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Valve Mechanism for Gasoline Engine with Linear Motor (Fundamental Consideration Using Electromagnetic Field Analysis)

by

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Abstract

Recently, high efficiency of an automobile engine is demanded from the viewpoint of energy saving. Therefore, the authors designed a linear motor capable of the engine valve action, and the authors proposed a valve system that can improve combustion efficiency and reduce pumping loss by arbitrary valve lift and valve timing. In this study, the authors derived the target thrust in this basic study and aimed for optimization of the electromagnetically driven valve system (EDVS) design. In the analysis of a model with one coil and two permanent magnets (PMs), stable thrust could not be obtained. A model with three coils and three PMs, change of thrust was observed by the respective arrangement of the coil and PM. The condition with most stable and highest thrust with respect to the change of obtained stroke was found, when the upper surfaces of the three coils are present near the halfway position of each PM, when the valve is fully opened.

Keywords: Linear motor, Air-pass system, Gasoline engine, Position arrangement, Electromagnetic field analysis

1. Introduction

Recently, high efficiency of an automobile engine is demanded from the viewpoint of energy saving. Items that are rapid combustion, increase in the amount of intake air and reduction in friction loss should achieve high efficiency, and various studies, such as a study on the thermal efficiency of diesel engines by Yoshida, *et al.*[1] and a study on piston ring as friction ross by Tanihata, *et al.*[2], are being conducted. To increase the amount of intake air, improvement of charging efficiency and high rotation are required. Particularly, it is said that valve springs are a major factor hindering high-speed rotation. In general, mechanisms including cam and valve springs are used for the valve train of the conventional engine. In this case, the resonance of the valve spring by the influence of vibration from the engine would cause valve action, without the different expected valve timing corresponding to the camshaft.

On the other hand, unequal pitch springs changing the natural frequency are used to eliminate surging of coil spring in the prior art, but the occurrence of resonance in the high rotation range has not yet been solved. To solve this problem, a system for valve action by using a linear motor without a cam mechanism has been proposed. Electromagnetic valve designs have also been carried out by automobile manufacturers such as GM and Honda[3,4]. In addition, control of valves using electromagnetic motors has been confirmed by Okazaki *et al.*[5], although it is limited to the conditions in motorcycle engines. In this method, a disk shape is added to the shaft portion of the valve, electromagnets are installed on the disk's upper and lower surfaces, and the attraction force acting on the disk and the electromagnet (EM) is taken as the driving force of the valve. However, the gap between the electromagnet and the disk greatly changes due to the operation of the valve, the thrust characteristic becomes nonlinear, and therefore it is considered as difficult to precisely control the positioning. On the other hand, Uchida

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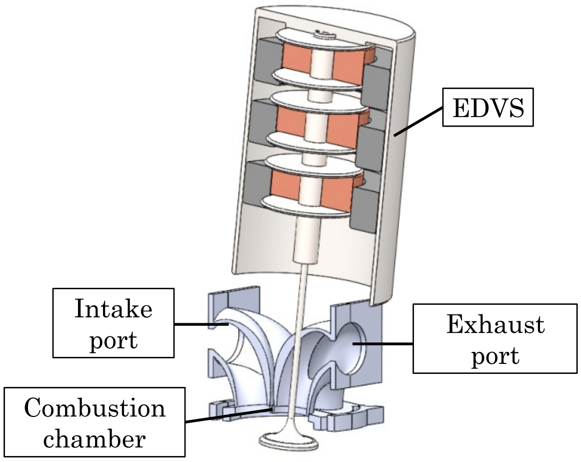


Fig. 1 Electric valve system for gasoline engine.

et al.[6)] proposed an electromagnetic valve using a coil and a permanent magnet, whereby their shapes were optimized, indicating that a constant thrust can be generated even when the valve is displaced. However, these studies have focused on solving the surging phenomenon of the valve spring, and studies have not been conducted using the point that the valve lift amount and timing can be changed positively for efficiency improvement.

