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A Stirrer Driven by a Spherical Stepping Motor

***Abstract**. This study applies the spherical stepping motor the authors developed to the driving device of a stirrer and develops a proto-type stirrer. The developed stirrer is composed of a rotor, a stator, a control PC, an electric-magnet excitation circuit, and a power supply. The rotor is composed of double spherical shell in order to contain liquid in its inner spherical shell. Totally 91 permanent magnets are arranged in the rotor. On the other hand, 80 electro-magnets are arranged on the stator. The applicability of the stirrer to material production is evaluated by stirring experiments.*

*Streszczenie. Artykuł opisuje badania sferycznego silnika krokowego zastosowanego jako napęd mieszadła. Zbudowany został prototyp mieszadła, który składa się z wirnika, stojana, mikroprocesora, obwodu wzbudzenia elektromagnetycznego i bloku zasilania. Stosowalność mieszadła do produkcji materiałów wykazano w eksperymentach mieszalniczych. (**Mieszadło napędzane sferycznym silnikiem krokowym**).*

Keywords: spherical stepping motor, stirrer, double spherical shell.
Słowa kluczowe: sferyczny silnik krokowy, mieszadło, sferyczna powłoka.

Introduction

There are several advantages in spherical motors compared with usual motors that rotate around an axis. Because a spherical motor can rotate around any axis, only one spherical motor is needed to move an object to any location in the case of considering only the moving direction of the object and arranging the spherical motor in the root of the arm. By the advantageous feature, the number of motors necessary for a system will decrease and the system will be small and consume lower energy. In addition, the rotation center of a spherical motor coincides with its geometrical motor center. Therefore, the rotation control of a spherical motor is easy compared with an integrated system using several motors.

Up to now, spherical motors by several working principles have been developed such as a spherical ultrasonic motor[1], a spherical induction motor[2], spherical stepping motors[3, 4, 5, 6], and a spherical motor using magnetostriction[7]. The authors developed spherical stepping motors[8, 9] that can rotate in any direction with the rotation angle errors of some degrees. The spherical stepping motor the authors developed has 32 or 92 permanent magnets on a spherical rotor whose diameter is 0.1 [m] and 84 electro-magnets on a semi-spherical stator.

Spherical motors are expected to be applied to the driving device of a robot arm, a holonomic mobile robot, a pointing device, and so on. This study applies the spherical stepping motor the authors developed to the driving device of a stirrer and develops a proto-type stirrer for material production under the condition of small influence of gravitational force. The mixing performance of the rotation method by changing rotation direction at random in order to reduce the influence of gravitational force is evaluated by the experiments to dissolve salt in water.

Structure of Stirring Machine

The developed stirrer is composed of a rotor, a stator, a control PC, an electro-magnet excitation circuit, and a power supply. Figure 1 shows the components of the stirrer except the control PC. In the right hand of the figure, the spherical rotor is placed on the stator. The electro-magnet excitation circuit[8, 9] is seen in the left front of the figure. The box in the left back is the power supply. Its output voltage and maximum output power are 12 [V] and 600 [W], respectively. The electro-magnet excitation commands are sent from the control PC to the excitation circuit through a RS-232C serial communication cable.

The outer diameter of the rotor is 0.2 [m] that is twice of that of previous studies[8, 9]. As shown in Fig. 2, the rotor is composed of inner and outer spherical shells made of acrylic resin in order to contain liquid in its inner spherical shell. On the inner surface of the inner shell, there are 31 short sticks made of acrylic resin to increase stirring performance.

