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DESIGN OF A NEW ELECTROMAGNETIC VALVE WITH A HYBRID PM/EM ACTUATOR IN SI ENGINES

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Key words: electromagnetic valve, magnetic flux, finite element analysis (FEA), permanent magnet (PM).

ABSTRACT

Numerous devices have been developed for controlling valve timings in SI engines. Among them, the electromagnetic valve train (EMV) actuator can fully control valve timings to improve fuel consumption and emission. In addition, an EMV with a permanent-magnet and electromagnetic-coil (PM/EM) hybrid actuator has several advantages of control, energy consumption, and time response compared over conventional EMVs. This paper proposes a novel EMV with a PM/EM hybrid actuator that differs considerably from existing EMVs. Finite element analysis was used for analyzing the EMV design. The optimization was based on criteria that ensured the EMV to satisfy holding forces in closed and open states at high speed in SI engines. Several parameters such as PM, armature dimensions, and electromagnetic coil sizes were analyzed. The results indicated that the EMV satisfies the required space limit. Furthermore, the optimal EMV design also matches the transition time and holding force. A holding force of approximately 719 N is created when the desired current is supplied to the coils, and the efficiency of the force dropped by 42.22%. Therefore, the EMV can fully control the timings of the closed and open valves at high speed in SI engines.

I. INTRODUCTION

Numerous devices, such as mechanical, hydraulic, motor-driven, and electromagnetic actuators, have been developed for deriving variable valve timing in SI engines. Furthermore, an electromagnetic valve train (EMV) actuator has a simple structure and controls valve timings without a camshaft in wide operating ranges compared with other actuators. Using an EMV eliminates the throttle valve and camshaft in SI engines. A camless engine can use variable intake valve timing for controlling the engine load to reduce pumping losses considerably, thus improving the efficiency and emission in SI engines [8]. A camless engine, which often refers to electromagnetic actuators and electrohydraulic valve actuators (EHVAs), can fully optimize valve timings to improve the engine fuel economy, emissions, and torque output performance. However, an EHVA has two potential problems: large energy consumption and poor valve lift repeatability over the lift cycle of the engine [9]. An electrohydraulic system can demonstrate a high flexibility in selecting control strategies of valve timings through the design of a highly complex structure; however, the control is imprecise and ineffective because of oil fluid viscosity and temperature in the system [6].

In [2], an EMV with a double solenoid actuator (or double E-core actuator) was studied. The advantages of this system are simplicity in structure and ease of control. However, this EMV solenoid actuator consumes considerably high amounts of energy for operation. A substantial starting power is required to catch the armature at its middle neutral position during engine startup. Furthermore, a substantial amount of energy is constantly consumed in maintaining the armature at a top or bottom position when the valve is in closed or open states, respectively. Compared with an EMV that contains a solenoid actuator, a hybrid EMV, which contains both a permanent magnet and electromagnet (PM/EM) coils, has several advantages of energy consumption, actuator control, and time response [3].

Novel EMVs with new hybrid magnet engine valve actuators have been proposed by researchers. Kim and Lieu [4] proposed a new EMV design. They used finite element analysis for comparing two proposed EMV configurations. They reported that the EMV demonstrated acceptable dynamic responses and can be used in internal combustion engines. Additionally, unlike a conventional double E-core solenoid actuator, this new EMV design obviously does not require a high actuating energy. An EMV comprising a hybrid magneto-motive force has several advantages, such as compactness, fast response, less energy consumption, compared with

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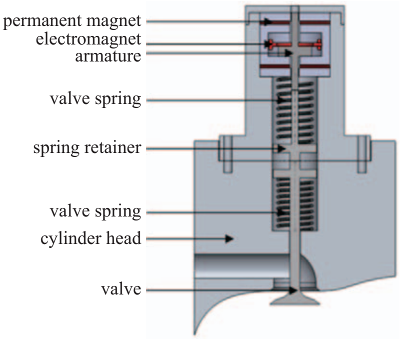

Fig. 1. Structure of the proposed EMV design.

