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ELECTROMAGNETIC ACTUATOR WITH ZERO CURRENT-FORCE HYSTERESIS FOR HYDRAULIC PROPORTIONAL CONTROL VALVE OPERATION

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Abstract. An electromagnetic proportional solenoid is used as a force control device to generate the thrust force act on a valve element in a hydraulic pressure control valve. However, a conventional proportional solenoid has a problem that the hysteresis appears in its current-thrust force characteristics. The factors are friction and magnetic hysteresis. In order to reduce hysteresis, the 3-dimensional 3-phase AC proportional solenoid that reproduces a pseudo magnetic bearing was developed. A proportional solenoid has three requirements for high performance. Firstly, it cannot control the thrust in push-pull both directions. Secondly, it cannot use materials other than a heavy ferromagnetic material such as iron for an armature. Finally, it can only move a few millimeters. In order to solve these requirements, a bi-directional long-stroke proportional solenoid using the driving principle of linear induction motor was developed.

Keywords: Actuator, Electromagnetic proportional valve, Hysteresis

INTRODUCTION

A solenoid is an electromagnetic actuator that outputs a thrust force in a determined stroke by a magnetic flux generated by energized windings. Generally, the thrust force of solenoid increases in proportion to the square of the reciprocal of the air gap between the armature and stator. On the other hand, by controlling the flow of the magnetic flux by the special magnetic pole shape, it is possible to output a constant thrust force proportional to the current irrespective of the position of the armature within a certain distance (control zone), which is called a proportional solenoid. Since the proportional solenoid has a control zone, it is used in industrial equipment requiring position control and force control. The typical application of a proportional solenoid is an operational device for a hydraulic control valve. However, there are hysteresis which affects the control precision, such as a difference in output thrust for the electric current command. The cause of hysteresis is distinguished between friction hysteresis and magnetic hysteresis. In the friction hysteresis, when the position of the armature is eccentric while the thrust force outputs, the armature is attracted lateral direction by the magnetic flux flowing from the stator to armature, and is touched with the surface of sleeve guiding the armature. The resulting frictional force is a cause of hysteresis. As a countermeasure, the armature is supported by the linear bearings. There are problems such as an increase in the length of the solenoid due to the increase of mounting space of the bearings, complication of the structure, an increase in cost, and so on. The magnetic hysteresis is that when magnetized by applying external magnetic field to a ferromagnetic material, its magnetization intensity changes not only by the strength of the magnetic field but also by the history of magnetic field change. Magnetic hysteresis prevents the magnitude of the magnetic flux from being uniquely determined with respect to the electric current value, which causes hysteresis of the thrust force of the solenoid.

In order to reduce these hysteresis, against for the conventional proportional solenoid driven by direct current (DC), this study proposes the proportional solenoid which is driven by alternating current (AC) and outputs direct-current-like thrust force. The three-dimensional three-phase AC proportional solenoid has a structure that can reproduce pseudo magnetic bearings that hold the armature in the air. The yokes to conduct the magnetic flux to the armature are around the armature orthogonal to the moving direction of the armature. The arrangement of the yoke for each phase of AC excitation of the windings prevents the contact between the armature and sleeve, and reduces the influence of friction. Further, the magnetic hysteresis is reduced by using the average magnetic flux due to the alternating magnetic field generated by AC excitation.

In addition to hysteresis, the proportional solenoid has several requirements for high performance. Firstly, it can only control the push- or pull- unidirectional force. Therefore, 4-port flow directional control valve needs to be installed a pair of solenoid to both sides of the spool. If it is possible to drive in push-pull both directions with one proportional solenoid actuator, the number of actuators will be reduced and the size of the equipment can be expected to be reduced. Secondly, it cannot use materials other than a heavy ferromagnetic material such as iron for an armature. If lightweight metal can be used for the armature, it is possible to move faster. Furthermore, when using the driving principle of a linear induction motor, it is also possible to realize a mechanism capable to drive a spool valve of aluminum or copper directly. Finally, it can only move a few millimeters. In order to solve these requirements, the induction-type proportional solenoid using the driving principle of AC current driven linear induction motor was developed.

