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Simulation results of a hexahedron-octahedron based spherical stepping motor†

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Abstract

The simulation results of a novel stepping motor based on a pair of a regular hexahedron and a regular octahedron (call "6-8 spherical stepping motor" afterward) are presented. The 3D electromagnet and motion coupled simulation program "Magnet 6" is used for the simulation. As the conditions of simulation, the excitation current and frequency is 1 A and 5.3 Hz, respectively. Three phase sinusoidal excitation currents are applied to two pairs of three coils of the stator individually at 120 deg intervals. The simulation results show that the rotor rotates along the rotating magnetic field and the output torque is 0.04 Nm. The simulation results prove the correctness of the 6-8 spherical motor driving method. The developed 6-8 spherical stepping motor is air-core type without back yoke for avoiding the cogging torque. When using iron core with back yoke, the proposed motor will be a high-torque spherical motor. The 6-8 spherical stepping motor was tested and the experimental results were compared with the simulation results. Then, the simulation program was used for optimum design of the 6-8 spherical stepping motor.

Keywords: Electromagnet and motion coupled simulation; Multi DOF; Spherical motor; Stepping motor

1. Introduction

From humanoid robots to automobiles, the number of degrees of freedom of mechanical systems continues to grow. There has also been a proportional increase in the number of motors used in the mechanical systems.

On the other hand, human joints like the shoulder joints have at least three degrees of freedom (lateral direction, anteroposterior direction, and arm rotation).

A spherical motor with multi degrees of freedom like a human shoulder joint generally has the following advantages:

(1) It makes the mechanical system smaller and lighter by cutting down the number of motors used for a system.
(2) Simplified control makes higher speed possible
(3) Easy realization of the direct drive mechanism
(4) Easy miniaturization
(5) Striking energy saving effect
(6) Making ultrahigh precision mechanical system possible

A practical spherical motor would revolutionize the designs of mechanical systems. I have manufactured by way of trial and conducted research into a wide range of electromagnetic spherical motors, including an induction motor, synchronous motors, stepping motors and an AC servo motor; I have examined their characteristics and performances [1-3], and found new applications thereof [4]. Meanwhile, the output torque of these spherical motors is not enough for driving the robot joints. Therefore, I proposed a novel high torque stepping motor principle based on a pair of polyhedrons [5].

In this paper, the simulation results of the developed 6-8 spherical stepping motor are presented.

At first, the structure and the driving principle of the developed 6-8 spherical stepping motor are shown. Next, the simulation model is made and simulates the motion of the rotor by the proposed driving method.

2. Design and the driving principle of the 6-8 spherical stepping motor

2.1 Design

Fig. 1(a) shows a picture of the developed 6-8 spherical stepping motor and Fig. 1(b) shows the structure of it. Both the rotor and the stator are sphere shaped.

The motor has a rotor supported by six spherical bearings and a stator. Fig. 2(a) shows the structure of the rotor and Fig. 2(b) shows the structure of the stator.

Eight NdFeB permanent magnets are attached on the spherical shell at the vertexes of the virtual hexahedron inscribed in the rotor so that the north and the south poles are located alternately. Six iron cores are also attached on the spherical shell at the center of the faces of the virtual hexahedron inscribed in the rotor. The spherical shell is made of iron, the inner diameter is 52 mm and the thickness is 5 mm. The

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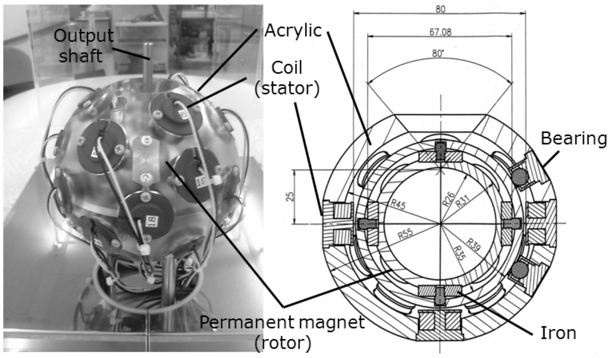
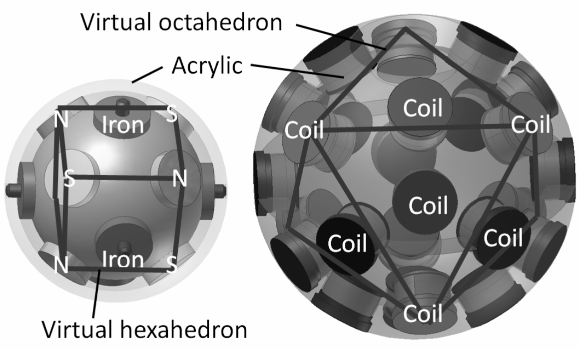