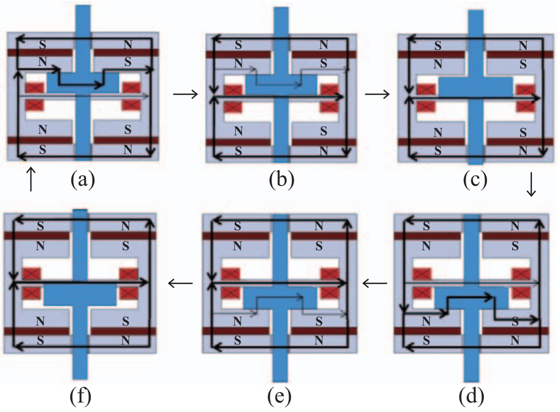

Fig. 2. Operating principle of the EMV. (a) The PM holds the armature at top position; (b) the current is supplied to the coils; (c) the armature is released to the bottom position; (d) the PM holds the armature at the bottom position; (e) the current is supplied to the coils; (f) the armature is caught at the top position.

the conventional EMV [5]. Similarly, a novel EMV, which uses both PM and EM, was introduced in [1]. This study reported that the proposed EMV achieved a 15% volume reduction and 20% holding force enhancement through a special armature design. With the aid of PM and valve releasing strategies, this novel EMV requires only a limited amount of EMV actuating power compared with conventional EMVs.

The present study optimized the design parameters of a new EMV with a PM/EM hybrid actuator, which comprises a structure and operating principle as described in [7]. The parameters affecting the magnetic force in the EMV system were considered and analyzed using finite element analysis (FEA). The design parameters were optimized so that the EMV can be fully operated at high engine speed in SI engines (approximately 6000 rpm). In addition, the EMV must meet the required space limit in cylinder head. The EMV design analysis was mainly based on the flux density and saturation state on the armature when the coils were excited or not excited by the desired current.

II. NEW EMV CONFIGURATION

1. New EMV Structure

Fig. 1 shows the structure of an EMV actuator. It has a hybrid PM/EM actuator equipped with four PMs, a pair of electromagnetic control coils, an armature, two springs, and the valve body. When the armature moves up and down, the corresponding valve is in either a closing or opening position alternatively. The two upper and lower PMs create magnetic forces on the armature for opening and closing the valve. A pair of electromagnetic coils reduces the magnetic force on the armature when they are energized by the desired current. The unique arrangement of the PM and EM facilitates controlling the actuator and energy consumption.

2. Operating Principle of the Proposed EMV

Fig. 2 shows the operating principle of the EMV. The solid lines indicate the magnetic flux generated by the PMs. The thickness of the solid lines represents the intensity of the magnetic flux. In the starting state, the upper PMs hold the armature at the top position. The valve moves to its closed position because the PM creates a magnetic force that exceeds the spring force. When the electromagnetic coils are energized by the desired current, the coils become electromagnets with polar directions opposite to that of the PM poles. Therefore, most of the magnetic flux enters the coil cores. The magnetic force is reduced because the magnetic flux that flows into the armature is substantially decreased (Fig. 2(b)). Next, when the holding force is lower than the spring force, the armature is released, and the valve opens. When the armature is not in contact with the EMV body, all the magnetic flux enters the coil cores, and the PM force becomes zero (Fig. 2(c)). Therefore, stored energy in the spring quickly moves the armature downward. The coils are not energized after the valve reaches its neutral position. The lower PMs produce a magnetic force again to keep the armature at the bottom, and the valve is maintained in an open position (Fig. 2(d)). Similarly, as illustrated in Figs. 2(e)-(a), the motion of the armature from the bottom to the top occurs through the same processes.