STRUCTURE AND PERFORMANCE OF 3-DIMENSIONAL 3-PHASE AC PROPORTIONAL SOLENOID

The structure of a 3-dimensional 3-phase AC proportional solenoid is shown in FIGURE 1. The magnetic pole to produce the thrust force is the same as the conventional proportional solenoid with a triangle-shaped magnetic pole. It has 3 yokes and a winding around each yoke. A winding energized by an alternating current (AC) with the offset direct current (DC) produces the thrust force in axial direction at the magnetic pole, which is expressed by Eq. (1).

$$F = A - A\cos 2\omega t \tag{1}$$

where, F is the thrust force generated by one phase unit, ω is the angular frequency of AC. In Eq. (1), A is a constant determined by the surface area, S, where magnetic flux linkage penetrates and the magnetic flux density, B_m, at the surface, and is expressed by Eq. (2) in SI unit.

$$A = \left(10^7/16\pi\right)\cdot SB_m{}^2 \tag{2}$$

3-phase AC is supplied each winding with the phase difference of $2\pi/3$. Then the thrust force in axial direction generated by 3 windings energized by 3-phase AC is expressed by;

$$F = 3A \tag{3}$$

It means that the thrust force fluctuation by AC component does not appear on the thrust force in axial direction. Therefore, the behavior of the thrust force is the same as one of a conventional proportional solenoid.

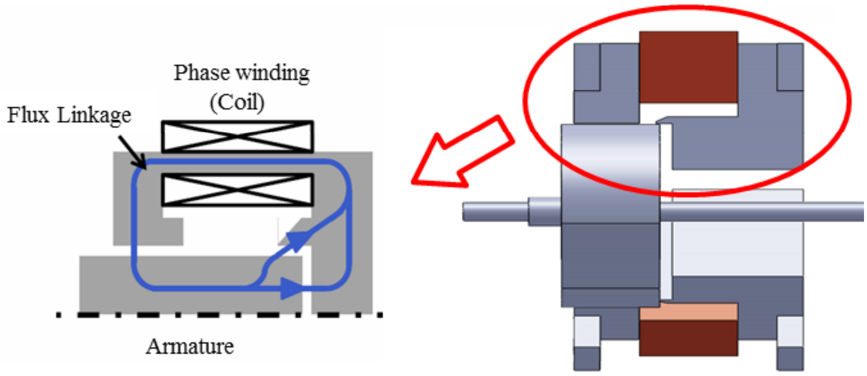


FIGURE 1. 3-dimensional 3-phaseAC proportional solenoid

The lateral force F_r as shown in Eq. (4), which is the attractive force in the radial direction appearing in the clearance between the armature and the yoke, is generated to each yoke periodically according to AC energization. For low frequency AC, the lateral attractive force makes the armature touch down to the yoke, then the noise and vibration, and friction are generated. For high frequency AC, the direction of the lateral attractive force always switches before the armature touch down. It behaves just like a magnetic bearing, as shown in FIGURE 2. As the result, since the armature keeps some clearance to all yokes, the hysteresis caused by the friction is remarkably reduced.

$$F_r = 1/2\left(N \cdot I\cos(\omega t + \phi)\right)^2 \cdot \mu_0 S / \delta^2 \tag{4}$$

where, F_r, N, I,μ_0, and δ are the lateral force, the turn number of phase windings, the current amplitude, the permeability of air, and the radial clearance between the armature and yoke, respectively.