(a) Picture (b) Structure

Fig. 1. Design of the 6-8 spherical stepping motor.



(a) Rotor (b) Stator

Fig. 2. Rotor and stator.

rotor is covered with an acrylic spherical shell to make the rotor surface sphere. The outer diameter of the acrylic shell is 78 mm and the thickness is 4 mm. The shape of the permanent magnets and iron cores is cylindrical, which diameter is 20 mm and the thickness is 5 mm.

The base of the stator is an acrylic spherical shell. Twenty-five armature coil units are attached through the acrylic spherical shell. Six of them are attached at the vertexes of the virtual octahedron inscribed in the stator. Twelve of them are attached at the center of the edges of the virtual octahedron inscribed in the stator. Seven of them are attached at the center of the faces of the virtual octahedron inscribed in the stator without the upper face. The upper face is open for the output shaft. The inner diameter and the outer diameter of the acrylic shell are 90 mm and 110 mm, respectively. The number of the turns of each armature coil is 153.

Six spherical bearings are also attached on the unused space of the acrylic spherical shell.

The developed motor is air-core type without back yoke. The output torque of the developed motor will be small but motor control will be easy.

2.2 Driving principle

Fig. 3 is the upper view of the designed 6-8 spherical stepping motor when the output shaft is at the vertical position.

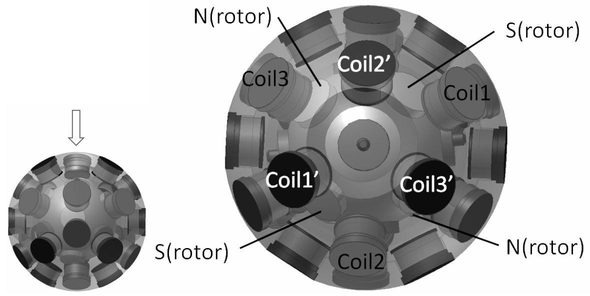


Fig. 3. Top view.

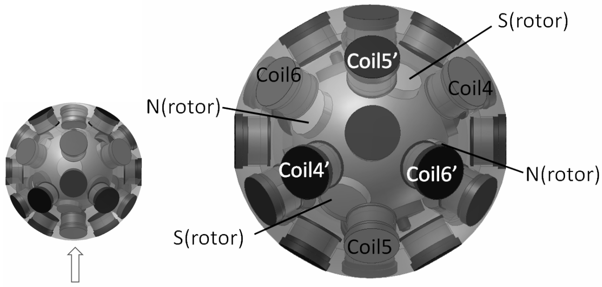


Fig. 4. Bottom view.

The permanent magnets are positioned at every 90 degrees around the output shaft and north poles and south poles are positioned alternately. The pairs of coils (1,1'), (2,2') and (3,3') are positioned at every 120 degrees around the output shaft.

The relationship between the permanent magnets and the armature coils is similar to that of the conventional three-phase planer stepping motor with two pairs of permanent magnets.

Therefore, when three-phase sinusoidal currents are supplied to the armature coils (1,1'), (2,2') and (3,3'), the rotor will rotates around the output shaft.

Fig. 4 is the bottom view of the designed 6-8 spherical stepping motor when the output shaft is at the vertical position. The positions of the permanent magnets and the coils (4,4'), (5,5') and (6,6') are the same as in Fig. 3.

Therefore, when three-phase sinusoidal currents are supplied to the armature coils (4,4'), (6,6') and (5,5'), the rotor will rotates around the output shaft in the same direction as Fig. 3.