III. OPTIMIZED EMV DESIGN

In the proposed EMV design, the parameters include the coil core dimension and coil turns, which directly affect the flux density on the armature. These parameters determine the holding force when the coils are not energized; the magnetic force drops when the coils are energized. In addition, these parameters influence each other; this study thus examined them by using different cases in which all of these parameters were analyzed. The sensitivity of the parameters to the holding force was analyzed using an FEA tool. FEA is highly accurate to solve electromagnetic field features including magneto-static, eddy current, transient, and electric problems. In this study, the magneto-static and transient analysis were used for determining the holding force, flux density, required current, and optimal parameters of the proposed EMV system. Parameters with negligible effects were ignored to simplify

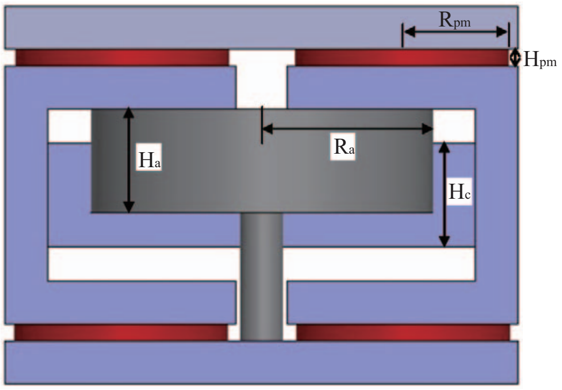

Fig. 3. EMV parameters.

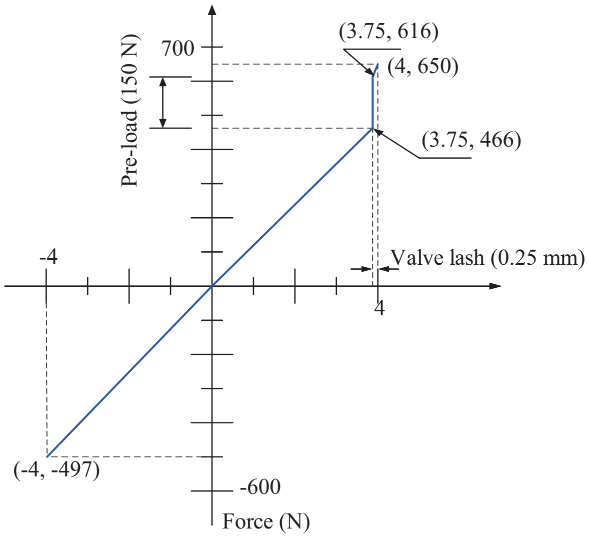

Fig. 4. Spring force and armature displacement at high engine speed.

the optimization process. Fig. 3 shows the EMV structure and parameters.

The optimal design parameters were based on the following criteria:

- When the coils are not energized, the holding forces created by the PMs must overcome the spring force in closed states (approximately 650 N; Fig. 4).
- When the desired current is supplied to the coils, the magnetic force on the armature decreases to the value smaller than the spring force in open states (approximately 500 N; Fig. 4).
- The difference in force between the two aforementioned states achieves the highest value.

1. Permanent Magnet

The PM produces a magnetic force directly on the armature. Therefore, it was derived to create a magnetic force that could overcome the spring force to hold the valve in closed and open positions. The proposed design comprises four PMs: two top PMs to hold the armature in the closed position, and two bottom PMs to hold the armature in the open position. The PMs are circular because this shape has advantages compared with other shapes. The characteristics of PMs depend on temperature because of the effect of the demagnetization phenomenon. The performance of PMs decreases at high temperatures; hence, temperature influences the holding force in the EMV design. In this study, the effect of temperature on the characteristics of the PM was not examined. The PM dimension includes thickness and radius, which influence the magnetic force on the armature. The PM dimension was analyzed using the optimal parameters for the electromagnetic coil and armature. Fig. 5 shows the effects of the PM thickness on the magnetic force.

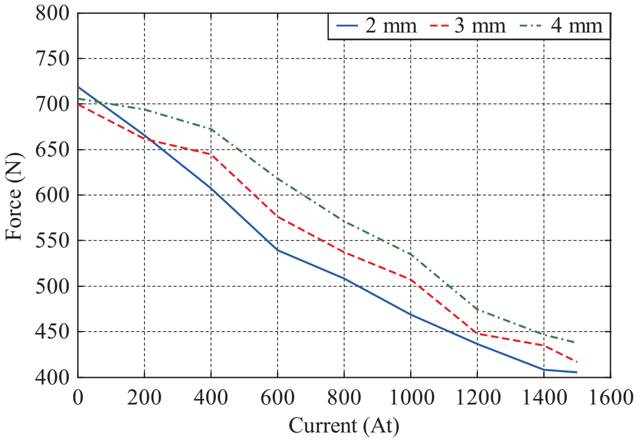

Fig. 5. Effects of PM thickness on the magnetic force.

