

# Development of Linear Motor Electromagnetic Valve Drive System (Fundamental Considerations of Magnetic Circuit According to Actuator Shape)

by

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## Abstract

In developed countries, electric vehicles are being promoted to achieve carbon neutrality. Although the electrification of vehicle power is expected to accelerate in the future, internal combustion engines are expected to continue to be used. To further improve combustion engine performance, a method for driving engine valves using linear actuators is evaluated. Driving the valves with linear actuators can lead to ideal valve operation, and a stepless change in valve displacement and timing in response to engine rotation is expected to further improve engine output. However, no method for freely changing the operating timing in response to the operating conditions has yet been realized. Therefore, this research group has developed an intake and exhaust system using an electromagnetic valve drive system that opens and closes valves with a linear actuator. It can operate at low alternating current frequencies, has high responsiveness, and enables precise operation with a direct drive, the aim of which is to improve engine performance in consideration of environmental conservation. In this study, three models are constructed for the proposed linear actuator, and a basic study on the effect of the actuator geometry on thrust characteristics is conducted using electromagnetic field analysis.

**Keywords:** Linear actuator, Electromagnetic valve drive system, Magnetic field, Lorentz force

## 1. Introduction

In developed countries, the electrification of automobiles is being promoted to achieve carbon neutrality, and further performance improvement of internal combustion engines such as gasoline and diesel engines is required. Improving the combustion state of engines leads to improved performance. The combustion state of an internal combustion engine is determined by the parameters of the valve train, such as the timing when opening and closing the intake and exhaust valves and the amount of displacement. The motion of the valves is constant, and depending on the engine operating conditions, fuel economy and power output are affected. This is because a valve is operated by a cam mechanism and is dependent on the cam shape. These problems are addressed by mounting a

mechanism with multiple cam shapes and using a variable valve mechanism that switches cams according to the operating conditions<sup>1-5)</sup>. The variable valve mechanism switches the cam shape based on each engine speed range, which improves engine performance by ensuring proper valve open/close timing and displacement. However, conventional variable valve mechanisms cannot ideally match the open/close timing and displacement for all engine rotations. Therefore, in this study, an electromagnetic valve drive system is proposed to overcome this limitation. The linear actuator can drive a valve to achieve ideal valve operation, and a stepless change in valve displacement and timing in response to engine rotation is expected to further improve engine output. Other research groups have proposed intake and exhaust systems using actuators, but these systems have problems such as increased mass resulting from the large size and complex structure of the actuator, increased power consumption needed for the electromagnet, and difficulty in controlling the timing for valve opening and closing owing to the small thrust force generated<sup>6-10)</sup>. Hence, we propose a linear actuator operated by the Lorentz force. This actuator has a simple structure by using a coil as the mover and operates at a low alternating frequency, which allows for high responsiveness. In addition, the coil wiring has little effect on the short reciprocating

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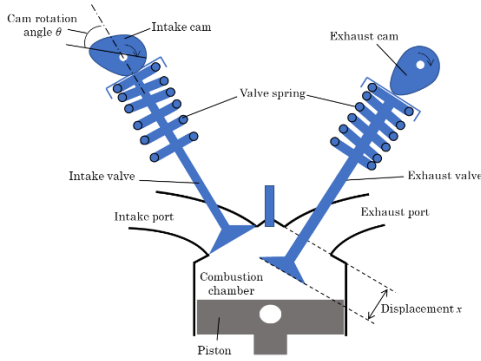


Fig. 1 Schematic of conventional cylinder head mechanism

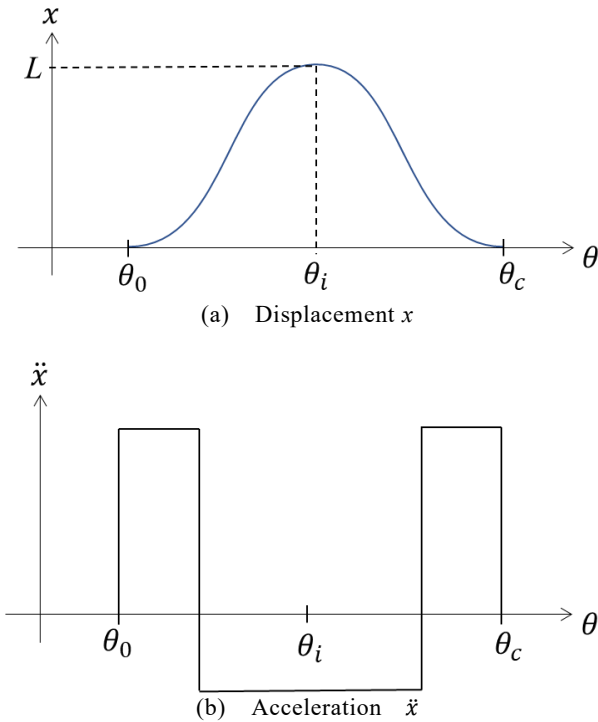


Fig. 2 Relationship between valve displacement, cam rotation angle, and acceleration in a conventional engine.

