Abstract--Authors propose the spherical electromagnetic actuator that applied Surface Motor. The feature of this actuator is the ability to arrange the magnetic poles uniformly by distributing the stator's magnetic poles in triangular lattice. In this paper, we report that the fundamental structure of this actuator and secondary side permanent magnets arrangement, and we measure the thrust force characteristics of one phase excitation. The measurement result shows that the detent force distorts the thrust force waveform of one phase excitation.

Index terms—Spherical Motor, Surface Motor, Step Motor, Canceling out detent force

I. INTRODUCTION

Recently, many automated manufacturing processes (NC machines, robot manipulators) have brought about an urgent need for novel electromechanical performance characteristics. Additionally, the design of the devices are consideration on operating flexibility, small size, force per weight ratio, and control capability, etc. The Application for robot's joint actuator is currently underway in direct drives involving rotary DC stepping brush less motor and linear motor. These devices normally use to accomplish a single degree of motion manipulation at each joint (1). The plural these devices need to use for movement of many degrees of freedom. The device for many degrees of freedom using only one actuator (induction type or VR type) is researching from such a problem (2)(3)(4).

As approach of the different many degrees of freedom actuator, look at the two-dimensional positioning stage that are called X-Y plotter and X-Y stage in the field of office automation and factory automation. These positioning stages are based on the common technology which is combination of the single positioning stage and have some disadvantage such as complex mechanism, larger scale and so on. To improve these disadvantages, the researchers are doing research on Surface Motor (SFM) that can drive two directions by one linear motor (5). Authors propose the spherical electromagnetic actuator that applied SFM. This actuator can be applicable not only the robot's joint but also fields such as antenna drives of satellite, spherical structure, etc.

In this paper, we present the basic performance of this actuator and measured thrust force characteristics with using experimental prototype unit and studied about control and drive system.

II. THE BASIC STRUCTURE

Fig.1 shows basic structure of the spherical electromagnetic actuator. This actuator is based on same principle of PM type Linear step motor. The spherical motor consists of the stator, the mover, and the mover support mechanism (bearing). The magnetic poles of the stator are round-shaped and it distribute in triangular lattice. This actuator is enabling the spherical plane drive by this magnetic poles distribution. When driving only the 2-dimensional plane like SFM, the lattice distribution that distributes magnetic poles in parallel with x-axis and y-axis is sufficient, however, when driving a spherical plane, the magnetic poles cannot distribute uniformly. In the triangular lattice distribution that distributes the magnetic poles in the position used as a triangular vertex, if a surface of a sphere considers extension of polygonal, this distribution can uniformly distribute the magnet poles to a surface of a sphere. The mover has three basic axes of 0, +60, and -60 degree of angle as shown illustrated in Fig 1. The mover is composed of round-shaped permanent

![Fig.1 The basic structure of the spherical electromagnetic actuator](image-url)
magnets. According to bearing of the mover, we plan to use air bearing. On the driver for this actuator, we try to use micro step drive for smooth movement and fine positioning.

III. SECONDARY SIDE PERMANENT MAGNETS DISTRIBUTION

The mover does not need electric supply due to use of permanent magnets. Permanent magnets on the mover generate detent force that is due to attractive force between the stator and the mover. The detent force causes (of a thrust force waveform) distortion, and it affects out of linearity on micro step drive. From such a problem, Authors propose secondary side permanent magnets distribution that eliminates detent force. As the mover advances in 0 degree, 60 degrees, and -60 degree that are the basic direction in the coordinates of Fig.1, a permanent magnet moves between the adjoining the magnetic poles. At this occasion, we estimate that the detent force $F_d$ becomes sine wave as shown in Fig.2. In the case that the detent force $F_d$ is sine curve, the detent force $F_{do}$ shifted by half-wave to $F_d$ it can cancel out the detent force $F_d$. The permanent magnet position $x$ to cancel out is given by the equation (1).

$$x = \frac{\tau}{a(an+1)} \quad (1)$$

In the equation (1), $a$ is the number of the permanent magnets that is used in order to cancel out each other to one basic direction, and $n$ is integers.

In the case of two magnets cancel out the detent force in each basic direction, each positions to the magnet put on $(\alpha, \beta)$ are given by the equation (2)〜(4).

In the direction of 0 degree,
$$(A,B)=(\alpha \cap \tau /2(2n+1), \beta \cap m\tau) \quad (2)$$

In the direction of 60 degree,
$$(A,B)=(\alpha \cap n\tau, \beta \cap \tau /2(2m+1)) \quad (3)$$

In the direction of -60 degree,
$$(A,B)=(\alpha \cap \tau /2(2n+1), \beta \cap \tau /2(2m+1)) \quad (4)$$

$n, m=$integer

In the case of the plural magnets cancel out the detent force in each basic direction, the value of $a$ changes. For example, when canceling out the detent force of the direction of $A$ axis by five magnets, the value of $a$ in a equation (1) is set to $a= 5$. Similarly, in the direction of $B$ axis, cancel out by the five magnets.