The optimal thickness of the PM was 2 mm compared with the other cases. The PM at this thickness demonstrated the highest holding force when the coils were excited and lowest holding force when the desired current was supplied to the coils, respectively. The holding force of the PM was approximately 720 N, which overcame the spring forces (Fig. 4); therefore, the valve was maintained at closed and open positions. When the coil cores were excited by the desired current, the magnetic force decreased to 400 N. This force is lower than the spring forces, thus releasing the valve to open or closed positions.

This study also used FEA for analyzing the distribution of the magnetic flux density with the supply current at 0 and 1500 NI, respectively. The results showed that the magnetic flux densities through the armature for all cases were almost in a saturation state when the coils were not excited (Fig. 6). Therefore, the peak magnetic force for all PM thickness was higher than the spring force.

The flux densities had not reached saturation when the desired current was supplied to the coils. Therefore, the magnetic force on the armature decreased. When the desired current is supplied to the coils, the magnetic flux easily trends through coil cores because the electromagnetic coils become electromagnets. This thus reduces the magnetic flux that

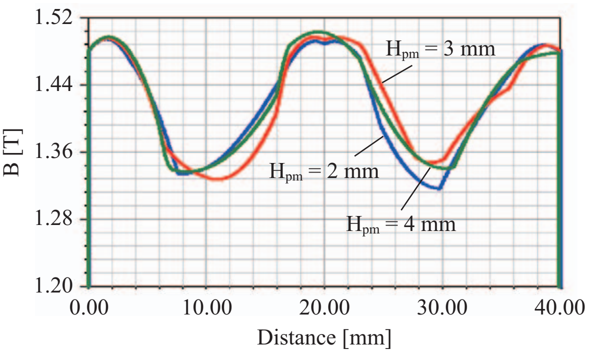

Fig. 6. Distribution of the magnetic flux density on the armature with different PM thicknesses at 0 NI.

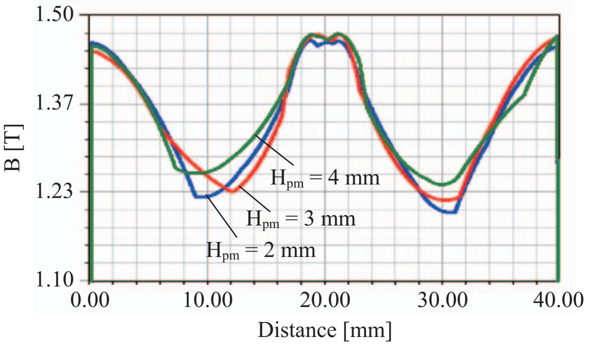

Fig. 7. Distribution of the magnetic flux density on the armature with different PM thicknesses at 1500 NI.

enters the armature. The magnetic flux for the 2-mm-thick PM decreased substantially compared with the other cases (Fig. 7). Consequently, this case registered the highest value of force drop. The PM thickness was optimized at 2 mm for the EMV design.

This study also analyzed the PM radius. The PM radius, which was higher than 13.5 mm, was not examined because of the space limit of the EMV structure. Fig. 8 shows the effects of the PM radius on the magnetic force. The results indicated that the values of the magnetic force and force drop at a radius of 10.5 mm were lowest compared with the other cases. The optimized PM radius was between 11.5-13.5 mm. They seemed to demonstrate the same holding force when the coils were excited and not excited. The effects of these radii, between 11.5-13.5 mm, on the magnetic force were significant.

