Torque Analysis of a Noncontact Spinning System Using Linearly Actuated Magnets

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This paper analysed the torque characteristics of a noncontact spinning system using linearly actuated magnets. This noncontact spinning system spins the suspended object (here is an iron ball) without contact by the remanent magnetization and the linear movement of four permanent magnets. The four magnets are driven by four VCM (Voice Coil Motor). In this paper, the remanent magnetization point is modelled as a small permanent magnet, whose one magnetic pole is at the surface of the ball, and the other magnetic pole is at the centre of the ball. An analysis model of IEM (Integral Element Method) is created to calculate the rotational torque of the iron ball, and a measurement device using strain gauges is set up to measure the rotational torque. According to the IEM analysis results and the experimental results, the rotational torque characteristics of the noncontact spinning system are discussed.

Key Words: Noncontact spinning, Torque analysis, Permanent magnet, IEM analysis, Strain gauge.

1. Introduction

Until now, many kinds of noncontact suspension systems and spinning systems have been proposed using electromagnet and permanent magnet. With the development of high performance permanent magnet, more and more researchers focus on the magnetic suspension system using permanent magnets. Oka et al. have proposed an active magnetic levitation system using a permanent magnet and a motion control mechanism [1]. Ikuta et al. have proposed a noncontact magnetic gear acting as a transmission [2]. The authors have proposed two kinds of noncontact spinning systems using permanent magnets. One system is using the rotational disk magnets to vary the magnetic flux filed around the suspended object [3]; the other system is using the linearly actuated magnets to approach the suspended object [4]. Using these two spinning systems, the suspended objects (they are iron balls.) have been spun successfully without contact.

This paper focuses on the rotational torque characteristics of the spinning mechanism using linearly actuated magnets. Basing on the simplification of the remanent magnetizations on the surface of the iron ball, the IEM analysis is carried out for the rotational torque in different given conditions, and the analysis results are examined by the measurement experiment.

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2. Prototype and Spinning Principle

2.1 Prototype

Fig. 1 shows the configuration of the noncontact spinning system using linearly actuated magnets. The mechanism has two parts: one is a suspension part which consists of a permanent magnet, a voice coil motor and two eddy current sensors, and the other is a spinning part which consists of four permanent magnets and four VCMs.

In the suspension part that is the centre part of the device, the suspended object is an iron ball. A cylinder permanent magnet was equipped on the lower top of the slider of VCM, and a sensor target was installed on the upper top of the slider. The permanent magnet and the sensor target were moving with the slider together. The upper sensor measured the magnet position through the sensor target. The lower sensor measured the position of the iron ball.

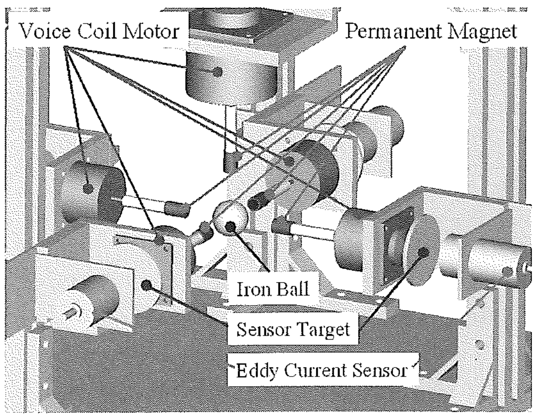

Fig. 1 Configuration of noncontact spinning system.

The spinning part is the surroundings of the device shown in Fig. 1, and consists of four same and independent units. Each unit consists of a permanent magnet, a linear actuator motors, a sensor target, and an eddy current sensor. Each permanent magnet is same with that using in the suspension part. The magnet is driven to approach and depart from the suspended iron ball by the linear actuator. Each unit is installing on the adjustable frame, can be adjusted freely in the vertical and horizontal directions.

