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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.

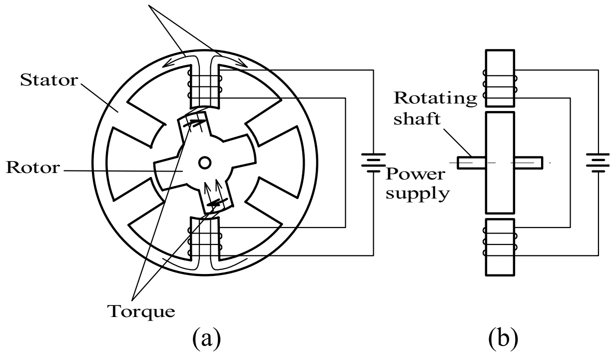

Figure 1 Principle of VR-type stepping motor

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.

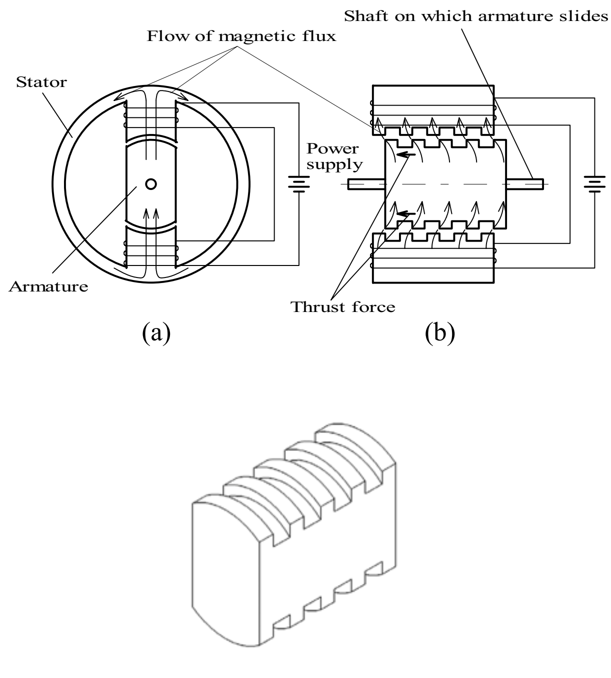

Figure 2 Principle of multi-step pole type electro-magnetic actuator

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.

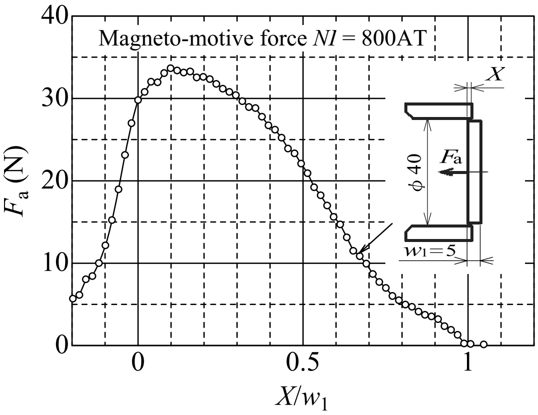

Figure 3 Relationship between X/w_1 and F_a

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

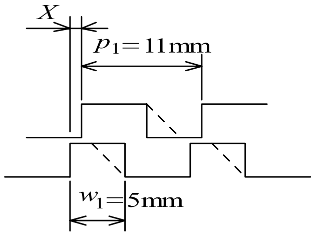

Figure 4 A rectangular tooth shape

the rectangular tooth was cut slanted, and then the intervals of the teeth could be reduced [3].

Figure 5 shows the tooth shape of the slanted rear edge. 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.

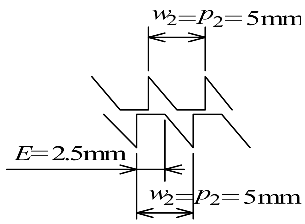

Figure 5 Triangular groove shape

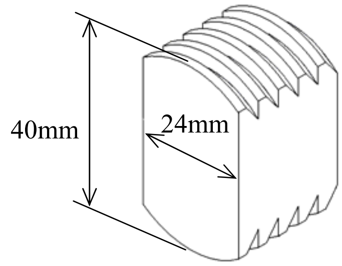

Figure 6 Armature with triangular groove shape teeth

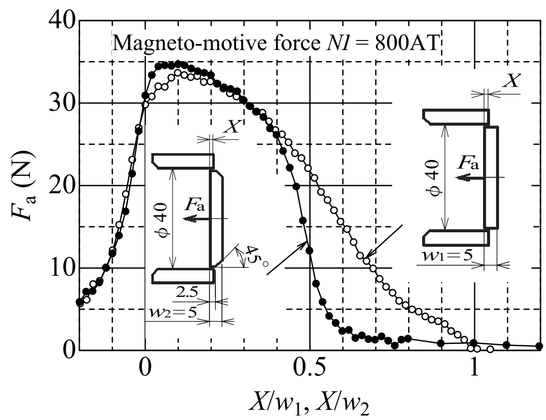

Figure 7 Comparison of relations between X/w_1 , X/w_2 and F_a

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 NI (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 NI when X_1 is less than 2mm and NI is less than 1200AT.