Therefore, this research group proposes an electromagnetic valve that achieves the desired thrust by laminating simple structure modules. As an initial study, electromagnetic field analysis was performed on a linear motor for driving a valve, and output characteristics of an electromagnetically driven valve system were studied.

2. Electromagnetically Driven Valve System (EDVS)

2.1 *EDVS*

EDVS moves the intake and exhaust valves of the engine by solenoids consisting of coils, magnets and iron cores. EDVS fundamentally solves valve surging, valve-jump and valve bounce generated in a system using a conventional valve spring. Additionally, though valve lift amount and valve timing fixed conventional engine, EDVS can realize variable valve lift and valve timing in a wide range and without steps, by using an electromagnetic valve. This stepless variable valve lift and valve timing makes it possible to control the amount of air inflow without a throttle valve, and it is possible to eliminate the resistance of the intake air by the throttle valve. Because parts such as a camshaft and a throttle valve are not required according to the above characteristics, it is also possible to reduce weight. As mentioned in Chapter 1, electromagnetic valve designs have also been carried out by automobile manufacturers such as GM and Honda. In addition, control of valves using electromagnetic motors is confirmed by Okazaki *et al.*, although it is limited for the conditions of motorcycle engines. Figure 1 shows a combination of an engine model and an electromagnetic valve. The premixed gas flows from the intake port and the combustion gas is discharged from the exhaust port. Engine valves are installed to open and close these orifices. The engine valve is connected to the EDVS at the cylinder head part, opening and closing the orifice by driving it up and down.

2.2 *EDVS target capability*

Because the thrust required for opening and closing the valve varies greatly depending on the engine speed and displacement, it is important to set a detailed target thrust according to the specification of the installed engine. Therefore, we assume an engine using a relatively high revolution range as usually used for motorcycles. Under such conditions, if the valve lift amount is 10 mm, the maximum revolution speed is 12,000 rpm, the crank rotation is 2 revolutions per crank, and the operating angle is 250 degrees, the acceleration required for valve operation is 7.90×10^3 m/s^2. Furthermore, because the diameter of the intake valve needs to be larger than the exhaust valve. If the mass of the intake valve is assumed to be heavy, for example 25 g, we calculated a force of 190 N from the equation of motion. Therefore, we set the target thrust in this study as 200 N with a certain margin.

3. Study on EDVS Basic Model by Magnetic Field Analysis

3.1 *Outline of analysis model*

We optimized EDVS shape for setting in a practical engine to achieve the target thrust. We modeled the electromagnetically-driven valve and analyzed the magnetic field. In this chapter, we analyzed the basic model consisting of one of the simplest coils and two PMs as the initial stage. General-purpose 3D CAD software was used for modeling, and we evaluated thrust characteristics for a drive valve with electromagnetic field analysis software JMAG Ver. 11.1 (manufactured by JSOL Corporation) for electromagnetic field analysis. Figure 2 shows the model used in this analysis. Figure 2 shows a cross-section of the basic EDVS model. Coil, inner yoke and valve are collectively referred to as mover, PM and case are referred to as stator in Fig. 2. The layout of the stator and mover shown in the figure is in the state that the stroke of the valve is 0 mm, and the valve is completely closed at this time. Furthermore, the direction that the valve opens is positive. In addition, when determining the dimensions of the analytical model, the number of coil turns

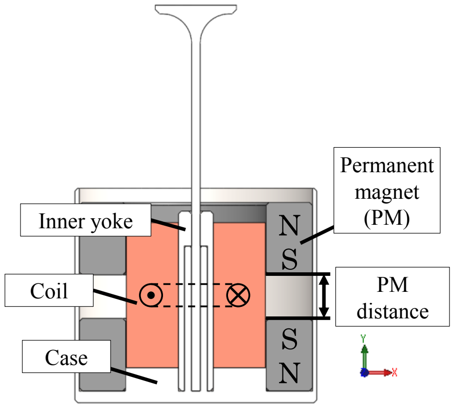


Fig. 2 Basic analysis model.