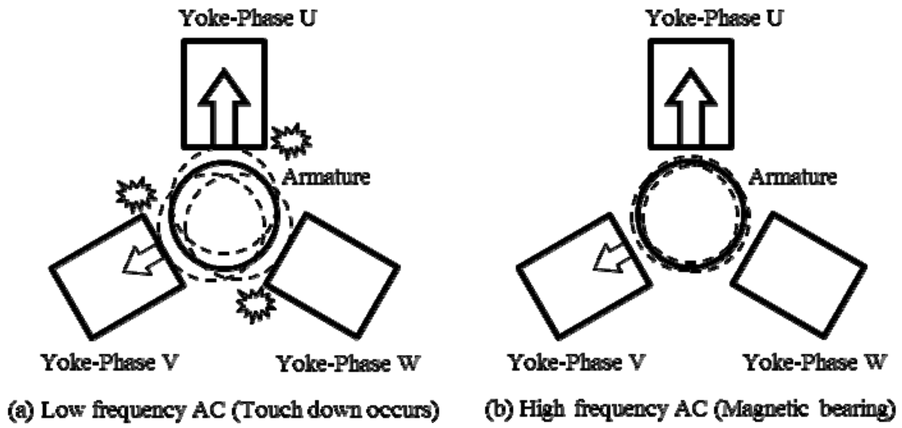


FIGURE 2. Lateral force generated by AC energization in each yoke

FIGUURE 3 (a) shows the prototype 3-dimensional 3-phase AC proportional solenoid and its testing apparatus. It is possible to attach the force sensor and the position sensor to the linear stage, and measure the stroke and the thrust force simultaneously. FIGURE 3 (b) is an appearance view of a prototype machine without triangular magnetic poles to confirm the performance of the 3-dimensional 3-phase AC proportional solenoid.
FIGURE 4 (a) and (b) show the measured results of the prototype of the 3-dimensional 3-phase AC proportional solenoid. Since this prototype does not have triangular magnetic poles on the magnetic poles, there is no control zone like the conventional proportional solenoid in these results. In FIGURE 4 (a), the frequency of the three-phase alternating current was increased and decreased to 50 Hz and the current amplitude was changed to a sinusoidal waveform of ± 3 A at a frequency of 1 Hz under a constant stroke of 0.26 mm. Although the thrust force vibrates, since the thrust force coincides with the round trip of the current amplitude, it is effective in reducing the hysteresis. In FIGURE 4 (b), when the stroke was increased or decreased at a current amplitude of 3 A and the frequency of the three-phase alternating current at 50 Hz, it was confirmed that the hysteresis was reduced.