motion. The direct-drive design also allows for precise operation<sup>11)</sup>. Conventionally, the camshafts and valve springs that operate the valves are located on the cylinder head, the timing chain and sprockets that transmit the engine power to the camshafts. If the valves can be driven by the electromagnetic valve drive system (EVDS), all of these parts can be replaced by the EVDS. Furthermore, power loss can be reduced because engine power is not required to drive the valves. In addition, because a throttle valve does not need to be installed, a reduction in pumping losses can be expected. In this study, three models of the proposed linear actuator were constructed and the thrust characteristics were evaluated using electromagnetic field analysis.

## 2. Electromagnetic valve drive system with linear actuator

### 2.1 Valve drive mechanisms in conventional internal combustion engines

A schematic of the cylinder head in a conventional internal combustion engine is shown in Fig. 1. The engine

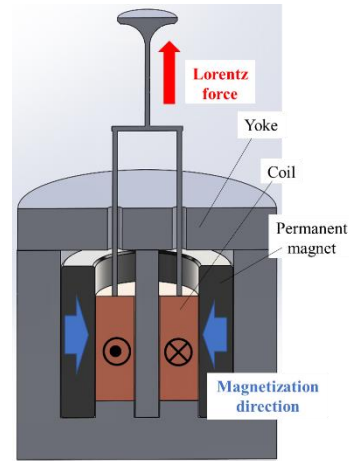


Fig. 3 Electromagnetic valve drive system

valve is located in the cylinder head of the engine. The engine valve is in contact with the cam and is driven by the cam rotation. Fresh air is drawn into the combustion chamber from the intake port. By opening the exhaust valve,  $H_2O$  and  $CO_2$  produced by combustion are discharged from the waste port. When the valve is closed, it is actuated by the restoring force of the valve spring, which was compressed when the valve was opened. The relationship between the cam rotation angle  $\theta$ , valve displacement  $x$ , and acceleration  $\ddot{x}$  is shown in Fig. 2. The positive direction in this figure is the direction in which the valve opens. The valve (controlled by the cam) begins to open at  $\theta_0$ , reaches its maximum displacement at  $\theta_i$ , and closes at  $\theta_c$ . Fig. 2(b) shows that positive acceleration is applied at the beginning of the opening, whereas negative acceleration is applied in the middle at  $\theta_i$ . Negative acceleration is also added after  $\theta_i$ , and positive acceleration is supplied again just before the valve closes, bringing it to rest. Positive acceleration is generated by the cam, and negative acceleration is generated by the valve springs. As the engine rotation speed increases, the acceleration driving the valves also increases. Negative acceleration varies depending on the engine type and operating conditions, but for a typical automobile, about  $300 \text{ m/s}^2$  is required at an engine speed of 6000 rpm. In particular, because negative acceleration depends on the restoring force of the valve springs, it is not possible to generate sufficient negative acceleration in the high-rpm range, resulting in valve chatter, which can cause performance degradation and damage to the engine itself.

### 2.2 Schematic of the proposed valve drive system

As shown in Fig. 1, there are engine valves on each intake and exhaust port, and linear actuators are installed above them to drive each engine valve. As shown in Fig. 3, the linear actuator generates a Lorentz force with a solenoid consisting of a magnet, coil, and iron core to drive the intake and exhaust valves of the engine. The yoke and permanent magnet are stators, and the coil and valve are movers.

### 2.3 Thrust necessary to drive engine valves

The thrust required to operate the engine valves is determined. First, find the valve opening and closing time when the engine with a camshaft of working angle  $\Phi$  has a revolution speed of  $N$  rpm. The time  $T_{crank}$  takes for the