2.2 Spinning principle

The spinning principle can be understood from Fig. 2, which shows a plan view of an iron ball and four magnets. There exist remanent magnetization points on the surface of the iron ball. The strongest magnetization determines the upper side of the suspended ball. The next strongest magnetization point is assumed in the horizontal plane and shown in Fig. 2. This remanent magnetization causes the suspended ball rotate about the vertical axis due to its attraction to the approaching magnet. Four magnets are installed perpendicular to each other, and the N magnetic poles of all magnets are arranged to face the iron ball. According to the arrangement of the magnets, we assume that the magnetic pole of the remanent magnetization point is S pole. The figure shows that magnet I approaches to the iron ball, the remnant is attracted to the nearest magnet I. If the positions of the magnets are not changed, the iron ball will stop at the position as shown in Fig. 2, and we call this situation of the iron ball as stable point. Next, the magnet I departs from the ball and the magnet II approaches to the ball. This time, the stable point will be at the position of facing to the magnet II. Theoretically, repetitions of this approach-depart cycle of the four magnets can make the iron ball spin.

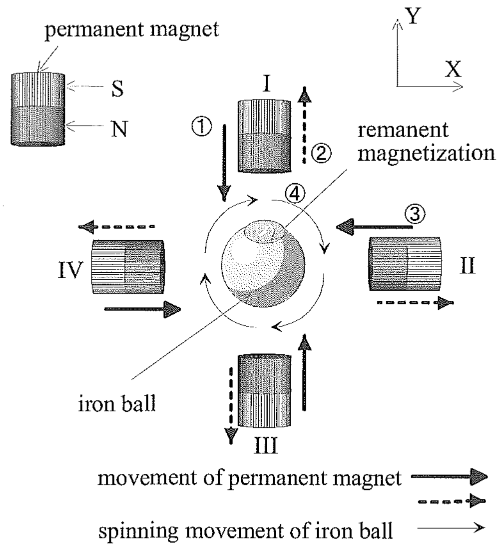

Fig. 2 Spin principle of spinning mechanism.

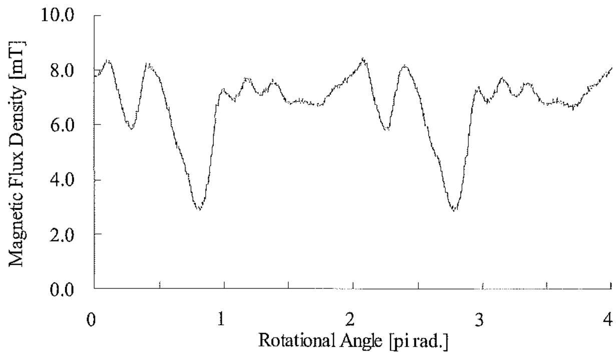

Fig. 3 Magnetic flux density along equator of iron ball.

3. Remanent Point Examination and Modelling

3.1 Examination for remanent magnetization point

In order to understand the existence of the remanent magnetization points on the surface of the suspended ball, the magnetic flux density was measured using a gauss meter along the equator of an iron ball. Before measurement experiment, the used iron ball was suspended by the suspension system to decide the poison of the strongest remanent magnetization point on the surface of the iron ball. The position of the strongest point was marked, and located at the top of the ball. And then, the magnetic flux density along the equator was measured at the position from the iron ball 0.5 mm. The measurement was done in two revolutions of the iron ball. The measurement results are shown in Fig. 3. The place with large magnetic flux density is seemed as N pole, and the place with small magnetic flux density is seemed as S pole. Therefore, there are one strong and one weak S pole in one revolution of the iron ball. Based on this result, the existence of the remanent magnetization points on the surface of the iron ball is proved. The result shown in Fig. 3 may be the one case of the various arrangements of the remanent magnetization points on the surface of the iron ball.

3.2 Modelling for remanent magnetization point

The strength of the remanent magnetization point on the surface of the iron ball is very weak, and the rotational torque of the iron ball cannot be analysed directly. In order to examine the rotational torque of the mechanism, the remanent magnetization points were simplified as permanent magnets. As shown in Fig. 4, one pole of magnets is located on the surface of the iron ball, since the remanent magnetization points are on the surface of iron ball. And the other pole of magnets is located at the centre of the iron ball for avoiding to influence the rotational torque. Moreover, the vertical magnet is seemed as the remanent magnetization point for suspension on the top of the iron ball. The horizontal magnet is seemed as the remanent magnetization point on the side of the iron ball for rotation. The arrangements of the magnets are agreed with the Fig. 2 and Fig. 3. The S pole is located on the surface and the N pole is located at the centre of the iron ball.