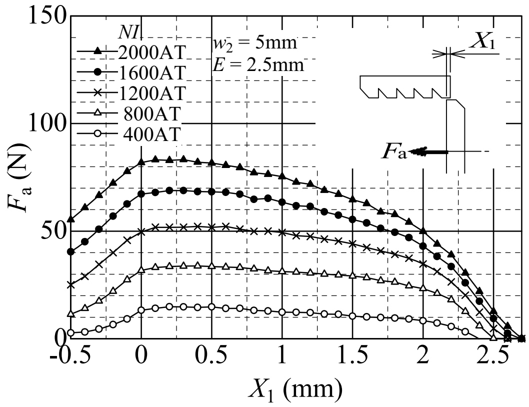

Figure 8 Relationship between X_1 and F_a

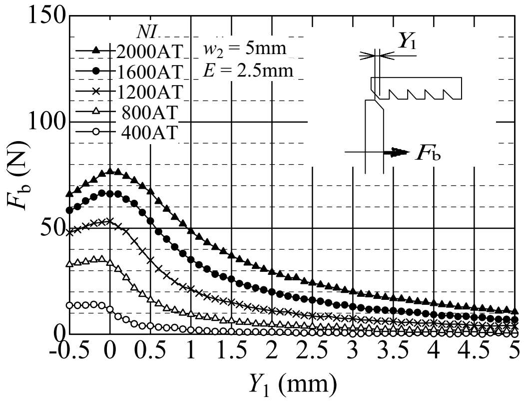

Figure 9 Relationship between Y_1 and F_b

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 NI, 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].

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

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 =7mm is similar to the curve of w_2=8mm. The length of the actuator in the case of w_2=7mm can be made shorter than that of the case of w_2=8mm. Therefore, the actuator with the teeth thickness w_2=7mm was selected for designing the actuator as follows.