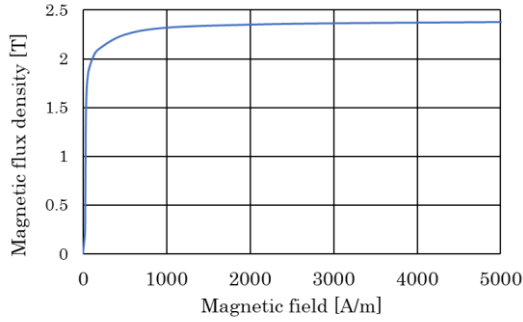


Fig. 6 Permdur's BH curve

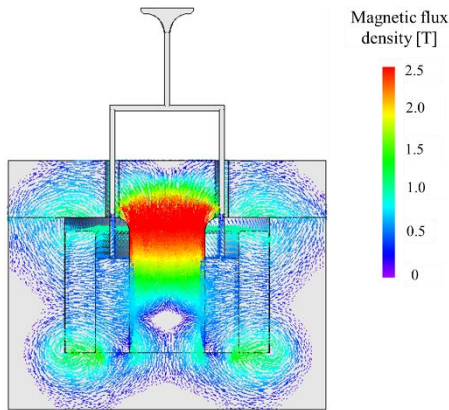


Fig. 7 Analyzed magnetic flux density of Mode A

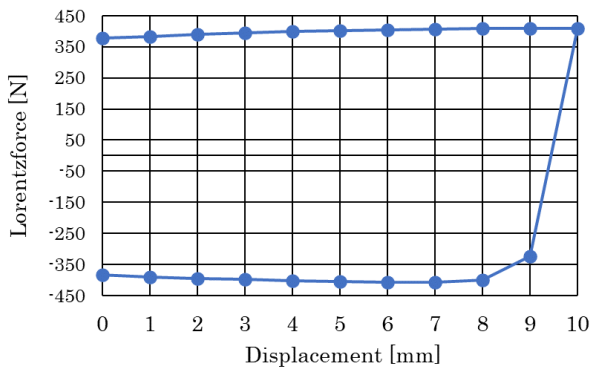


Fig. 8 Relation between Lorentz force and displacement

The following procedure was employed as the analysis condition. For this model, the displacement of the valve is set to 10 mm assuming the opening and closing motion of an engine valve when it performs intake and exhaust, and the valve is moved 1 mm per 0.1 s. A forward voltage is applied when opening the valve at the 0 mm to 10 mm point during ascent, and a reverse voltage is applied at the 10 mm to 0 mm point during descent. From 0 to 1.0 s, the coil was raised by 1 mm every 0.1 s, with a voltage of 20 V applied during this period. Subsequently, at the 10 mm mark, the direction was reversed, and from 1.1 to 2.0 s, the coil was lowered by 1 mm increments while a voltage of -20 V was applied. This condition was used to investigate the changes in thrust relative to the coil position. A transient response analysis was performed with the number of steps set to 21. The analysis was performed using JSOL Corporation's electromagnetic field analysis software JMAG. The supply voltage and coil

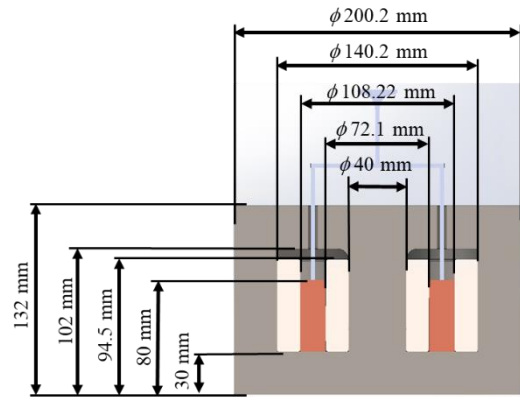
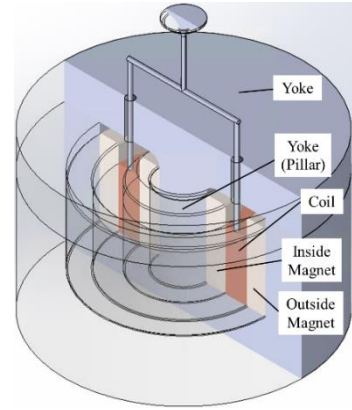


Fig. 9 Analytical models (Model B) of linear actuators for proposed magnetic valve drive system.