2. Armature

The dimensions of the armature in the EMV design include armature radius and thickness. These dimensions affect the magnetic flux on the armature directly. The armature radius and thickness are related to the contact area between the armature and steel core. Therefore, they determine the saturation state in the EMV design. In this analysis, the armature radius and thickness were investigated at 19-21 mm and 8-12 mm, respectively. The parameters of the electromagnetic coil

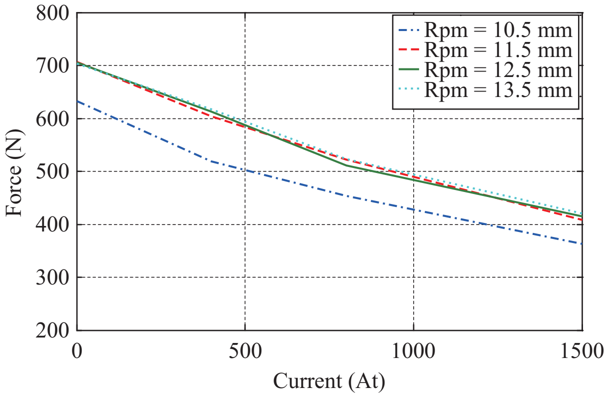

Fig. 8. Effects of PM radius on the magnetic force.

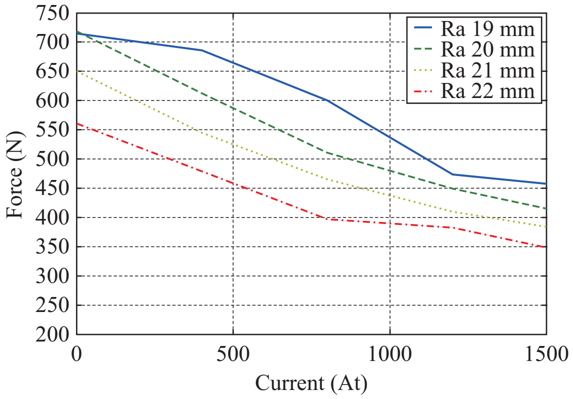

Fig. 9. Effects of armature radius on the magnetic force.

and PM were also optimized. The investigation was performed at 0 and 1500 NI for determining the optimal armature design.

1) Armature Radius

Fig. 9 illustrates the effects of the armature radius on the magnetic force, indicating that the optimal case is the armature radius of 20 mm. This case had a peak holding force of approximately 718 N at 0 NI, and the magnetic force dropped to 415 N with a force drop of approximately 42.2%. However, the holding forces and force drops of the different armature radii did not satisfy the performance requirements of the EMV.

The effects of the armature radius on the magnetic flux density were also investigated using FEA. Figs. 10 and 11 show the investigation results corresponding to the current at 0 and 1500 NI. The flux densities of the armature radii did not reach the saturation state (Fig. 10). The armature radii of 21 and 22 mm demonstrated lower flux densities compared with the other cases. Therefore, they had smaller holding forces than the other cases. The flux density decreased when the coils were supplied by the desired current. The flux densities of the armatures with radii of 21 and 22 mm decreased significantly; thus, their values were lower. However, they still could not meet the required magnetic force. Furthermore, the

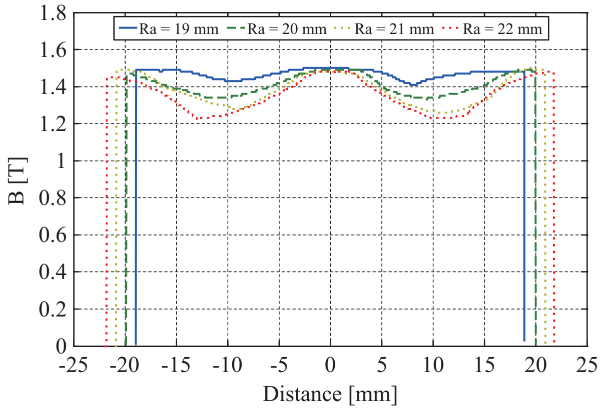

Fig. 10. **Distribution of the magnetic flux density on the armature with different armature radii at 0 NI.**