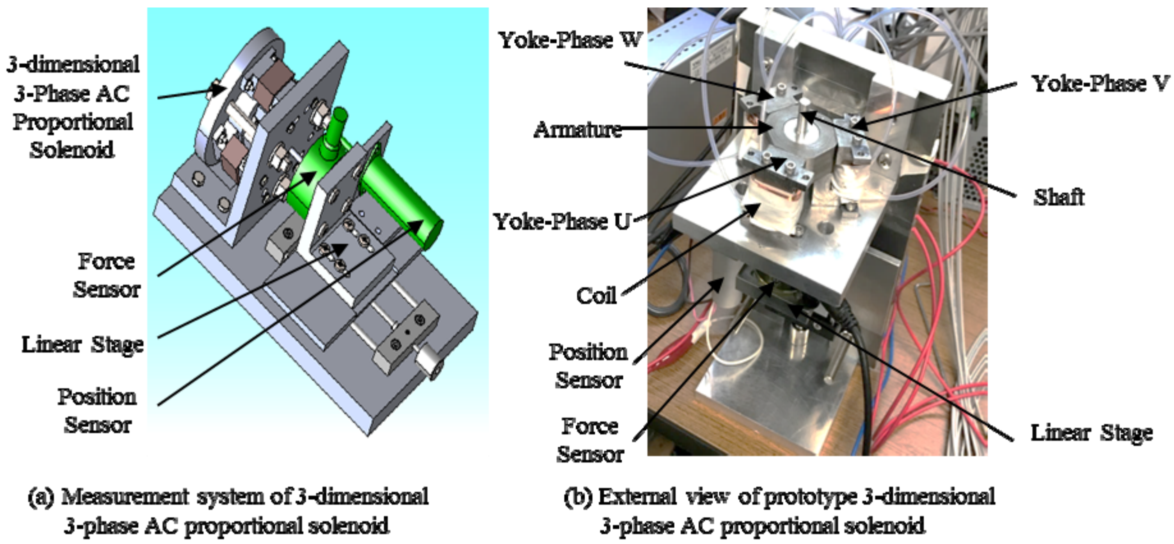
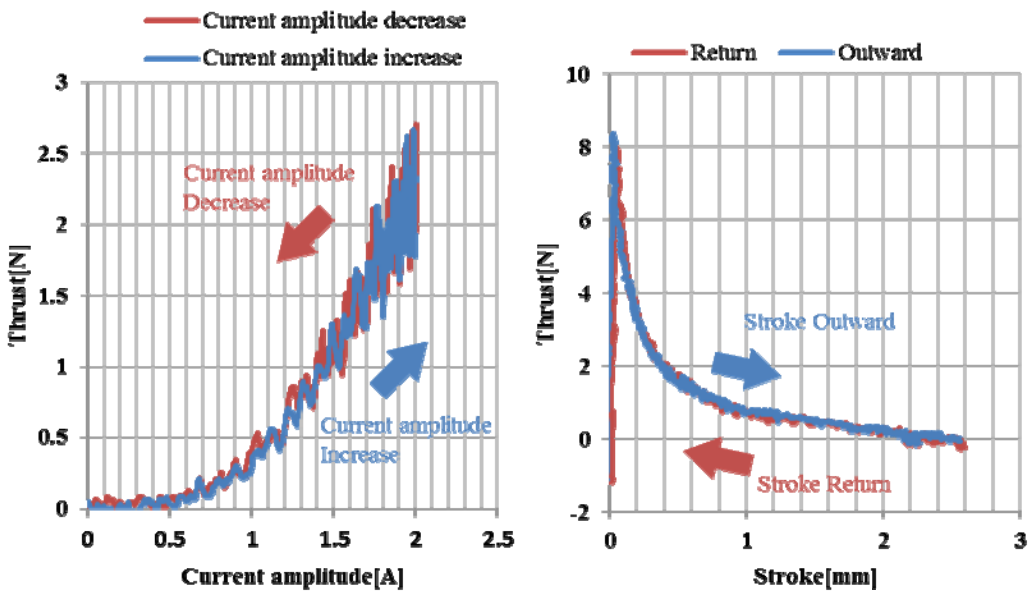


FIGURE 3. Prototype of 3-dimensional 3-phase AC proportional solenoid

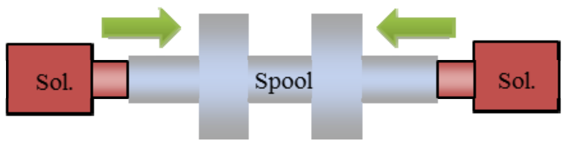


(a) Thrust force-current (b) Thrust force-stroke

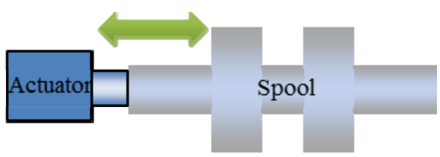
FIGURE 4. Thrust force characteristics of 3-dimensional 3-phase AC proportional solenoid

