnetic engine valve actuator that uses permanent magnets to latch the valve is introduced.

Keywords: Permanent magnet; Solenoid; Finite element analysis; Linear actuator; Variable valve timing

1. Introduction

The current internal combustion engine normally uses poppet valves for intake and exhaust. These are driven by cam and camshaft. The cams lift the valves for a certain amount of duration during each intake and exhaust cycle and the shape of cam lobes on the camshaft is optimized for a certain engine speed. Optimization of cam shape, however, is possible only at narrow range of engine speed (Levin et al., 1991), which results in a sub-optimal compromise between engine torque output, low fuel efficiency, and large emissions at other speeds. For example, at a high speed an engine requires large amounts of air. However, the intake valves may close before all the air has been given a chance to flow in, reducing performance. On the other hand, at lower unburned fuel exits the engine since the valves are still open if the cam keeps the valves open for longer periods of time. This brings in lower engine performance and increased emissions.

Variable valve timing (VVT) is a key technology to overcome a conventional camshaft engine valve system. VVT allows the cam profile to change, which results in greater efficiency and power. Valve events are controlled independently of crankshaft rotation. As a result, fuel consumption may be reduced up to 15%, torque output is enhanced in wide range of engine speed, and CO2 emission may be decreased up to 15% (Barkan et al., 1989; Pischinger et al., 2000).

Some of the devices developed in the past years to achieve variable valve timing include mechanical, hydraulic, motor driven, and electromagnetic actuators. The simplest VVT systems advance or retard the timing of the intake or exhaust valves like Mazda's S-VT. On the other hand Honda's VTEC

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switches between two sets of cams at a certain engine RPM. However, these systems add complexity, and there is not much improvement to torque (Hamazaki et al., 1991). Another technology altogether uses small electric motors to control valve motion (Chang et al., 2002). But this technology is still very near the beginning stage of development.

The most advanced system is the electromagnetic actuator using solenoid. Figure 1 shows the schematic diagram of solenoid actuator. The main operation principle is mass-spring oscillation and variable valve timing is achieved by control of voltage applied to the coils (Wang et al., 2000; Stubbs, 2000; Wang et al., 2002). The duration of valve events and the phase between the intake valve and exhaust valve are thus very flexible (Sugimoto et al., 2004). Several automotive manufactures experimented with solenoid actuator design. However, this type of actuator suffers the inherent problem of high-energy consumption for operation. There are two significant causes for the high-energy consumption (Giglio et al., 2002). When the turnkey is switched off, the clapper is located at the neutral stroke position because the coils are no longer energized. To start the engine, the upper coil of solenoid actuator is energized to pull up the clapper from mid to upper end. This first "catching" of the clapper is a critical stage because there is no net potential energy in springs. Therefore, catching the clapper requires that a large amount of current be supplied to the upper solenoid in a reasonably short time (Giglio et al., 2002). During normal operation (after starting), current is continuously required because one or the other solenoid needs to be energized to latch the clapper at either end position of the stroke.

Therefore, the studies to solve the problems associated with the solenoid actuator have been performed (Okada et al., 2004; Kim et al., 2005; Kim, 2005).

In this paper, a new design of electromagnetic engine valve actuator is introduced utilizing permanent magnets to aid in valve latching. To characterize the performance of the proposed actuator, finite-element analyses are performed using a commercial FEM solver.

2. A new design of actuator for valve control

2.1 Operating principle

Figure 2 shows the schematic diagram of new design. This actuator is composed of two pieces of permanent magnet, electromagnetic coil (solenoid), a laminated steel core and clapper, two springs and the valve body. The armature and the valve are one continuous body. As the armature moves up and down, the engine valve closes and opens. The total travel distance of clapper is 8 mm. Figure 3 shows the operating principle. The solid arrows show the magnetic flux generated by the permanent magnets and the dotted arrows show the flux generated by the electromagnet. At start, the permanent magnets hold the armature at the upper position, i.e. the valve is closed, because the magnetic force exceeds the spring force. To open the valve, the coil is energized. As the flux of permanent magnet is partially cancelled, the spring force exceeds the magnetic force. The armature is thus released, the valve starts opening, and is it accelerated by the stored energy in the springs. After the neutral stroke position, the coil is reversely energized, and the permanent magnet and electromagnet catch the armature at the bottom. The motion from the lower end to the upper end is the inverse operation of the steps above.

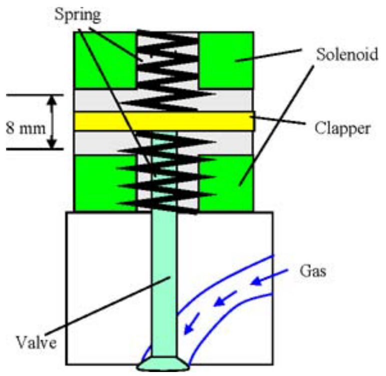


Fig. 1. Schematic diagram of solenoid actuator.