Table 1 Materials of elements in analysis model.

Coil bobbin	YEP-B(Permalloy)
Valve	S45C
Coil	Copper
Yoke	YEP-B(Permalloy)
Magnet	NEOMAX-P11

Table 2 Dimensions of basic analysis model.

Case	Case outer diameter	ϕ 45.0 mm
	Height	60.0 mm
	Weight	2531.0 g
PM	Inner diameter	ϕ 30.0 mm
	Outer diameter	ϕ 41.0 mm
	Thickness	15.0 mm
Inner yoke	Inner diameter	ϕ 3.4 mm
	Outer diameter	ϕ 7.6 mm
	Height	50.0 mm
Coil	Inner diameter	ϕ 12.0 mm
	Outer diameter	ϕ 48.0 mm
	Number of turn	200 turn
	Diameter of wire	2.0 mm
	Height	50.0 mm
Valve head	Outer diameter	ϕ 28.0 mm
Valve shaft	Height	133.0 mm

was derived from the following equation.

$$N_t = \frac{t}{d} - \frac{d}{2} \quad (1)$$

$$N_h = \frac{2(h-d)}{d\sqrt{3}+1} \quad (2)$$

where, N_t is the number of turns in the thickness direction, N_h is the number of turns in the height direction, t is coil thickness [mm], h is the coil height [mm], and d is the diameter of the winding including the coating [mm]. Table 1 shows materials for each part of the model and Table 2 shows dimensions of the model. In addition the target thrust was 130 N from the previous research by Uchida *et al.*[1].

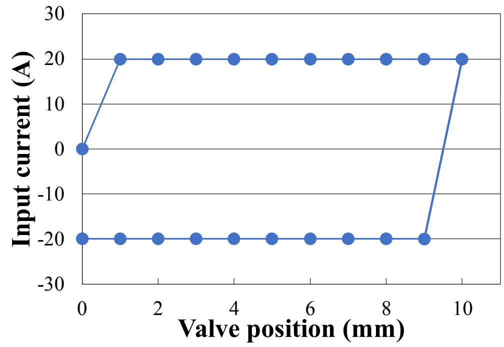


Fig. 3 Analytical condition of coil current in each stroke.

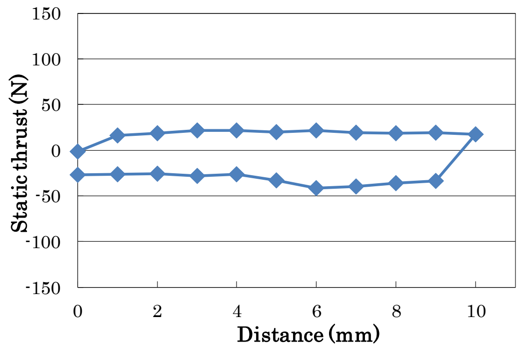


Fig. 4 Analysis result of basic model.

3.2 *Analysis conditions*

We obtained the thrust force characteristic generated in the movable part when a direct current of 20 A was applied to the electromagnet. At that time, the mover moved 1 mm at a time and lifted the valve to 10 mm. After that, the valve was similarly returned to the completely closed state (original point). We obtained the thrust characteristics during one round trip. The wire diameter of the coil at the time of analysis was 2.0 mm, and the number of turns was 200. Therefore, the current to be applied was set to 20 A with reference to JSIA 302 of the Japan Switchboard & Control System Industry Association. Figure 3 shows the applied current to the displacement of the valve during analysis. When a positive current was passed, the direction of the current flowing through the coil was set as shown in Fig. 2. The direction of the magnetic pole of the PM is as shown in the same figure. First, 20 A was applied at the time of opening direction, and -20 A was applied during the closing direction.

3.3 *Analysis result*

Figure 4 shows the analysis results of the proposed model. We confirmed that the EDVS can generate thrust of about 20 N and the change in the thrust is small when the valve is displaced. However, generated thrust is not achieved target thrust. Therefore, in next section, a method of improving thrust is investigated.