When three phase sinusoidal currents are supplied to the armature coils (1,1'), (2,2') and (3,3') and (4,4'), (6,6') and (5,5') simultaneously, the output torque will be doubled.

Fig. 5 is the view of the designed 6-8 spherical stepping motor from the direction of the arrow. One of the iron cores is just under the armature coil 245. The position of the armature coil 245 is the center of the triangle formed from coil2, coil4 and coil5. The positions of the permanent magnets and the coils (2,6'), (5,24') and (4,25') are the same as in Fig. 3.

Therefore, when three-phase sinusoidal currents are supplied to the armature coils (2,6'), (5,24') and (4,25'), the rotor rotates around coil 245.

At the back view of Fig. 5, the relationship between the permanent magnets and the armature coils is same as Fig. 5.

Therefore, when three-phase sinusoidal currents are supplied to the appropriate armature coils, the rotor rotates around coil 245.

The rotor has six iron cores and the stator has seven armature coils at the center of the face of the octahedron inscribed in the stator. When one of the iron cores is positioned just under the armature coil, the rotor can be rotated around the noticed armature coil by supplying three-phase sinusoidal currents to the armature coils around the noticed armature coil.

From the discussion above, the rotor can be rotated in almost any direction by the following algorithm:

(1) Attract appropriate iron core by the armature coil which will be the rotational center.
(2) Supply three-phase sinusoidal currents to the six pairs of armature coils around the rotational center.
(3) When the rotation axis is changed, go to step 1).

3. Simulation results of the 6-8 spherical stepping motor

Fig. 6 is the mesh model of the developed 6-8 spherical stepping motor made by the 3D electromagnet and motion coupled simulation program Magnet 6.

Supply three-phase sinusoidal currents to the armature coils (1,1'), (2,2'), (3,3') and (4,4'), (6,6'), (5,5') simultaneously. The amplitude and the frequency of the armature currents are 1A and 5.3 Hz, respectively.

Fig. 7 shows the simulation results from 0 msec to 50 msec. It has been confirmed that the rotor exactly rotates around the vertical axis.

Fig. 8 shows the rotor position around axis X, axis Y, and vertical axis Z. The rotor positions around X axis and Y axis are between -9 deg to 2 deg.

The synchronous speed to the current frequency of 5.3 Hz is 954 deg/sec around Z axis, which means that the rotor position around Z axis is 477 deg at 500 msec. The rotor position around Z axis is slightly larger than the synchronous speed at 500 msec. This is explained by the fact that the magnetic field distribution is not sinusoidal. Fig. 9 shows the output torque around vertical axis Z. At first, the rotor is accelerated by the strong magnet field and then decelerated by the weak magnetic field. The maximum output torque is 0.04 Nm.

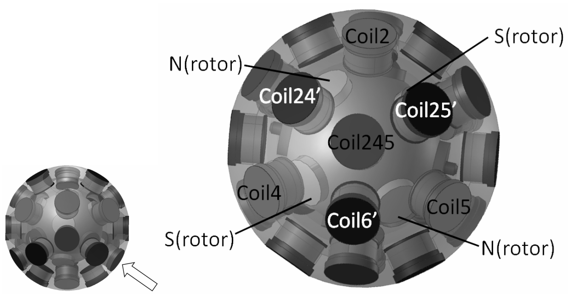


Fig. 5. Tilt view.

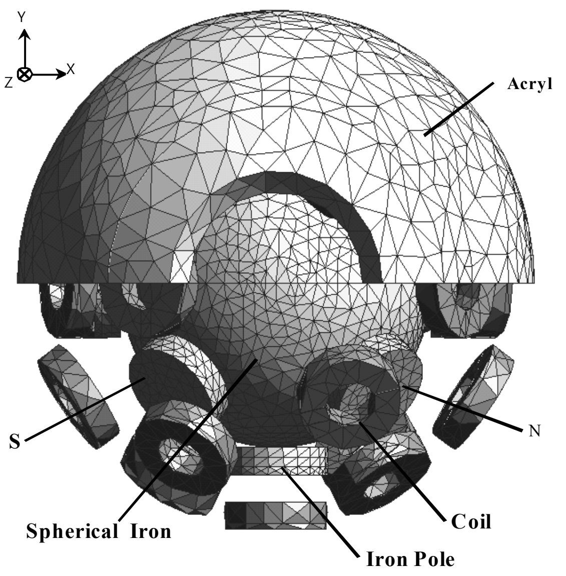


Fig. 6. Mesh model of the 6-8 spherical stepping motor.