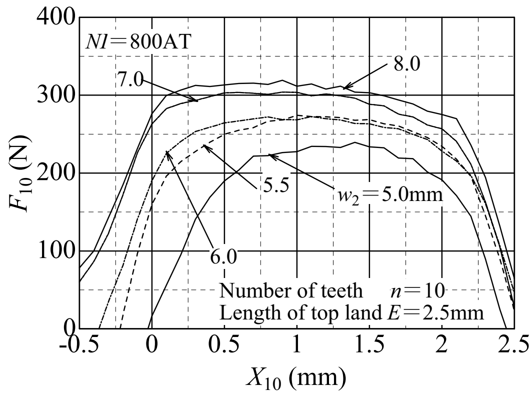

Figure 10 Relationship between X_{10} and F_{10} in the case of varying w_2

EXAMINATIONS OF 10-STEP POLE TYPE ACTUATOR

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

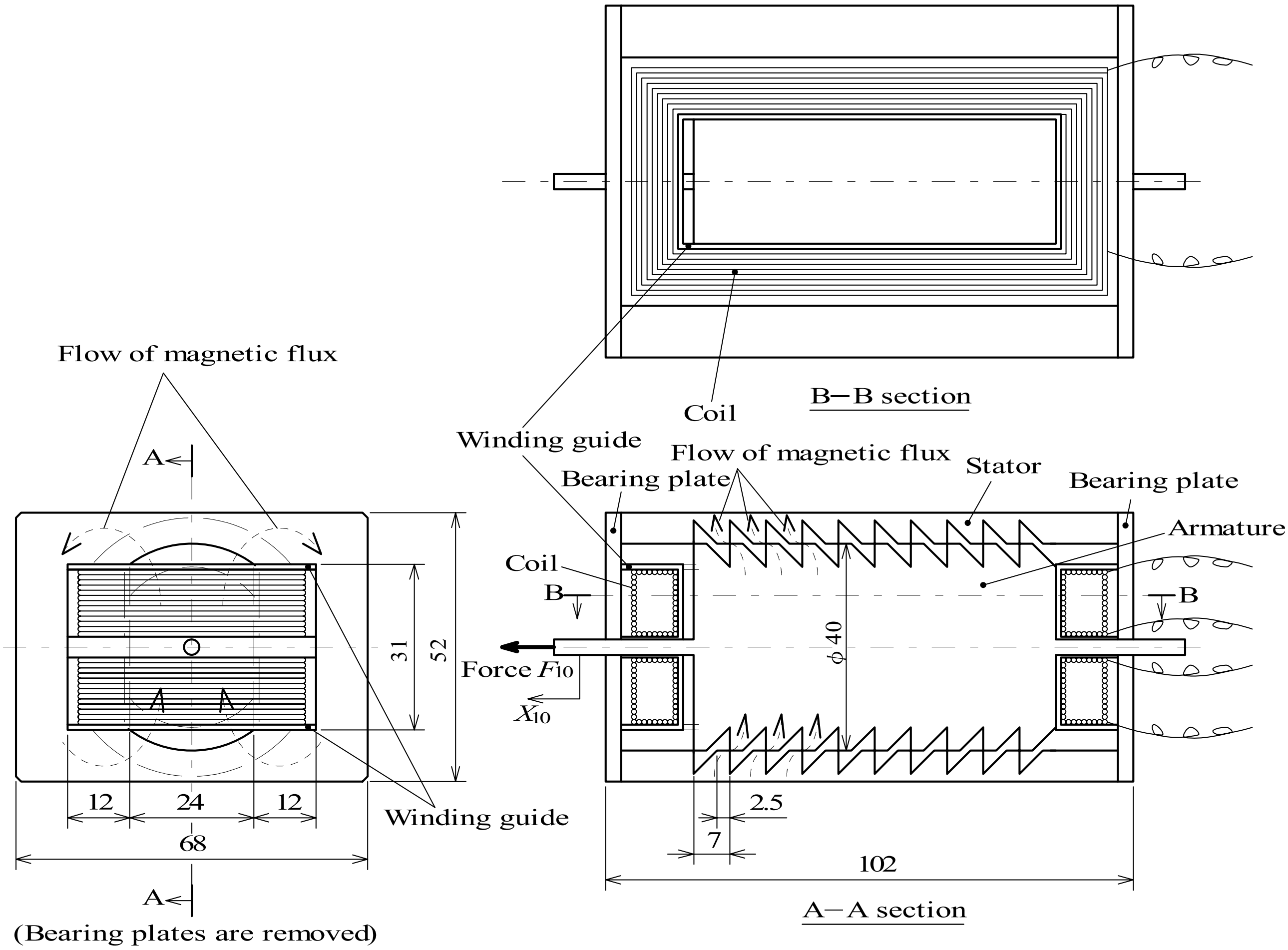

Figure 11 Structure of a 10-step pole type actuator

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}=0mm 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 12 shows the curve when X_{10} is 1mm. As shown in Figure 12, the thrust force F_{10} is in proportion to the

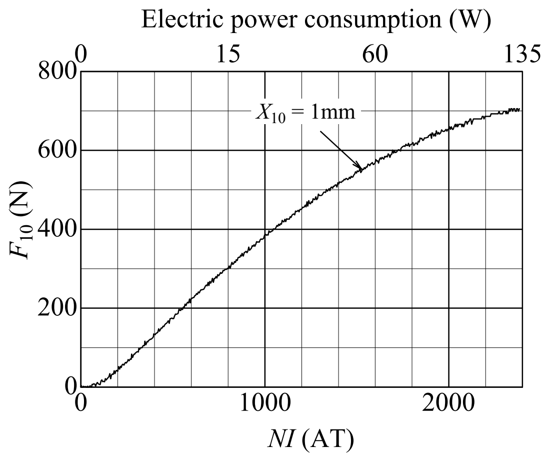

Figure 12 Relationship between NI and F_{10}

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.

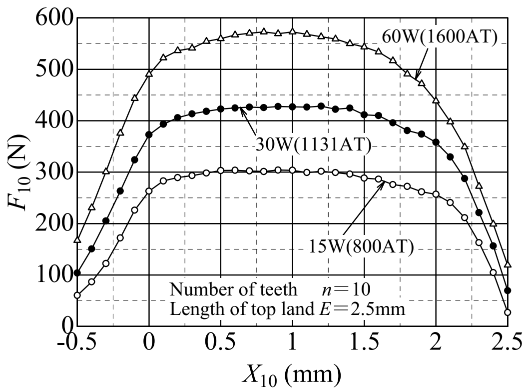

Figure 13 Relationship between X_{10} and F_{10}

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.

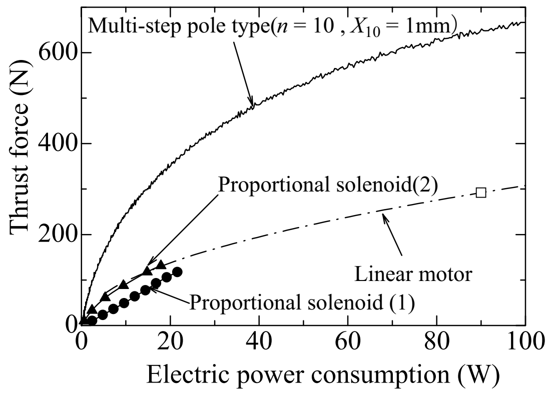

Figure 14 Comparison thrust force characteristics of electro-magnetic proportional actuators

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.

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