When canceling out by the plural magnets, the permanent magnets that use for canceling out in each basic direction generate detent force, too.

Therefore, when canceling out by the plural magnets, the $a$ $\cap a$ pieces permanent magnets are need.

In the case of canceling out by five magnets in the one direction, the permanent magnets need 25 pieces at the mover. Its position is given by the equation (5)〜(7).

In the direction of 0 degree,
$$(A,B)=(\alpha \cap \tau /a(an+1), \beta) \quad (5)$$

In the direction of 60 degree,
$$(A,B)=(\alpha, \beta \cap \tau /a(an+1)) \quad (6)$$

In the direction of -60 degree,
$$(A,B)=(\alpha \cap \tau /a(an+1), \beta \cap \tau /a(an+1)) \quad (7)$$

$a$ is the number of the permanent magnets that is used in order to cancel out each other to one basic direction, and $n$ is 1〜a - 1. Fig.3 is the permanent magnet distribution of nine poles (9 $\bigcirc$ 9). In this distribution, the detent force of the direction of $A$ axis cancels out the detent force of the permanent magnets " $\bigcirc$ " and " $\bigcirc$ " that shift to $\bigcirc 4\tau /3$ in the direction of $A$ axis. How to cancel out detent force, however, has condition that the detent force of the one pole is sine wave.
IV. OPERATION PRINCIPLES

The operational principle of this actuator is the same as PM-type linear step motor. This actuator operates by controlling the plural magnetic poles of the stator. Magnetic poles of the stator have 16 phases, that are phase A to phase P. Fig.4 shows phase arrangement of magnetic poles. Excitation of the phase A is as shown in Fig.3 and Fig.4. At this time, the mover's permanent magnet "P" is in the same position as pole of phase A. When the mover moves in the direction of A axis, the excitation of phase changes to D, C, B, and A. When the mover moves in the direction of B axis, the excitation of phase changes to M, I, E, and A. When the mover moves in the direction of C axis, the excitation of phase changes to H, K, N, and A. At this time, the mover steps at intervals of π/3. As mentioned above, the mover will move in basic direction by changing the excitation of the phases.

V. DRIVING PRINCIPLES

A. The Equations of The Thrust Force

We are taking into consideration to use the micro step drive on this actuator smooth driving and discretional positioning. The micro step drive can move discretionary positions by controlling excitation current given to each phase. In this chapter, the equations of the static thrust force that need for the micro step drive are examined. This equation applies the theory of the thrust of SFM that authors have proposed (6). The thrust force in the direction of A axis and the thrust force in the direction of B axis assume that these are sine wave. The thrust force \( F_{AA} \) in the direction of A axis of the phase A and The thrust force \( F_{BA} \) in the direction of B axis of the phase A are given by the equation (8), (9).

\[
F_{AA} = -F_0 I_A \sin \left( \frac{\pi}{\tau} - \alpha \right) \cos \left( \frac{\pi}{\tau} \beta \right) \tag{8}
\]

\[
F_{BA} = -F_0 I_A \cos \left( \frac{\pi}{\tau} - \alpha \right) \sin \left( \frac{\pi}{\tau} \beta \right) \tag{9}
\]

\( F_0 \): The thrust force constant
\( I_A \): Excitation current of phase A
\( \tau \): Pole pitch

The equation of the thrust force by other phases is decided by the position from phase A to other phases. Fig.5 shows the relation of the position of each phase. In Fig. 5, \( \Phi = 20 \text{mm} \) of the distance between stator magnetic poles signifies 3 \( \Phi /4 \) in electrical angle. The thrust force \( F_{AB} \) and \( F_{BB} \) by phase B is given by the equations (10), (11).

\[
F_{AB} = -F_0 I_B \sin \left( \frac{\pi}{\tau} - \frac{3}{4} \pi \right) \cos \left( \frac{\pi}{\tau} \beta \right) \tag{10}
\]

\[
F_{BB} = -F_0 I_B \sin \left( \frac{\pi}{\tau} - \frac{3}{4} \pi \right) \sin \left( \frac{\pi}{\tau} \beta \right) \tag{11}
\]

The thrust force by other phases is given similarly. The thrust force of the whole in direction of A axis \( F_A \) and The thrust force of the whole in direction of B axis \( F_B \) are the equations (12), (13).

\[
F_A = F_{AA} + F_{AB} + F_{AC} + \cdots + F_{AM} + F_{AN} + F_{AO} + F_{AP} \tag{12}
\]

\[
F_B = F_{BA} + F_{BB} + F_{BC} + \cdots + F_{BM} + F_{BN} + F_{BO} + F_{BP} \tag{13}
\]

B. Excitation current

The micro step drive is fractional of the full step drive to have fine positioning.
Movement of the mover along target point $\alpha, \beta$ on the A-B coordinate, is excited by current $A$ axis and $B$ axis. If the standard is set to phase $A$ in Fig.5, the excitation current of phase $A$ is given by the equations (14).

$$I_A = I_0 \cos \delta_A \cdot \cos \delta_B$$

(14)