resistance were set to 20 V and 1  $\Omega$ , with reference to actuators in other studies, respectively, to keep the current density below 10 A/mm<sup>2</sup>. The number of coil turns was set to 200. The thrust characteristics of the reciprocating motion of the valve were investigated under these conditions. Table 1 lists the properties of the components used for electromagnetic field analysis. In Yoke, the highest saturation magnetic flux density among the materials available for analysis was used for permendur. The BH curve of the permendur used is shown in Fig. 6. The analysis was performed without considering the stacking of the permendur because of the low eddy current effect under the conditions of the present analysis. In this analysis, for the purpose of confirming the actuator's thrust characteristics, NMX-S52 permanent magnets with the highest residual flux density among those available for the analysis were used, without considering restrictions due to material or temperature. In this study, we focus on improving volumetric efficiency through the formation of magnetic circuits. To evaluate the thrust characteristics of the proposed actuator under ideal conditions, we conducted analyses at a temperature setting of 20°C. Considering the potential application in high-temperature environments, it is feasible to avoid thermal demagnetization by incorporating a cooling mechanism that uses coolant to cool the actuator. If future investigations lead to the development of an actuator with sufficient thrust, the use of samarium-cobalt magnets, which have a high Curie temperature, could make the actuator viable for high-temperature applications. This study primarily investigates the enhancement of thrust relative to the actuator's volume under ideal conditions, serving as a foundational step in the

development of electromagnetic valve systems. This study aims to conduct a fundamental evaluation of the characteristics of a linear actuator, without considering constraints related to external dimensions. The electromagnetic valve system offers greater layout flexibility compared to cam mechanisms. By utilizing components such as rocker arms, it is possible to relocate the installation position from the cylinder head. In the stage where actual engine integration is considered, design modifications will be necessary to account for the engine installation space. Specifically, we plan to undertake optimization design to achieve compactness and improved efficiency of the linear actuator.

A vector plot of the magnetic flux density obtained from the analysis is shown in Fig. 7 for Model A. As shown in the figure, Model A exhibits magnetic saturation at the pillar of the yoke, where the magnetic flux concentrates. Next, the thrust force acting on the mover of Model A is shown in Fig. 8. The vertical axis represents the Lorentz force, and the horizontal axis represents the displacement of the mover. Fig. 8 shows the changes in thrust relative to the position of the coil and does not indicate the presence of hysteresis. The mover moves up from the 0 mm point, stops at the 10 mm point, and then descends toward the 0 mm point. Model A shows no significant disturbance of thrust due to mover motion, and when the mover displacement is 10 mm, it is driven stably with almost constant thrust at any displacement point, from 0 mm to 10 mm in the upward direction and from 9 mm to 0 mm in the downward direction. The thrust also increased as the actuator became larger.

#### 4. Effect of actuator geometry on magnetic circuit and thrust

##### 4.1 Effects on thrust due to the addition of permanent magnets.

Two new models were created based on the results of Model A. These models are shown in Fig. 9 And Fig. 10. In the analysis results of Model A, the magnetic flux is not chained perpendicular to the coil at the top and bottom of the coil, which is thought to cause loss of thrust. To solve this problem, in Model B (Fig. 9), permanent magnets were also installed inside the coil to attract the magnetic flux of the permanent magnets installed on the outer circumference of the coil. Model C (Fig. 10) is a further development of Model B. The thickness of the yoke and the diameter of pillars are further increased to eliminate magnetic saturation. The dimensions of all models are presented in Table 2. In this study, the cross-sectional area of the coil remains unchanged, and therefore, the number of windings also remains constant. We examined how variations in the magnetic flux distribution affect each model under fixed coil winding and voltage conditions. Model A serves as the basic model, extending from previous studies. It simply increases the thickness of the yoke without any special magnetic circuit design, serving as a reference model to evaluate basic volumetric efficiency and thrust characteristics. Next, Model B adopts a structure where the coil is sandwiched between permanent magnets. This

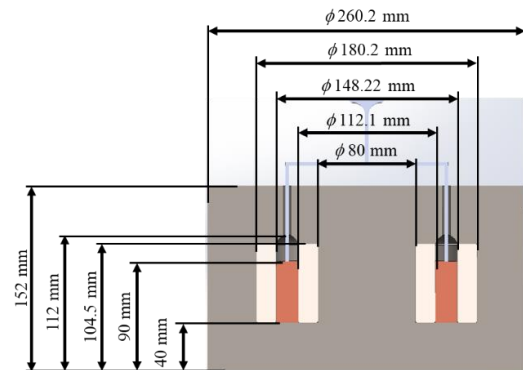
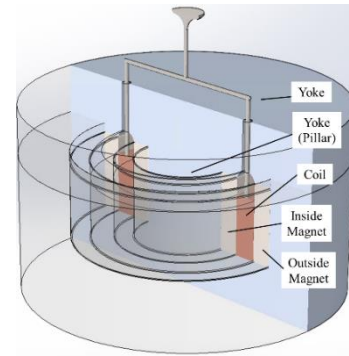


Fig. 10 Analytical models (Model C) of linear actuators for proposed magnetic valve drive system.

design aims to improve the efficiency of the magnetic circuit by allowing more magnetic flux linkage through the coil, thereby enhancing the thrust characteristics. By sandwiching the coil with permanent magnets, the model aims to concentrate the magnetic flux and form an efficient magnetic circuit. Lastly, Model C features an increased diameter of the central yoke and an increased thickness of the outer yoke. This design aims to achieve higher thrust characteristics by widening the magnetic flux path and preventing magnetic saturation. By increasing the diameter of the central yoke and the thickness of the outer yoke, the model aims to create a more efficient magnetic circuit with a wider magnetic flux path and reduced magnetic saturation.