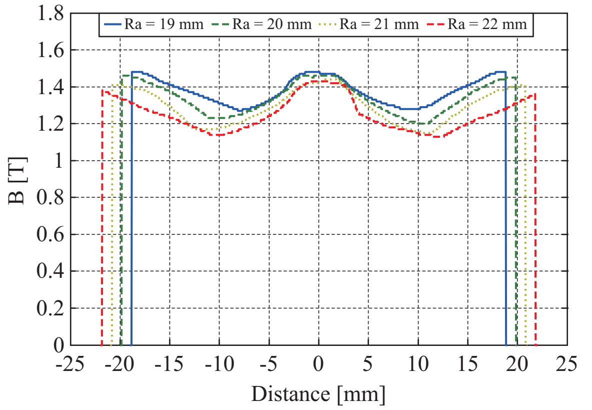

Fig. 11. **Distribution of the magnetic flux density on the armature with different armature radii at 1500 NI.**

reduction in flux density of the 19-mm armature was low, and it thus could not satisfy the required force drop. The optimal armature radius was 20 mm, and the flux density decreased considerably at 1500 NI. This thus caused the magnetic force to be lower than the spring force. Therefore, the EMV can fully operate at this radius.

2) Armature Thickness

The effects of the armature thickness on the magnetic force were also examined using the optimal parameters and armature radius of 20 mm. Fig. 12 shows the analysis results, indicating that the armature thickness of 12 mm has the highest holding force and force drop compared with other cases. Furthermore, the armature thicknesses of 8 and 10 mm did not meet the required magnetic force when the coils were both excited and not excited. The optimal thickness, which was 12 mm, satisfied the EMV criteria to ensure that the valve can fully open and close.

Figs. 13 and 14 show the distribution of the magnetic flux density on the armature at 0 and 1500 NI, respectively. As illustrated in Fig. 13, at 0 NI, the flux densities of the armature thicknesses did not reach the saturation state. However, the highest flux density was registered at the armature thickness of 12 mm; it thus had the highest holding force (Fig. 8). This force was higher than the spring force, and the armature can thus be easily caught in open or closed positions. When the desired current was supplied to the coils, the magnetic flux density through the armature decreased, thus reducing the magnetic force on the armature. As shown in Fig. 14, the flux densities at armature thicknesses of 8 and 10 mm were lower than those of the other cases. Hence, they demonstrated low magnetic forces. However, their holding force could not catch

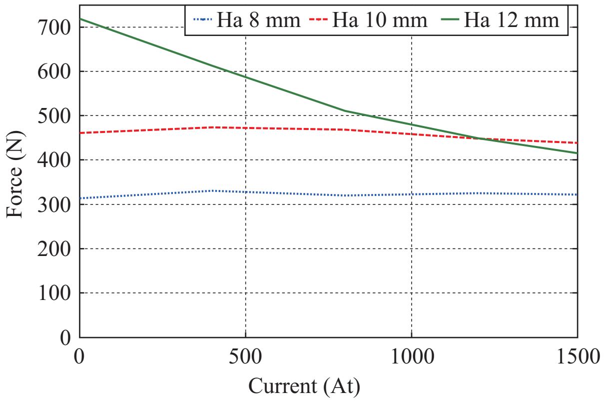

Fig. 12. **The effects of armature thickness on magnetic force.**

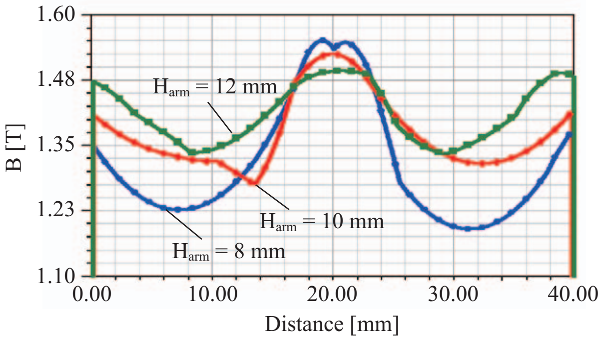

Fig. 13. **Distribution of the magnetic flux density on the armature with different armature thicknesses at 0 NI.**