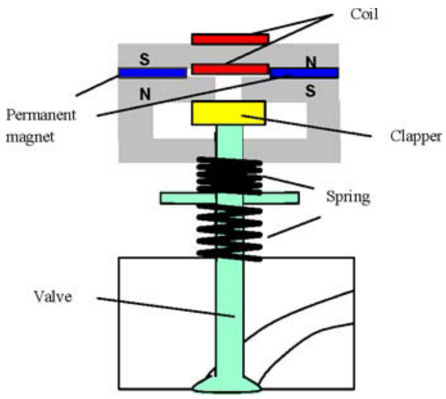
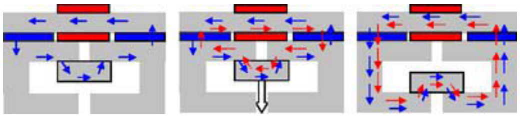


Fig. 2. Schematic diagram of proposed new actuator.

2.2 Comparison with solenoid actuator

Compared with the conventional solenoid actuator, the newly proposed design of actuator using permanent magnet reduces the consumption of power for operation.

First of all, the proposed actuator using permanent magnet needs no electric power to pull up the clapper from mid to upper end at the initial starting like solenoid actuator because the residual magnetic force of permanent magnet holds the clapper at end position during the recess of engine. Table 1 shows the closure current, maximum current, and maximum power required to attain the first valve lift for operation of conventional solenoid actuator which is not required for operation of proposed actuator.

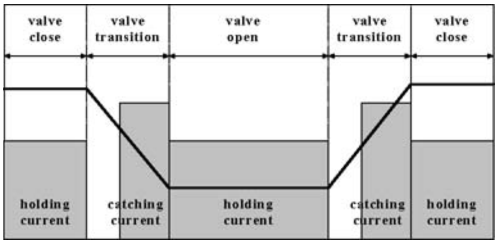


(a) At upper end (b) At starting (c) At lower end

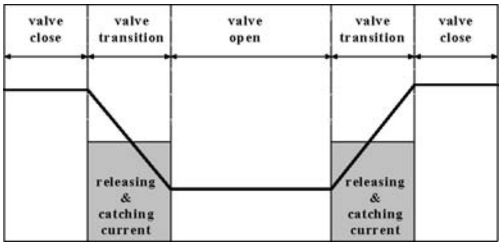
Fig. 3. Principle of operation.

Table 1. Closure current, max current and max power required to attain the first valve lift (Giglio et al., 2002).

Closure current [A]	Max current [A]	Max power [W]	Energy [J]
3	65.3	1500	176



(a) Solenoid actuator



(b) New proposed actuator with permanent magnet

Fig. 4. Current control profile for normal valve operation.

During normal operation (after starting), current is not required by new actuator to latch the clapper at either end position of the stroke because of the holding force of permanent magnet. Figure 4 shows the current control profile for normal valve operation of solenoid actuator and suggested new actuator with permanent magnet. As shown in Fig. 4(a), the solenoid actuator needs current for catching moving clapper to end position and holding clapper at either end position to maintain valve opened or closed while new actuator with permanent magnet needs current only for releasing and catching clapper. In result, the solenoid actuator consumes more current than the new actuator during normal operation (Kim, 2005). The holding duration of the clapper at each position during one complete cycle is dependent on engine RPM. As the engine speed decreases, the ratio of holding duration to one cycle time increases proportionally. At 3000 RPM, which is a nominal engine speed, the holding duration time of clapper per each engine valve actuator is as much as 80 percent of one cycle time (40 milliseconds).

2.3 Simulation by finite element analysis

To simulate the actuator, finite-element model (FEM) is created and dynamic finite-element analysis was performed using the nonlinear FEM solver MAXWELL. The new actuator is composed of three subsystems: a mechanical system, an electrical system, and a magnetic system, which are all coupled to each other.

The magnetic subsystem is governed by equation (1). The nonlinear magnetic B-H properties of silicon steel were assigned to the core and the clapper, and the magnetic properties of samarium cobalt (SmCo 28) were assigned to the permanent magnet. The SmCo28 permanent magnet is utilized in these actuators because these actuators operate just outside engine where the temperatures are over 150°C. Samarium cobalt magnet still has good performance at these temperatures. Table 2 shows the specifications of the SmCo28 permanent magnet.

$$\nabla\times\left(\frac{1}{\mu}\nabla\times A\right)=J_{ext}+\frac{1}{\mu}\nabla\times M \quad (1)$$

boundary condition $A_z=0$

The mechanical system is governed by equation (2). The moving mass clapper and the stiffness of springs are specified. The moving mass includes clapper, engine valve, keeper and a fraction of spring. Table 3 shows the specifications of the mechanical subsystem.

$$m\ddot{x} + 2kx = F_{magnetic} \tag{2}$$
initial condition $x(0) = -4mm, \quad \dot{x}(0) = 0$