In summary, the design modifications of each model aim to improve volumetric efficiency through the enhancement of the magnetic circuit.

##### 4.2 Thrust characteristics of each model

A vector plot of the magnetic flux density obtained from the analysis of each model is shown in Fig. 11. In models B to C, the surface area of the magnet increases with the diameter, whereas the Yoke cross section increases with the square of the diameter. Therefore, the magnetic saturation is expected to be eliminated in the calculation. However, in Model C, as shown in the figure, magnetic saturation occurred because the magnetic flux density was about 2.5 T at the columns of the yoke, where the magnetic flux concentrates. In contrast, in model B, permanent magnets were placed between the coils, and despite the increased magnet volume, magnetic saturation did not occur with a magnetic flux density of approximately 2 T at the yoke pillar. The reason for the occurrence of magnetic

Table 2 Dimensions of each model

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| Parameters        | Model A         | Model B     | Model C     |
|-------------------|-----------------|-------------|-------------|
| Yoke              | Outer diameter  | φ 168.5 mm  | φ 200.2 mm  |
|                   | Inner diameter  | φ 108.5 mm  | φ 140.2 mm  |
|                   | Height          | 132 mm      | 152 mm      |
|                   | Thickness       | 30 mm       | 40 mm       |
| Yoke (Pillar)     | Diameter        | φ 40 mm     | φ 40 mm     |
|                   | Height          | 72 mm       | 72 mm       |
| Outside Magnet    | Outer diameter  | φ 108.16 mm | φ 140.18 mm |
|                   | Inner diameter  | φ 76.2 mm   | φ 108.22 mm |
|                   | Height          | 64.5 mm     | 64.5 mm     |
| Inside Magnet     | Outer diameter  | φ 71.98 mm  | φ 111.98 mm |
|                   | Inner diameter  | φ 40.02 mm  | φ 80.02 mm  |
|                   | Height          | 64.5 mm     | 64.5 mm     |
| Coil              | Outer diameter  | φ 76.1 mm   | φ 108.1 mm  |
|                   | Inside diameter | φ 40.1 mm   | φ 72.1 mm   |
|                   | Height          | 50 mm       | 50 mm       |
|                   | Turns           | 200         | 200         |
| Coil space factor | 69.8%           | 69.8%       | 69.8%       |

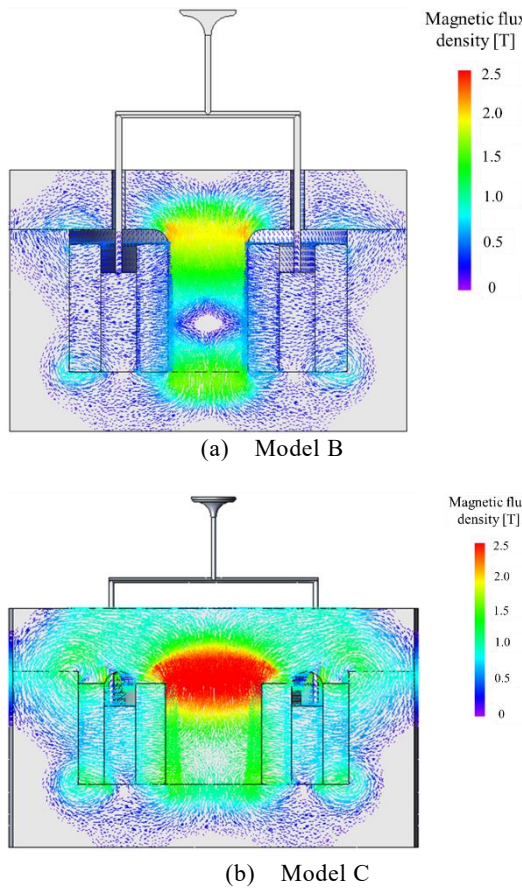


Fig. 11 Analyzed magnetic flux density of each model

saturation in Model C, which has a thicker yoke than Model B, is thought to be that the increase in the diameter of the central part also increased the permanent magnet volume, and as a result, the magnetic saturation that was reduced in Model B occurred again. We believe that eliminating these magnetic saturations will improve the thrust.

