A STUDY OF A MULTI-STEP POLE TYPE ELECTRO-MAGNETIC ACTUATOR FOR CONTROLLING PROPORTIONAL HYDRAULIC VALVE

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ABSTRACT
In this study, a new electro-magnetic proportional actuator composed of an armature and stator with multi convex teeth to control oil hydraulic valves was designed and examined. Each of the convex teeth forms a magnetic pole, and when multiple magnetic poles produce a force simultaneously, a large thrust force is generated in the actuator. The shape of the teeth was varied and influence on the thrust force was examined. As a result, the interval between the convex teeth could be reduced. A 10-step pole type actuator was designed, and its thrust force was estimated. When the dimensions of this actuator are 52mm height, 68mm width, by 102mm length, its thrust force is constant within 2mm of the armature stroke, producing about 300N at an electric power consumption of 15W, and it generates the thrust force in proportion to the coil current. The thrust force of this actuator is about 2.5 times as large as that of conventional proportional solenoids and linear motors of the same installation area to the valve body, length and power consumption.

KEY WORDS
Fluid power, Electro-magnetic proportional valve, Valve actuator, Multi-step pole, High force density

INTRODUCTION
There are 4 types of conventional electro-magnetic proportional actuators which can directly operate oil hydraulic valves in proportion to input signal; proportional solenoids, force motors, torque motors and linear motors [1]. A permanent magnet is built in these actuators except for proportional solenoids, therefore their structures are complex and the cost is higher. As well, proportional solenoids cannot generate a very large force in comparison with their dimensions. In this paper, in order to control oil hydraulic valves, a new electro-magnetic proportional actuator composed of an armature and stator with multi convex teeth was designed and its thrust force characteristics were examined. The principle of the producing force in this actuator is based on the changing reluctance when the overlap between the armature and the stator convex teeth changes. Since this actuator does not use a permanent magnet, there is a possibility of cheaper actuator production. As well, the multi convex teeth of the armature and the stator of the newly designed actuator becomes a multi-step pole, each of the poles producing a force simultaneously. Therefore a large thrust force is generated in the actuator. Furthermore, an electro-magnetic proportional actuator
composed of an armature and a stator with 10-step convex teeth of triangular groove shape was designed, and its thrust force was estimated and compared with conventional actuators.

**STRUCTURE AND BASIC ELECTRO-MAGNETIC CHARACTERISTICS OF THE ACTUATOR**

The principle of producing force in a newly designed actuator is based on the principle of producing force in a variable reluctance (VR) type stepping motor. A stator and an armature of the stepping motor are shown in Figure 1. Figure 1 (a) shows a front view of the stepping motor, and Figure 1 (b) shows the relation between the stator and rotor position in side view. In these Figures, there are 6 teeth on the stator and 4 teeth on the rotor. In this stator, a couple of coils are wound on the opposed convex teeth as shown in Figure 1 (a) (the other two couples of coils are omitted). When the electric current flows in the coil, magnetic flux is generated and it flows from upper convex tooth to the lower one through the outside of the stator, and then returns to the upper tooth. Hence, a couple of convex teeth, one on the stator and one on the rotor, in which magnetic flux flows, become a magnetic pole, and then magnetic force acts on these teeth. As illustrated in Figure 1 (a), if a couple of opposed convex teeth of the stator and the rotor are not in line with each other, the force acts on the teeth until the opposed teeth are in line. By this force, a torque is generated in the direction of the arrow illustrated in Figure 1 (a), and a rotating shaft as shown in Figure 1 (b) is turned, and the torque is transferred.

The principle of generating this torque is due to the change of reluctance of the magnetic circuit in this stepping motor as the convex teeth position of the rotor changes. Therefore, the magnetic energy in the air gap between the stator and the rotor convex teeth is transformed to mechanical energy, and then the force is generated between the teeth.

**Figure 2 shows the principle of producing force in the multi-step pole type actuator [2].** The armature in Figure 2 (a) does not turn in the rotating direction from this position. The armature fits with the shaft and can slide on the shaft along the axis direction. Then, as shown in Figure 2 (b), the armature and the stator with multi convex teeth are opposed to each other. Now, as illustrated in Figure 2 (b), each of the opposed convex teeth are not positioned in a lap. When the current flows through the coil in this state, magnetic flux flows between the armature and the stator around the outside of the stator as shown in Figure 2 (a). On the other hand, in Figure 2 (b), the magnetic flux produced by the winding coil on the lower stator flows in the armature convex teeth, and it flows from the armature to the upper stator. Also, as shown in Figure 2 (a), the magnetic flux flows through the outside of the stator, and then returns to the lower stator. This magnetic flux flow causes the convex teeth of the armature and stator to become magnetic poles, and a large force is generated in the axis direction by producing a traction force from each tooth simultaneously.