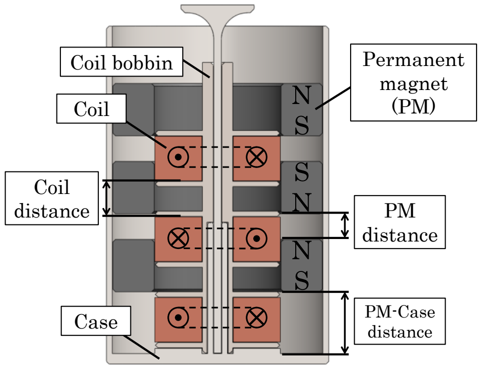


Fig. 5 Analysis model for position change.

Table 3 Dimensions of analysis model for position change.

Case	Case outer diameter	ϕ 85 mm
	Height	137.2 mm
	Weight	3259.8 g
PM	Inner diameter	ϕ 48.5 mm
	Outer diameter	ϕ 80.1 mm
	Thickness	20 mm
	Number	3
Inner yoke	Inner diameter	ϕ 3.4 mm
	Outer diameter	ϕ 7.6 mm
	Height	50.0 mm
Coil bobbin	Inner diameter (Adjacent to valve)	ϕ 3.4 mm
	Outer diameter (shaft part)	ϕ 11.6 mm
	Inner diameter (Adjacent to coil)	ϕ 11.6 mm
	Outer diameter (the maximum outer diameter)	ϕ 47.7 mm
	Height	111.0 mm
Coil	Inner diameter	ϕ 12.0 mm
	Outer diameter	ϕ 48.0 mm
	Number of turn	200 turn (total 3 coils)
	Number	1
	Thickness	17.0 mm
Valve head	Outer diameter	ϕ 28.0 mm
Valve shaft	Height	133.0 mm

4. Study on the EDVS Element Arrangement by Magnetic Field Analysis

4.1 *Analysis model and condition*

In the previous chapter, we did a basic study on the positional relationship between the two elements of PM and coil used in the proposed mechanism. In this section, the winding number of coils is increased to investigate how to improve thrust. The model material for analysis is PM and the number of coils was three each. In addition, we made a model of coil volume of 66, 67 and 67, totaling 200 volumes for comparative study. Figure 5 shows an example of an analysis model, and it shows the names of the parts and dimensions. We changed the distance between the coils to 9.4, 13.4, 15.4, 17.4 mm and the distance between the permanent magnets analyzed in the model as shown in Fig. 5. Table 3 shows the dimensions of the analysis model in this chapter. We set the current value to 20 A within the basic model. The direction of the magnetic pole of the PM is as shown in figure 5.

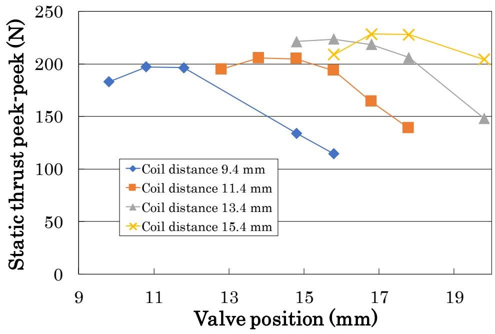


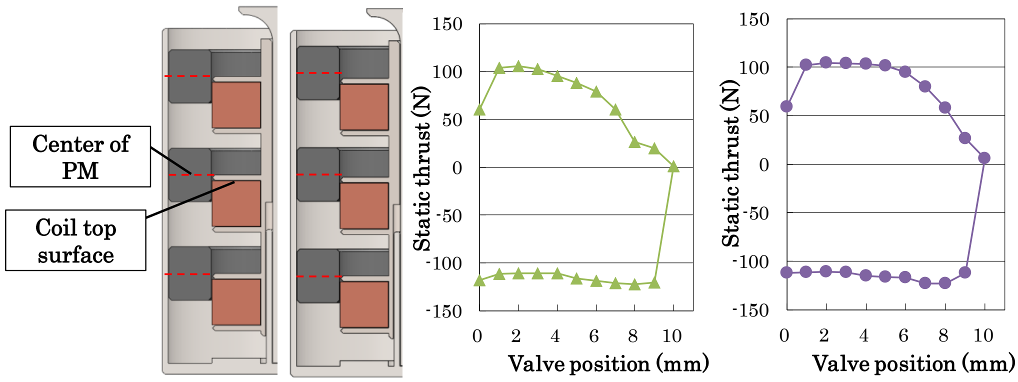
Fig. 6 Static thrust for each position.