A vector plot of the Lorentz force density and the magnetic flux density acting on the mover for each model is shown in Fig. 12. As shown in Fig. 12, the Lorentz force density increases in the upper pillar of the yoke in Model A (where magnetic saturation occurs), whereas the Lorentz force

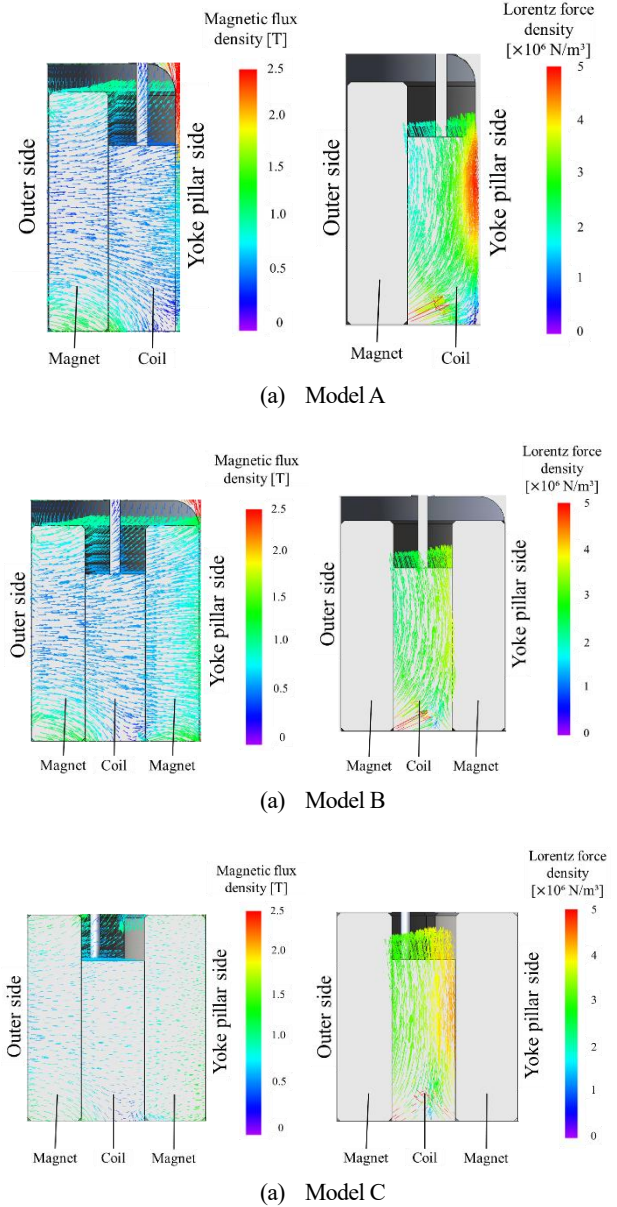


Fig. 12 Lorentz force density of each model by analysis

density decreases on the outer edge of the coil. The same phenomenon occurred in Model C, whereas Model B exhibited a roughly uniform Lorentz force density. In all models, the Lorentz forces were not oriented in the direction of the mover drive. This is considered to cause vibration when the actuator is driven because thrust loss occurs, and at the same time, the force acts in the radial direction of the actuator. The Lorentz force acting in the radial direction of the actuator is thought to be caused by magnetic fluxes that do not cross perpendicularly to the mover. As shown in Fig. 12, in all models, when the lower part of the permanent magnet is in contact with the yoke, the magnetic flux generated by the outer permanent magnet does not flow to the inner permanent magnet but instead flows to the yoke part. It is believed that further improvement in the magnetic flux flow can be achieved to further increase the thrust.

The thrust at each position for Models B and C obtained from the analysis is shown in Fig. 13. Fig. 8 shows the thrust during the reciprocating motion of the mover, while the thrusts

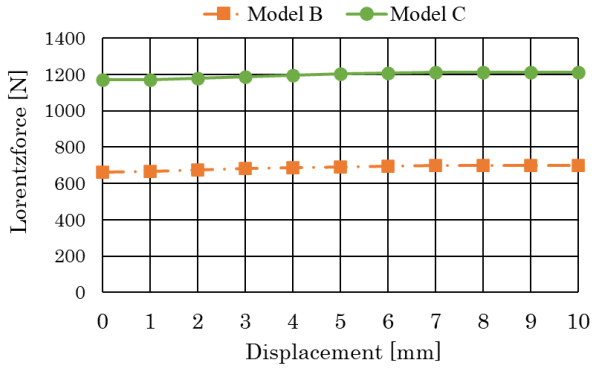


Fig. 13 Relationship between Lorentz force and displacement for Models B and C (only forward stroke shown due to similar trends as in Model A).