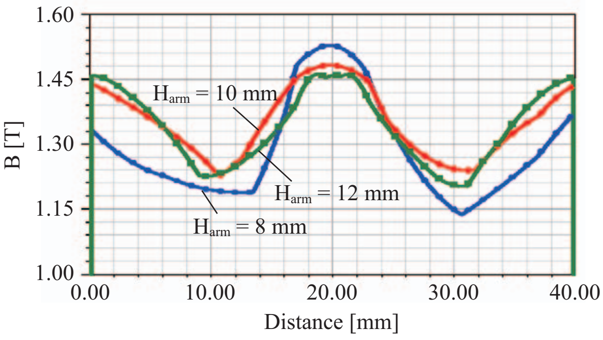

Fig. 14. **Distribution of the magnetic flux density on the armature with different armature thicknesses at 1500 NI.**

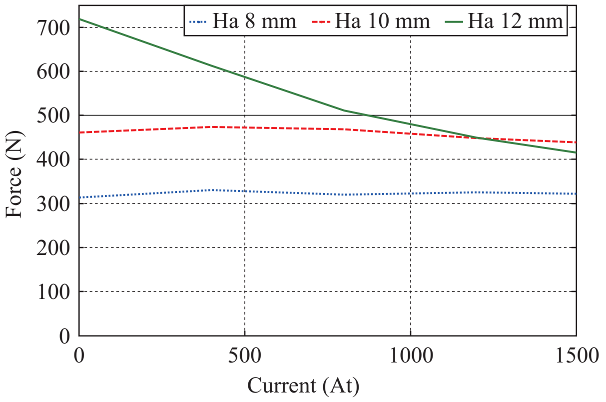

Fig. 15. Effects of armature thickness on the magnetic force.

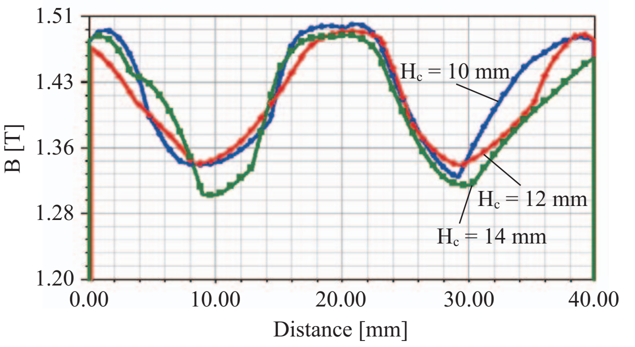

Fig. 16. Distribution of the flux density on the armature with various core sizes at 0 NI.

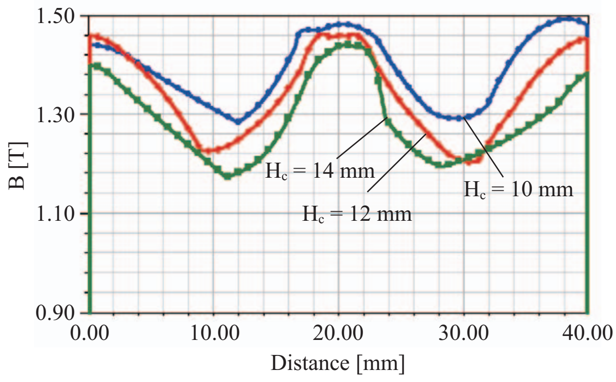

Fig. 17. Distribution of the flux density on the armature with various core sizes at 1500 NI.

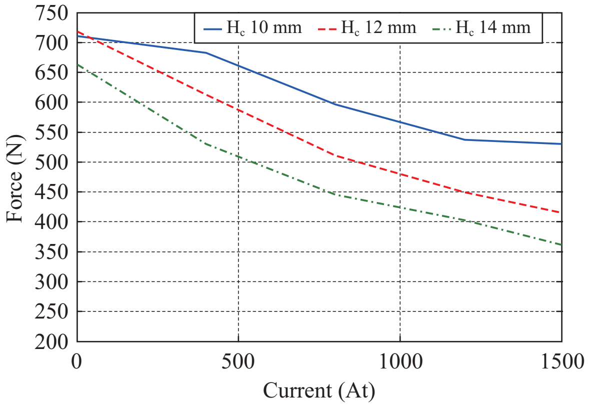

Fig. 18. Effects of electromagnetic coils on the magnetic force.

the valve at high engine speed in SI engines. At 1500 NI, the reduction in the flux density for the armature thickness of 12 mm resulted in a magnetic force that was lower than the spring force. Therefore, the valve can be released to open and closed positions when the coils are energized.