4. IEM Analysis for Rotational Torque

4.1 Analysis with one remanent magnetization point

Fig. 5 shows the IEM analysis model with one remanent magnetization point along the equator of the iron ball. In the model, we assume that the rotational angle of iron ball expresses as θ, the drive angle of the magnets for rotation expresses as φ. And the movement amplitude of the magnets for rotation L is 4 mm. The distance between the centre of the iron ball and the movement centre of the magnets P is 26 mm. The diameter and the length of the magnet regarded as remanent magnetization point are 5 mm and 15 mm. The size of the magnet for rotation is same with those used in experimental prototype.

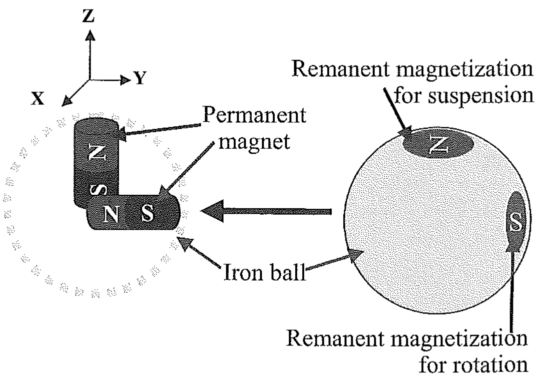

Fig. 4 Modelling for remanent magnetization point.

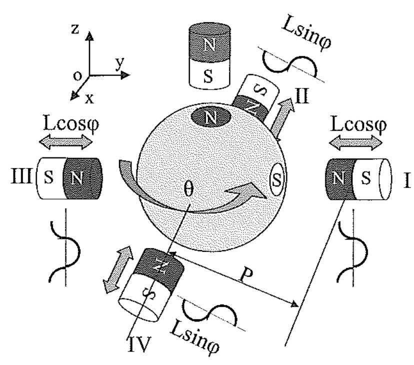

Fig. 5 IEM model with one horizontal remanent point.

Using this analysis model, the rotational torque was calculated, and the magnets were driven by the same way with the principle. The analysis started from the position when the remanent magnetization was facing to the nearest magnet. When the remanent magnetization rotated in steps of 5 degrees from 0 to 360 degrees, the rotational torque was calculated at each step. And then, the magnets were driven in steps of 30 degrees until 360 degrees.

The analysis results are shown in Fig. 6. The torque is expressed with respect to the rotational angle of the iron ball θ, and the parameters on the top of the figure express the angle φ of the driving magnets. The intersection between the downward-sloping section of torque graph and the horizontal axis is the stable point. When the remanent magnetization point is at the stable point, the torque equals zero, and if the remanent magnetization rotates around the stable point, the torque will make the remanent magnetization point return to the stable point. If the stable point moves, the remanent magnetization point will follow it. As a result, the iron ball spins.

In Fig. 6, the rotational torque is varying when the remanent magnetization is rotating and the magnets are moving. However, all the stable points are concentrated at 0, 90, 180, and 270 degrees, where the stable point is facing to the driving magnets. The results indicate that this model cannot spin the iron ball.

4.2 Analysis with two remanent magnetization points

In addition, the IEM analysis was carried out with two same remanent magnetization points along the equator of the iron ball, and the value of L and P were 10 mm and 39 mm, and the offset angle between two points is 45 degrees. The analysis results are similar to Fig. 6, but the stable points do

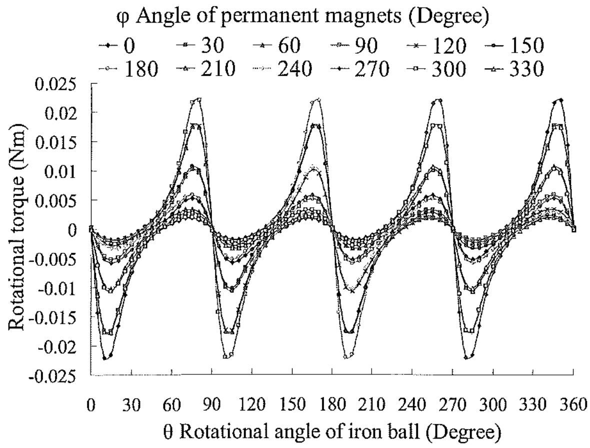

Fig. 6 IEM results with one horizontal point.