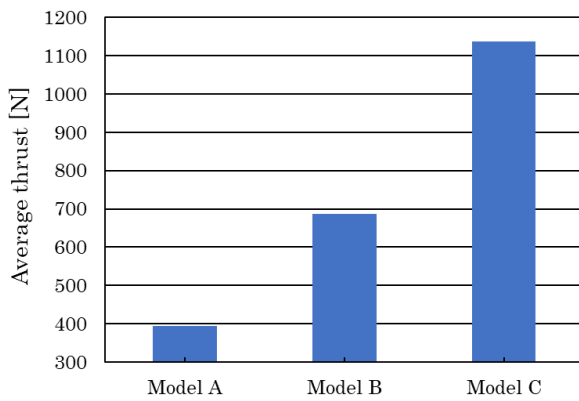


Fig. 14 Average thrust produced by each model

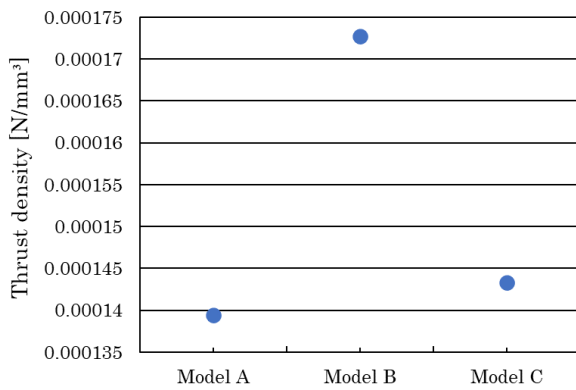


Fig. 15 Thrust density of actuator volume for each model

of Model B and Model C, shown in Fig. 13, are only for the forward stroke. This is because Model B and Model C exhibited similar trends to those observed in Fig. 8. Therefore, only the thrust during the forward stroke is presented in Fig. 13. The thrust force for both models was almost constant at all positions. A graph of the average thrust force for each model mover during the reciprocating motion from 0 mm to 10 mm, obtained from the analysis, is shown in Fig. 14. The vertical axis represents the average thrust and the horizontal axis represents each model. The graph in the figure shows that the average thrust increases as the actuator volume increases: approximately 395 N for Model A, 687 N for Model B, and

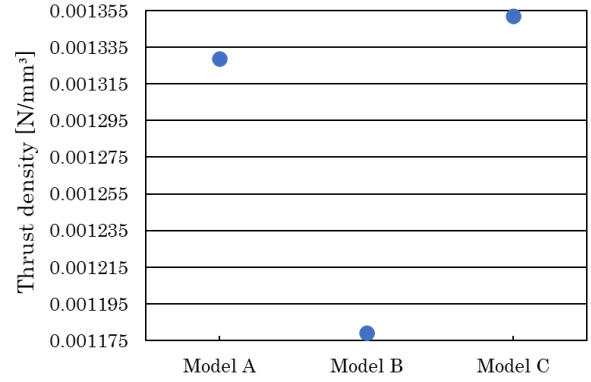


Fig. 16 Thrust density of permanent magnet volume for each model.

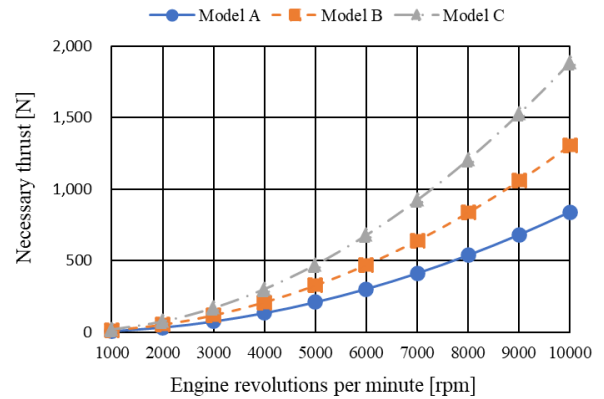


Fig. 17 Necessary thrust for each model

1137 N for Model C. There was a difference of approximately 700 N in the average thrust between Model A, which had the smallest volume, and Model C, which had the largest volume. Next, a graph of the thrust density, which is the thrust per unit volume, is shown in Fig. 15. The vertical axis represents the thrust density and the horizontal axis represents each model. The figure shows that the thrust density does not increase as the actuator becomes larger, and that the highest thrust per unit volume is approximately  $1.73 \times 10^{-4}$  N/mm<sup>3</sup> for Model B, which does not cause magnetic saturation. The reason for the lower thrust density in Model C is thought to be due to the occurrence of magnetic saturation, despite its increased yoke thickness and larger shaft diameter. The thrust per permanent magnet volume for each model is shown in Fig. 16. The figure shows that Model C has the highest thrust per magnet volume of approximately  $1.35 \times 10^{-4}$  N/mm<sup>3</sup>.