This study also examined the effects of armature thickness on the magnetic force by using the optimal parameters and armature radius of 20 mm. Fig. 15 shows the analysis results, indicating that the 12-mm-thick armature has the highest holding force and force drop compared with the other cases. In addition, the armature thicknesses of 8 and 10 mm did not meet the required magnetic force when the coils were excited and not excited. The optimal thickness of 12 mm satisfied the EMV criteria to ensure that the valve can fully open and close.

3. Electromagnetic Coil

The effects of the electromagnetic coil were also examined at 10, 12, and 14 mm. The size of the coil core determines the amount of magnetic flux that passes through electromagnetic cores. A large core reduces the magnetic force, but it cannot satisfy the required space limit in EMV design. However, a small-sized core causes the flux density that passes through the electromagnetic core to be consistently saturated when the coils are excited. Consequently, the magnetic force drops negligibly. Figs. 16 and 17 show the distribution of the flux density for the coil core sizes at 0 and 1500 NI, respectively. As shown in Fig. 16, the flux densities for the core heights of 10 and 12 mm were higher because less magnetic flux passed through the coil cores. Therefore, the holding force on the armature increases when the magnetic flux mainly enters the armature. By contrast, the core height of 14 mm demonstrated a higher amount of flux density that passed through the coil core; therefore, the magnetic force on the armature decreased (Fig. 18).

When the desired current was applied to the coils, as shown in Fig. 17, the flux density on the armature decreased because a high amount of flux density enters the coil cores. The flux density of the 10-mm core was higher compared with the other cases. Its magnetic force was higher than the spring force on the EMV; therefore, the valve cannot be released to open or closed positions. The flux density of 14-mm core decreased significantly; however, its holding force at 0 NI could not catch the valve and, thus, could not meet the performance requirements of the EMV design criteria. The magnetic density of the 12-mm core satisfied the required holding force and force drop in the EMV design. As shown in Fig. 18, the core size of 12 mm demonstrated a high holding force and low

Table 1. Optimal parameters in EMV design.

Description of parameters	Symbol	Value
PM thickness (mm)	H_{pm}	2
PM radius (mm)	R_{pm}	12.5
Armature thickness (mm)	H_{arm}	12
Armature radius (mm)	R_{arm}	20
Coil core height (mm)	H_c	12
Holding force at 0 NI (N)	F_h	718.86
Magnetic force at 1500 NI (N)	F_e	415.32
Force drop (%)		42.22

magnetic force at 0 and 1500 NI, respectively. Therefore, it was used as the optimal coil core in EMV design.

Table 1 lists the optimal EMV design parameters, as described in the preceding analyses. The EMV designed based on these optimal parameters satisfied the required magnetic forces when the coils were energized and not energized. The holding force was approximately 718 N, and the force drop efficiency was nearly 42.22%. The proposed EMV designed according to these parameters can catch and release the valve to open and closed positions.

IV. CONCLUSIONS

This paper proposes a new hybrid EMV with PM/EM actuator, which differs considerably from existing EMVs, for overcoming the drawback of large energy consumption and improving valve lift repeatability in conventional EMVs. The proposed hybrid EMV is characterized by a simple structure, simple actuation, and ultralow actuating power. This study used FEA for analyzing the magnetic flux density of the EMV and for optimizing the design parameters. The optimal armature parameters for the radius and thickness dimensions are 20 and 12 mm, respectively. The PM thickness and radius are 2 and 12.5 mm, respectively. Furthermore, the coil core height is optimized at 12 mm. When the coils are not excited by the desired current, the optimal EMV design can create a holding force of approximately 719 N and force drop efficiency of nearly 42.22%. Hence, the proposed EMV can be operated at maximum speed in SI engines.

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