STRUCTURE AND PERFORMANCE OF INDUCTION-TYPE PROPORTIONAL SOLENOID

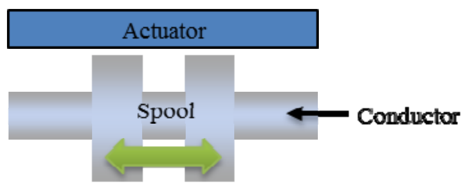
FIGURE 5 (a) shows a method of operating the spool valve when using a conventional proportional solenoid, and since it can only drive in one direction, it is necessary to install actuators on both sides of the spool valve. The induction type proportional solenoid using the driving principle of the linear induction motor (LIM) enables bidirectional driving by a single actuator and direct driving of the spool valve as shown in FIGURE 5 (b) and (c). In the driving principle of the LIM, a moving magnetic field is generated in the axial direction by three-phase AC driving of three sets of solenoid coils with a phase difference of 2π / 3 as shown in FIGURE 6. The Lorentz force generated by this moving magnetic field drives only the aluminum armature on the armature side.



(a) Conventional spool valve operation by two unidirectional solenoids



(b) Spool valve operation by bidirectional actuator



(c) Direct spool valve operation by bidirectional actuator

FIGURE 5. Hydraulic spool valve operation by actuator

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FIGUURE 7 (a) shows the prototype induction type proportional solenoid. It is possible to attach the force sensor and the position sensor to the linear stage, and measure the stroke and the thrust force simultaneously. FIGURE 7 (b) is an appearance view of the induction type proportional solenoid, which was fabricated as a prototype to confirm the performance of the linear induction motor. A cylindrical LIM has an axis symmetry structure in which the repulsive force and attractive force between the primary side and the secondary side becomes cancelled. This actuator uses three sets of three solenoid coils, and a total of nine solenoid coils were installed.

FIGURE 8 shows the measured results of the prototype of the induction type proportional solenoid. From FIGURE 8 (a), push-pull bi-directional drive was possible by the positive or negative of the current amplitude of the three-phase alternating current. From FIGURE 8 (b), constant thrust force was able to be output regardless of the stroke position with each current amplitude. [1]