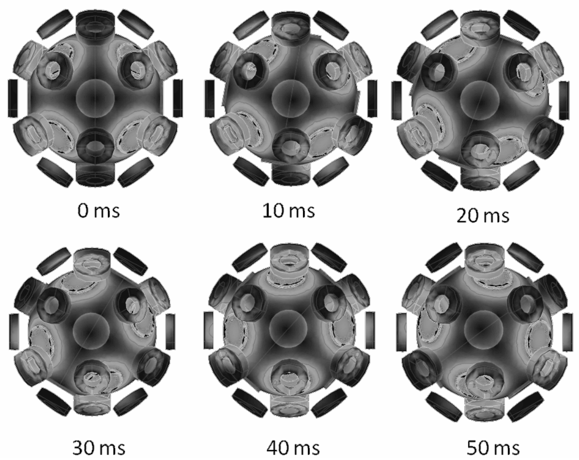


Fig. 7. Simulation results from 0 msec to 50 msec.

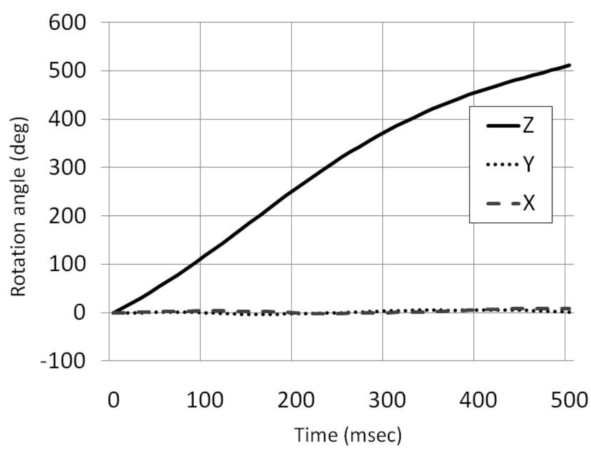


Fig. 8. Rotation angle around axis X, Y, and Z.

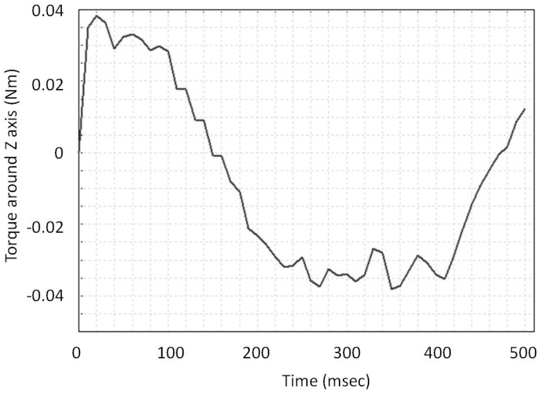


Fig. 9. Output torque around Z axis.

4. Conclusions

The simulation results of the developed 6-8 spherical stepping motor are presented by using 3D electromagnet and motion coupled simulation program Magnet 6.

The simulation results show that the rotor rotates around the vertical axes and the rotation speed is almost same as the synchronous speed. The movement of the rotor in the other direction is random and very small. The maximum output torque around the vertical axes is 0.04 Nm. The simulation results prove the correctness of the driving principle of the proposed 6-8 spherical stepping motor. All the forces between the magnets and the armature coils of the proposed motor are added to make the output torque. Therefore, the proposed motor will be a high torque, arbitrary directional spherical motor. The developed 6-8 spherical stepping motor is air-cored type without back yoke for avoiding the cogging torque. When using iron core with back yoke, the proposed motor will be a high-torque spherical motor.

I will design the high performance motor by the simulation and make the practical motor in the near future.

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