$I_0$: A constant of excitation current
$\delta_A, \delta_B$: Phase current that are matched as the mover to positioning target point ($\alpha, \beta$)

As for excitation current of other phases, a phase of sine wave shifts based on Fig.5. For example, excitation current of phase $B$ is given by the equations (15). Phase current $I_C \leftarrow I_P$ are given by the equations that is consider from phase $A$ respectively.

$$I_B = I_0 \cos \left( \delta_A + \frac{3}{4} \pi \right) \cdot \cos \delta_B$$

(15)

C. Evaluation of point of stability

The thrust force distribution generally expressed with sine wave is shown in Fig.6. Usually, the point of stability in the thrust force distribution is shown in Fig.6. Fig.7 shows differential-calculus value of the thrust force. At this time, differential-calculus value becomes the minimum in the point of stability. The stable point applied this idea to Two-dimensional point, the equation (16) will be applicable.

$$D_F = \frac{\partial F_A}{\partial \alpha} + \frac{\partial F_B}{\partial \beta}$$

(16)

If the equations of thrust force and the equations of excitation current are substituted into the equation (16), the equation (17) is obtained.

$$D_F = \frac{\partial F_A}{\partial \alpha} + \frac{\partial F_B}{\partial \beta} = \frac{2}{\tau} \cdot I_0 \cdot \cos \left( \frac{\pi}{\tau} \cdot \alpha - \delta \right) \cdot \cos \left( \frac{\pi}{\tau} \cdot \beta - \delta \right)$$

(17)

For making target points ($\alpha, \beta$) into the point of stability, $\delta_A$ and $\delta_B$ are set up with the equation (18).

$$\delta_A = \frac{\pi}{\tau} \cdot \alpha, \quad \delta_B = \frac{\pi}{\tau} \cdot \beta$$

(18)

The excitation current is controlled by $\delta_A$ and $\delta_B$ obtained from the equation (18). Fig.8 shows the stable point of (0,0) from the equations (17), (18).
VI. THE MEASUREMENT OF THRUST FORCE

A. The Experiment Machine

We verify the theory of canceling out detent force shown in the preceding chapter by experiment of measuring the thrust force characteristics. Fig.9 shows the experiment machine. Table 1 shows the dimension of the experiment machine. This experiment machine has the plane form for analysis of the basic performance. We use load cell for the measurement of the thrust force, and the laser displacement sensor for the measurement of position.

B. Detent force characteristics of one pole magnet

How to cancel out detent force in the preceding chapter has condition that the detent force of the one pole is sine wave. We examine that the detent force of the one pole actually satisfies condition. A permanent magnet arranges the position of 0mm in coordinate of Fig.1, and we measure the detent force from there to $\tau=20\text{mm}$ ($\tau$ is pole pitch) at intervals of 1mm in the direction of A axis. Fig.10 shows the measurement result of the detent force characteristics. Fig.11 shows Fourier series expansion of this detent force waveform. We see from this result that the detent force of the one pole contains harmonic wave ingredient. We predict that not all the detent force cancels out.

C. Thrust force characteristics of nine pole magnets

We measured the thrust force characteristics of the permanent magnets distribution shown in Fig.3. In addition, the mover fixes to the rail of y-axis at this experiment so that it might not move to the direction of y. The position of permanent magnet "①" in Fig.3 is set to 0mm, and we measure the thrust force from there to $x=55\text{mm}$ in the direction of A axis. Fig.12 shows the measurement of the thrust force characteristics of exciting one phase to 0[A], 0.5[A], 1.0[A], and 1.5[A]. The thrust force at the time of excitation current 0[A] is the detent force. The detent force became 25% of the peak value of the thrust force of excitation current 1.5[A] from the measurement result.

Table 1 Dimension of the experiment machine

<table>
<thead>
<tr>
<th>Item</th>
<th>Value and Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole Material</td>
<td>Soft Iron</td>
</tr>
<tr>
<td>Size (Top) $\phi \times t$</td>
<td>15x5 [mm]</td>
</tr>
<tr>
<td>Size (Bottom) $\phi \times t$</td>
<td>9x10 [mm]</td>
</tr>
<tr>
<td>Pitch $\tau$</td>
<td>20 [mm]</td>
</tr>
<tr>
<td>Pole Number</td>
<td>64 [pole]</td>
</tr>
<tr>
<td>Coil Diameter</td>
<td>0.35 [mm]</td>
</tr>
<tr>
<td>Number of Turn</td>
<td>200 [turn/phase]</td>
</tr>
</tbody>
</table>

![Fig.9 The experiment machine](image)

![Fig.10 Detent force characteristics of one pole magnet](image)

![Fig.11 Fourier series expansion of detent force waveform](image)
VII. CONCLUSION

Following articles are obtained as conclusion of this paper.
1. The basic study has conducted for the spherical actuator that is specific design structure to move three directional axes.
2. Elimination of harmonic components of detent force is a critical technique to obtain smooth movement and fine positioning with micro step drives.
3. For dynamic performance of this actuator, will discuss in future steps.

REFERENCES