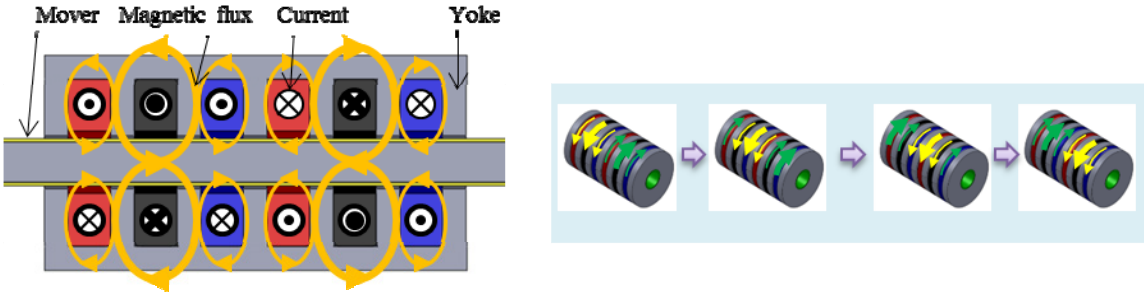


FIGURE 6. Moving magnetic field by three-phase alternating current

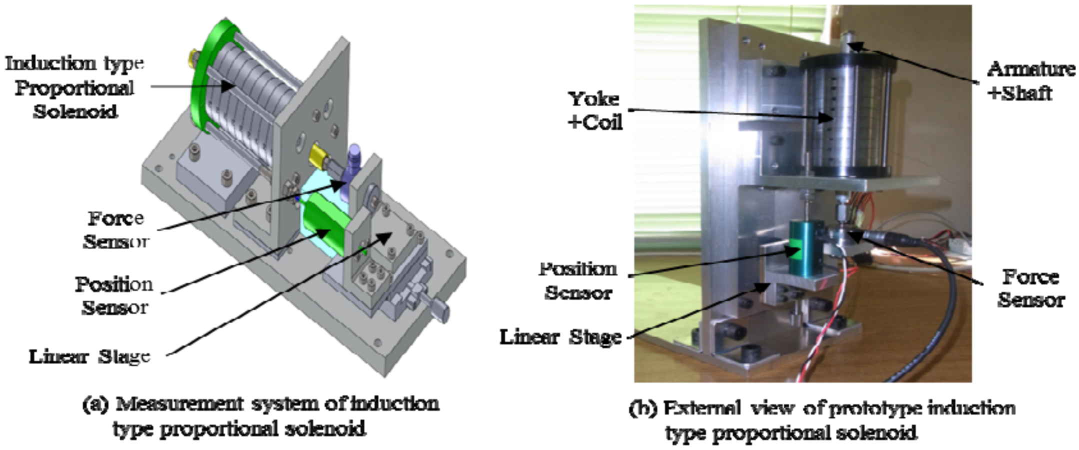
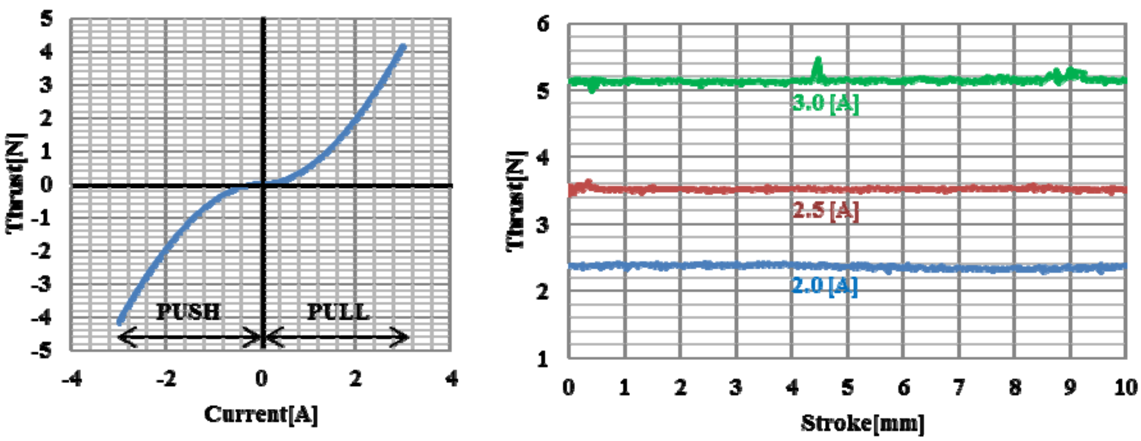


FIGURE 7. Prototype of induction type proportional solenoid



(a) Bidirectional drive

(b) Thrust force independent on stroke

FIGURE 8. Thrust force characteristics of induction type proportional solenoid

CONCLUSION

In this study, two electromagnetic actuators for hydraulic valve operation were developed to reduce the hysteresis and solve the requirements in the conventional proportional solenoid. One actuator developed to reduce hysteresis affecting control precision is a 3-dimensional 3-phase AC proportional solenoid having three magnetic poles and reproducing a pseudo magnetic bearing. Measurement of the current characteristics and stroke characteristics of the thrust force in the prototype of the 3-dimensional 3-phase AC proportional solenoid showed that hysteresis was reduced. Another actuator developed to solve the requirements for high performance is the induction type proportional solenoid that utilizes the driving principle of a linear induction motor. Measurement of the performance in the prototype of the induction type proportional solenoid showed that it was possible to drive the push-pull in both directions with a single actuator by changing the phase difference in AC current excitation. Furthermore, it was possible to use the armature with a lightweight metal other than iron. In addition, while the control zone of a conventional proportional solenoid is within a few millimeters, this actuator was able to output a thrust force independent of the stroke.

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REFERENCES

1. Takehiro TORII， Yasukazu SATO Electromagnetic Push-Pull Bidirectional Actuator for Hydraulic Control Valve Operation, Proceedings of the 3rd Cina-Japan Joint Workshop on Fluid Power， Aug 2014， pp.41-46