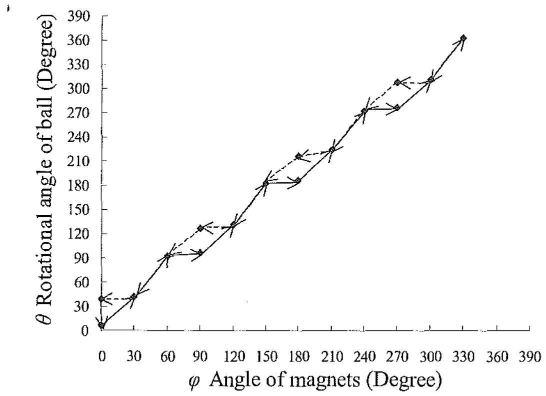

Fig. 7 IEM results with two horizontal points.

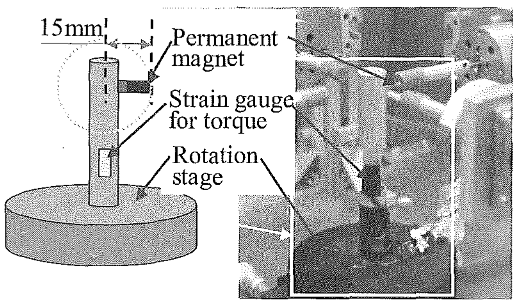

Fig. 8 Experimental measurement device.

not concentrate at some points. In order to understand the stable points distribution easily, the stable points has been summarized and shown in Fig. 7. Along with the movement of the magnets, the iron ball will vary along the solid line with arrows, and the return path will be along the dash line with arrow. This result indicates the iron ball can be spun.

5. Experimental Examination

In order to examine the validity of the IEM analysis, a measurement device shown in Fig. 8 was installed, and the rotational torque of the spinning system was measured with one remanent point in the horizontal direction.

In the experimental device, the remanent magnetization was simplified to a small neodymium permanent magnet, whose dimension is same with the IEM model. The magnet was attached to an aluminium pipe that is installed on a rotation stage. The N pole of magnet is installed at the rotation centre, and the S pole is seemed as on the surface of an iron ball. Two pieces of strain gauges with the type of KFG-2-350-D31-23 were pasted on the symmetry side of the aluminium pipe.

The measurement experiment was carried out in same conditions with the analysis model of Fig. 5. The experimental results are shown in Fig. 9. Some dispersion can be seen from these results, which is caused by the measurement error of the strain gauges. However, these results are almost agreed with Fig. 6. These results indicate that the IEM analysis results of Fig. 6 are available. In the same way, we can understand that all IEM analysis results are available.

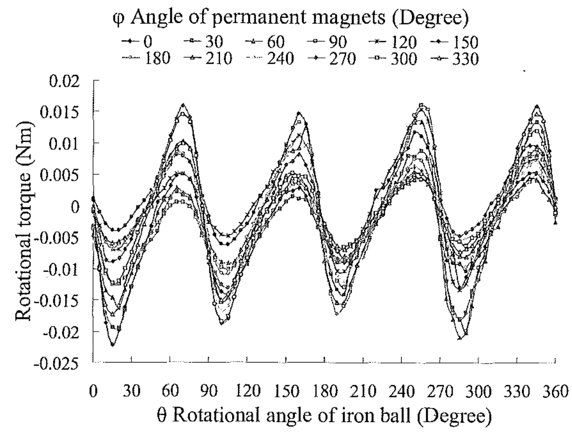

Fig. 9 Experimental results with one remanent point.

6. Conclusion

In this paper, the remanent magnetization point was simplified, and the IEM analysis and measurement experiment for rotational torque were carried out in some given conditions. The analysis results indicated that and the large movement amplitude and distance between the iron ball and magnets could make the iron ball spin using two remanent magnetization points. In addition, the experimental results indicated that all the IEM analysis results were available. Finally, except of the discussed models in this paper, certainly, there will be many complex models that can spin the iron ball.

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