Figure 2 (c) shows the solid shape of the armature with multi convex teeth. First, the convex teeth shape was made rectangular of the same teeth shape as the stepping motor.

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**Figure 1 Principle of VR-type stepping motor**

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Figure 3 shows the measured result of the relationship between $X/w_1$ and $F_a$. In order to examine the basic force characteristics of the multi-step pole type actuator, an armature with a single rectangular tooth was used. Thickness $w_1$ of the armature with a single tooth is 5mm, $X$ is an overlap between the tooth of the armature and stator, and $F_a$ is the force acting on the front edge of the armature tooth. As shown in Figure 3, $F_a$ decreases to less than 70% of the maximum force when $X/w_1$ is larger than 0.5.

Figure 3 Relationship between $X/w_1$ and $F_a$

In order to shorten intervals between the teeth as much as possible, the intervals $p_2$ and the root dimension $w_2$ of the teeth were equated. As shown in Figure 5, it is possible to make shorter intervals between the teeth, even though the root dimension $w_2$ of the teeth is the same as the root dimension $w_1$ of the teeth in Figure 4. Figure 6 shows the solid shape of the armature with the convex teeth of the slanting rear edge, in other words, the armature with triangular groove shape teeth.

Figure 5 Triangular groove shape

Figure 6 Armature with triangular groove shape teeth

Figure 4 shows the convex tooth shape of the actuator in Figure 2. The convex tooth shape in Figure 4 is rectangular, the thickness $w_1$ is 5mm, and the interval $p_1$ between the teeth is 11mm. If the convex tooth thickness $w_1$ becomes smaller, magnetic saturation occurs easily at the root of the convex tooth, and it is necessary to make the groove width larger than the tooth thickness. Therefore, it is difficult to make shorter intervals $p_1$ between the teeth.

An actuator does not need to move both directions like the stepping motor as shown in Figure 1, it only moves in one direction. Furthermore, as shown in Figure 3, force $F_a$ remarkably decreases when overlap $X$ exceeds half of the tooth thickness $w_1$. For these reasons, as shown on the dotted line in Figure 4, the rear edge of the rectangular tooth was cut slanted, and then the intervals of the teeth could be reduced [3].

Figure 7 Comparison of relations between $X/w_1$, $X/w_2$ and $F_a$
Figure 7 shows the comparison of relations between $X/w_1$, $X/w_2$ and $F_a$ when the convex tooth shapes differ as shown in Figure 4 and Figure 5. Force $F_a$ was measured using the armature with a single tooth. In Figure 7, both curves overlap when $X/w_1$, $X/w_2$ is less than 0.4, and both maximum forces of $F_a$ are the same. Therefore, the convex tooth shape as shown in Figure 5 can be used on a multi-step pole type actuator, if $X/w_2$ is in the range of 0 to 0.4.

Figure 8 shows the experimental results of relationship between $X_1$ and $F_a$ in the case of the armature with a single tooth. In these experiments, armature dimensions are as follows: the thickness $w_2$ of the armature is 5mm, the length $E$ (shown in Figure 5) of the top land of the tooth is 2.5mm, and the radial clearance between the armature and the stator is 0.05mm. Magneto-motive force $Nl$ (coil winding number $N$, current $I$) was varied from 400AT (Ampere Turn) to 2000AT at intervals of 400AT, and then force $F_a$ was measured. As shown in Figure 8, force $F_a$ is proportional to magneto-motive force $Nl$ when $X_1$ is less than 2mm and $Nl$ is less than 1200AT.

Figure 9 shows the relationship between distance $Y_1$ and force $F_b$ (the inverse working direction of $F_a$), in the case of the armature with a single tooth, same the armature as in Figure 8. As shown in Figure 9, force $F_b$ increases with increasing magneto-motive force $Nl$, and $F_b$ is relatively large even if distance $Y_1$ is 1mm. In the multi-step pole type electro-magnetic actuator, force $F_a$ and $F_b$ can be used to calculate the thrust force $F_n$ of $n$-step as follows [3].

$$F_n = nF_a - (n-1)F_b$$

(1)

Figure 10 shows characteristics of a 10-step ($n=10$) pole type actuator in the case of varying teeth thickness $w_2$ from 5mm to 8mm. Forces $F_a$ and $F_b$ were measured using the armature with a single tooth as in Figure 8 and Figure 9. Then, $F_{10}$ was calculated by using Eq. (1). When the length $E$ of the top land is 2.5mm, the more the teeth thickness $w_2$ thickens, the more the interval of the teeth extends and $F_b$ decreases. Therefore, as shown in Figure 10, $F_{10}$ increases with increasing teeth thickness $w_2$, and the range of $X_{10}$ in which thrust force $F_{10}$ becomes constant is spread. However, the curve of $w_2=7$mm is similar to the curve of $w_2=8$mm. The length of the actuator in the case of $w_2=7$mm can be made shorter than that of the case of $w_2=8$mm. Therefore, the actuator with the teeth thickness $w_2=7$mm was selected for designing the actuator as follows.