4.2 *Analysis result*

Figure 6 shows the maximum amplitude value of the thrust obtained by the model when changing the PM distance and inter-coil distance. We confirmed that the thrust changes according to the PM distance and the distance between each coil. Figure 7 shows thrust/stroke diagram of two models, when the maximum thrust was generated as shown in Fig. 6. The left side of the figure shows the positional relationship between the coil and the PM when the valve is fully opened with a stroke of 10 mm. When the valve is fully opened, the upper surface of each coil exists at the position near the center, in the thickness direction of the three PMs in the model in which relatively large thrust is generated from Fig. 7. Similarly, a high thrust was obtained when the positional relationship between the coil and the PM was came under also in other analysis models. Figure 8 shows the selection of two model conditions with reduced thrust in the same way from Fig. 6 under the condition, when the valve is fully opened. The upper surface of each coil does not exist at the position near the center in the thickness direction of the three PMs from the same figure. The relationships of the positions of the three PMs and the three coils are different from each other. We found that a stable thrust can be obtained by designing the positional relationship between PM and coil so that the coil top surface is located at the position near the center in the thickness direction of the PM, from this relationship at the position where the mover is the most displaced.

5. Summary

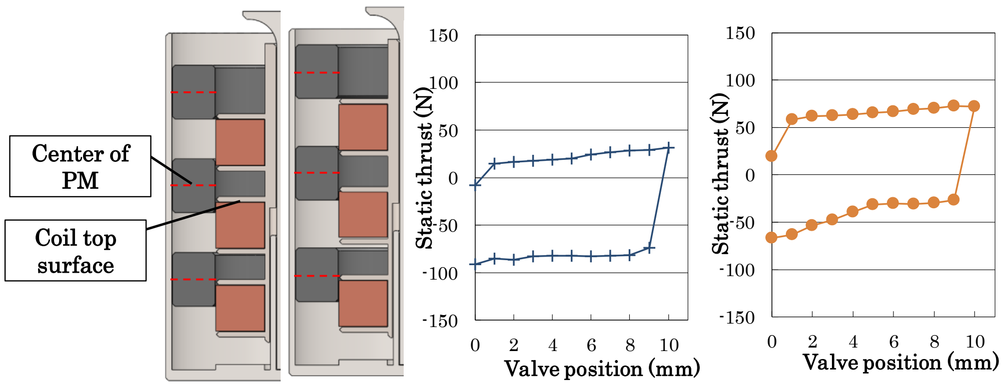
This study derived the target thrust as a basic study and examined the EDVS design aimed at it. We confirmed that a



PM dist.16.8 17.8 16.8 17.8

Coil dist. 15.4 15.4 15.4 15.4

Fig. 7 Layout of coil and PM for the case of large thrust.



PM dist. 15.8 17.8 15.8 17.8

Coil dist. 9.4 11.4 9.4 11.4

Fig. 8 Layout of coil and PM for the case of small thrust.

large thrust can be generated by analyzing the basic model with one coil and two PMs and there is little change in thrust against the displacement of the valve. Then, analysis of a model with three coils and three PMs showed a change in thrust due to the arrangement of the coil and PM. When the valve is fully opened, the upper surface of each coil exists at the position near the center in the thickness direction of the three PMs in the model in which relatively large thrust is generated. We will study how to change the coil shape and PM and how thrust changes in a future project.

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