The electrical subsystem consists of the coil, capacitor, voltage power supply and toggle switch. At first, the capacitor is charged when the switch is turned off. When the switch is turned on, the capacitor is discharged. The resulting current flows in the coils and oscillates under-damped. The period of current is designed to be half of the travel time of the clapper. The first half-cycle of current creates flux in the opposite direction of permanent magnet flux to release the clapper. From the neutral position of the clapper, the second half cycle of current is negative, so the coil creates the same direction of flux as the permanent magnet flux, thus adding magnetic flux to the permanent magnet to overcome the spring force and catch the clapper. The Eq. (3) is governing equation and initial condition. Table 4 shows the specifications of initial charge voltage, capacitance, coil turns, and coil resistance.

$$\frac{d\lambda(i,x)}{dt} + Ri = V \tag{3}$$
initial condition $i(0) = 0$

2-D dynamic finite-element model was created to assist in modeling these coupled systems. The dynamic motion of the clapper from the lower end to the upper end of stroke was simulated. The analysis is performed with 10 microsecond time steps over a period of 4 milliseconds. The magnetic force exerting on the moving clapper was computed through virtual work principle method.

Table 2. Magnetic properties of SmCo28 permanent magnet.

Br (T)	Hc (A/m)	μr
1.02	-754176	1.075

Table 3. Specification of mechanical subsystem.

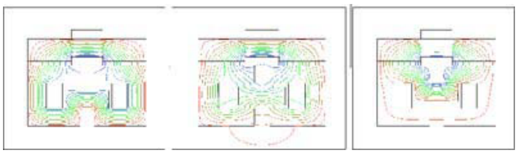
Mass	Spring stiffness	Natural Frequency(ωn)
110 gram	170 kN/m	1243

Table 4. Specification of electric subsystem.

Voltage	Capacitance	Coil turns	Resistance
200 Volts	100 μF	200	1 Ω

2.4 Results

Figure 5 shows the magnetic flux lines at three positions during the motion. Figure 5(a) shows that the magnetic flux from the permanent magnet holding the clapper at the lower end position of stroke. Figure 5(b) shows the magnetic flux lines when the clapper is located at mid-travel. The flux from the upper core and lower core are symmetric, and the magnetic force acting on the clapper is zero. Figure 5(c) shows the magnetic flux lines when the clapper is located at the upper, latched position. Figures 6 and 7 show the profiles of position and current respectively while Fig. 8 shows magnetic force and spring force. The transition time is 3.72 milliseconds. The current oscillates like a damped sine curve. The first-half posi-



(a) (b) (c)

Fig. 5. Flux distribution (a) at lower end (b) at neutral position (c) at upper end.

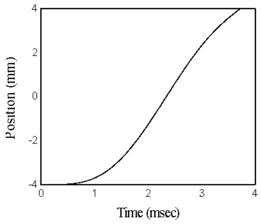


Fig. 6. Position profile.

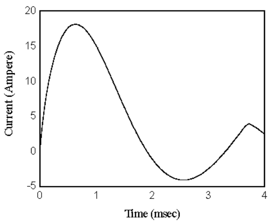


Fig. 7. Current profile.

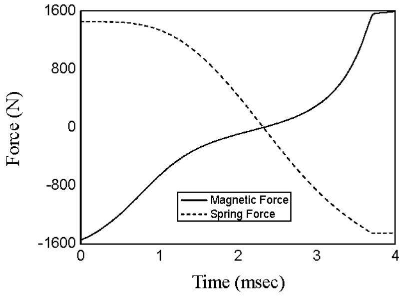


Fig. 8. Force profile.

tive current exerts a counter magnetic flux to the permanent magnet flux while second-half negative current provides magnetic flux that has the same direction as the permanent magnet flux. There exists a delay time for the clapper to be released from the lower position, mainly because of coil inductance.

4. Conclusions

New design of linear actuator for electromagnetic valve, using permanent magnets, is proposed to overcome the problem that is characteristic of solenoid actuator. To characterize the performance of the proposed system and compare with solenoid system, the simulations using FE analyses were performed. The results show that the dynamic response of the valve system may make this design suitable for application in an internal combustion engine. In addition, an amount of power can be saved by employing permanent magnet.

Acknowlegements

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Nomenclature

$\vec{A}$	:	Magnetic vector potential
B	:	Magnetic density
B_r	:	Residual induction
C	:	Capacitance
$F_{magnetic}$	:	Magnetic force
H_c	:	Magnetic coercitivity
i	:	Current
$\vec{J}_{ext}$	:	External current density
K	:	Spring stiffness
$\vec{M}$	:	Intrinsic magnetization density
m	:	Moving mass
V_i	:	Initial voltage
x	:	Displacement of moving part
λ	:	Flux linkage
μ_r	:	Relative permeability
ω_n	:	Natural frequency
R	:	Resistance
RPM	:	Revolution per minute
t	:	Time
V	:	Voltage
V_c	:	Charged voltage

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