The required thrust of the actuator was calculated using eq. (1) through (5). The working angle  $\Phi$  was set to 250° and the displacement  $L$  to 10 mm. Fig. 17 shows the required thrust for each model at each rotation speed. At this stage, Model A can be operated up to about 6,800 rpm, Model B up to about 7,200 rpm, and Model C up to about 7,700 rpm in a typical automobile engine. One of the notable features of the linear actuator is the ability to freely adjust the valve displacement and lift amount within the thrust range exhibited by each model, according to the engine's rotational speed and user preferences. Although specific target values have not been set, the thrust characteristics of each model provide a wide

operational range. This study focuses on the volumetric efficiency of the actuator, maintaining a constant cross-sectional area of the coil and, consequently, an unchanged number of windings. Under these constant conditions, we investigated how the thrust changes depending on the magnetic flux distribution. At this stage, no target rotational speed has been set. The current actuator design is not suitable for high rotational speeds, such as 10,000 RPM. However, within the rotational speed limits of each model, the valve movement can be freely adjusted according to the operating conditions and driver preferences. Additionally, since the redline of engines in standard production cars is around 8,000 RPM, the actuator developed in this study has the potential to be installed in commercial vehicles, provided there are no spatial constraints. Setting a specific target rotational speed would further clarify the design's validity and practicality by guiding the design and evaluation process. However, at this stage, we are examining how the proposed actuator's structural changes affect thrust characteristics.

## 5. Conclusion

In this study, three models were created for the purpose of improving the magnetic circuit and increasing the thrust of the EVDS. Transient response analysis was performed using magnetic field analysis software to investigate the thrust characteristics of the models. Under the analytical conditions of this study, all versions of the proposed model were found to remain stable with an almost constant thrust at any position of the mover.

The design of the magnetic circuit of the stator such that the magnetic flux intersects the mover coil at right angles tends to increase the thrust force (Model B and C). However, although magnetic saturation was reduced in the larger model (Model B), when the model was further enlarged (Model C), magnetic saturation reappeared, and the thrust density did not improve. The authors' goal is to mount this actuator on the cylinder head of an internal combustion engine. In Model B, the magnet volume itself was increased by placing a permanent magnet inside the coil, but the thrust per magnet volume was lower in Model B than in the other models. In Model C, by increasing the diameter of the yoke support, the coil diameter and magnet volume increased, and the average thrust and thrust per magnet volume improved. On the other hand, the increase in actuator volume resulted in a deterioration of the actuator's volumetric efficiency. Therefore, improving the volumetric efficiency is an important factor in actuators for valve opening/closing when mounted on a cylinder head. Future research will involve the application of a dual Halbach array to the actuator to enhance volumetric efficiency. This new design approach is expected to support higher rotational speeds and achieve further miniaturization.

This study primarily investigates the thrust characteristics during simple reciprocating motion based on the shape of the linear actuator, without delving into detailed control methods. The detailed construction of the control system has not yet been undertaken. The anticipated control method involves closing the valve completely during engine start-up, rotating the crank a few times with the starter motor without

combustion to sense the crank angle, and confirming the piston position. Subsequently, the valve opening will be adjusted to the optimal position to initiate engine combustion. During this process, the valve position will be verified using a displacement sensor attached to the mover. This approach ensures the appropriate initial valve position at engine start-up, enhancing system stability and efficient combustion initiation. The performance of the control system varies based on the target rotational speed and the sensing frequency. For example, if the crank angle is sensed every 1 degree and a speed of 12,000 RPM is assumed, the valve would operate at 200 Hz. Consequently, it would require processing signals at 7.2 kHz ( $200 \text{ Hz} \times 360^\circ$ ). To properly handle such high-frequency signals, fast data processing capabilities and highly accurate sensing technology are necessary. Future work will involve the detailed design and evaluation of this control system to address specific challenges for practical implementation and will include detailed examination and optimization of the control method through experimental validation.

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