Figure 11 shows a structure of the designed 10-step pole type actuator. In this actuator, the length $E$ of the top land of the convex teeth is 2.5mm and the teeth

EXAMINATIONS OF 10-STEP POLE TYPE ACTUATOR

Figure 11 shows a structure of the designed 10-step pole type actuator. In this actuator, the length $E$ of the top land of the convex teeth is 2.5mm and the teeth
thickness \( w_2 \) is 7mm. This actuator is composed of an armature with a shaft, stator and coil. The coil is wound \( N \) turns on the winding guide around four side of the armature as shown in Figure 11 upper view (B-B section). This winding guide is fixed to the stator by bearing plates. The bearing plates (non-magnetic material) are installed and fixed at both ends of the stator. The shaft of the armature is supported by those plates. When the current \( I \) flows through the coil, magneto-motive force \( NI \) is about 800AT (Ampere Turn) at an electric power consumption of 15W in the 10-step pole type actuator. Now, the armature position is indicated as \( X_{10} \), and the position when front edges of the convex teeth of the armature and the stator are just encountering each other is defined as \( X_{10}=0 \)mm in Figure 11 (lower right view). The thrust force \( F_{10} \) is generated and the armature moves to the left when the current flows through the coil. Figure 12 shows the relationship between \( NI \) and \( F_{10} \) in the 10-step pole type actuator. Here, the value of \( F_{10} \) is calculated using Eq. (1) by using the measured value \( F_a \) and \( F_b \) of the actuator with a single tooth armature.

Figure 11 Structure of a 10-step pole type actuator

Figure 12 Relationship between \( NI \) and \( F_{10} \)
magneto-motive force \( NI \) in the range of 100AT to 1200AT. Furthermore, the thrust force \( F_{10} \) increases with the increasing magneto-motive force \( NI \) until electric power consumption of 60W, and \( F_{10} \) does not tend to saturate remarkably.

Figure 13 shows the relationship between \( X_{10} \) and \( F_{10} \). The calculated value of \( F_{10} \) is similar to the calculated value of \( F_{10} \) in Figure 12. As shown in Figure 13, the variety of thrust force \( F_{10} \) curves is small, in the range of 0 to 2mm of \( X_{10} \). In this range, the thrust force \( F_{10} \) is about 300N at an electric power consumption of 15W (magneto-motive force of 800AT). Furthermore, a larger thrust force can be gained by increasing the electric power consumption more than 15W.

**Figure 13 Relationship between \( X_{10} \) and \( F_{10} \)**

COMPARISON OF THRUST FORCE CHARACTERISTICS WITH THE OTHER ACTUATORS

Figure 14 shows a comparison of the thrust force characteristics of the 10-step pole type actuator with conventional proportional solenoids and linear motors of the same installation area to the valve body, and length. In Figure 14, the axis of abscissa shows electric power consumption at room temperature. Plotting points are indicated at the catalogue value of A company for the linear motor, the catalogue value of B company for the proportional solenoid (1) and the measured value for the proportional solenoid (2). As well, the thrust force values on the curve of linear motor were calculated as the force is proportional to current of coil. When current flows through the coil in the actuator, the coil temperature rises. In this designed actuator, a rated electric power consumption of 15W at room temperature is proper for the allowable temperature of the coil [2]. As shown in Figure 14, the thrust force of the actuator is about 2.5 times as large as that of conventional proportional solenoids and linear motors at 15W.

**Figure 14 Comparison thrust force characteristics of electro-magnetic proportional actuators**

CONCLUSIONS

In this study, an electro-magnetic proportional actuator composed of an armature and a stator with multi convex teeth to control the oil hydraulic valves was newly designed. A rectangular shape and a shape that is cut slanted to the rear edge of the rectangular convex teeth were examined. A 10-step pole type actuator with convex teeth was newly designed. Length \( E \) of the top land of the convex teeth of the armature and the stator is 2.5mm, teeth thickness \( w_2 \) is 7mm. The dimensions of this designed actuator are 52mm height, 68mm width and by 102mm length. As results of estimation of the thrust force of this designed actuator, it became clear that its thrust force was constant within 2mm of the armature stroke, producing about 300N at an electric power consumption of 15W.

The thrust force of this actuator is about 2.5 times as large as that of conventional proportional solenoids and linear motors of the same installation area to the valve body, length and electric power consumption.

REFERENCES