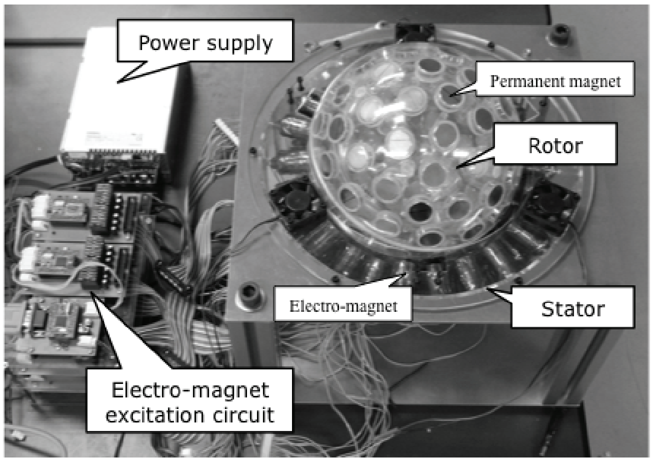


Fig.1. Stirrer driven by a spherical stepping motor

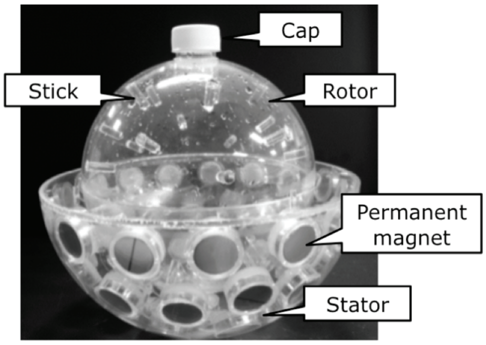


Fig.2. Outer and inner spherical shells

Totally 91 permanent magnets are arranged in almost spherical symmetry on the inner surface of the outer spherical shell. Each permanent magnet is 20 [mm] diameter and 5 [mm] depth and has the magnetic flux of 335 [mT]. The arrangement of permanent magnets are shown in Fig. 3. Thirty-two magnets are placed at the vertices of the polyhedron combining a regular dodecahedron and a regular icosahedron in a dual relation. The north magnetic poles of these magnets face outside. The remaining 60 magnets are placed at the cross-sections of the inner surface of outer rotor sphere and the semi-line connecting from the center of the rotor and the gravity center of the neighboring three vertices of the polyhedron combining with a regular dodecahedron and a regular icosahedron. The south magnetic poles of the magnets face outside. One permanent magnet is missing for the space of the cap of the inner spherical shell.

On the other hand, the electro-magnets are basically arranged on the stator of a semi-spherical shell by the following equation in the coordinate system shown in Fig. 4.

(1) $$x = R\sin\left(\frac{\pi}{12}i + \frac{\pi}{24}\right)$$

(2) $$y = R\sin\left(\frac{\pi}{12}j + \frac{\pi}{24}\right)$$

(3) $$z = -\sqrt{R^2 - (x^2 + y^2)}$$

where R is the inner radius of the stator and

(4) $$-\frac{\pi}{2} \le \frac{\pi}{12}i + \frac{\pi}{24} \le \frac{\pi}{2}$$

(5) $$-\frac{\pi}{2} \le \frac{\pi}{12}j + \frac{\pi}{24} \le \frac{\pi}{2}$$

(6) $$R^2 - (x^2 + y^2) \ge 0$$

An electro-magnet is made by winding a copper wire of 0.315 [mm] thickness around an iron core of 12 [mm] diameter for 1714 turns. The electric resistance of the electro-magnet is 28.6 [Ω].

As shown in Fig. 5, four ball plungers are arranged on the stator to support the rotor with small frictional force and to keep the gap of 0.005 [m] between the rotor and stator. Four electro-magnets are not arranged at the bottom of the stator for placing a ball plunger. The stator has three small fans on the brim of the stator to remove the heat generated in electro-magnets.

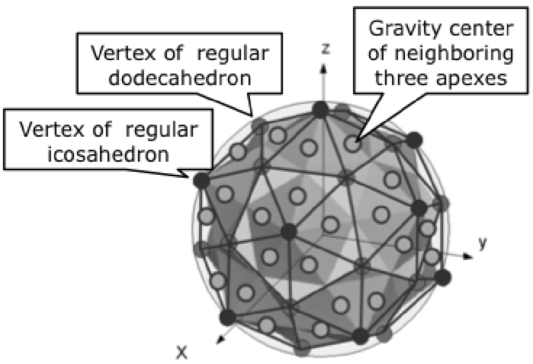


Fig.3. Arrangement of permanent magnets in rotor

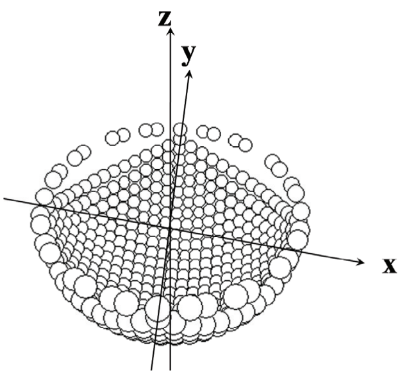


Fig.4. Arrangement of electro-magnets in stator

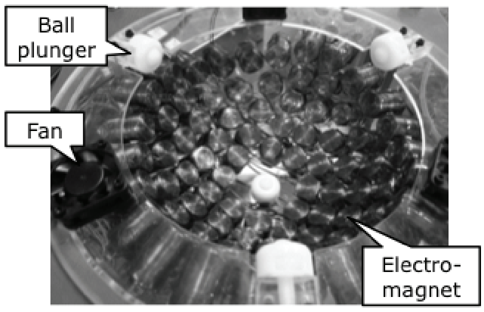


Fig.5. Appearance of stator

Method to Rotate the Stator in Any Direction

The electro-magnets on the stator are excited to be north or south magnetic pole so as to rotate the rotor in a specified rotation velocity (rotation speed and direction). Because the permanent magnets are arranged in almost geometrical symmetry, the posture of the rotor can be represented by the positions of a permanent magnet placed at the vertex of the regular icosahedron and its neighboring permanent magnet placed at the vertex of the regular dodecahedron.

Given the posture and the rotation velocity of the rotor at time t, the posture of the rotor after a short time interval Δt is predicted. Then, the positions of all permanent magnets in the rotor at $t + \Delta t$ are calculated. The electro-magnets of the stator in the area near the predicted positions of permanent magnets in the rotor within a predetermined allowance radius are excited to generate the attractive forces to the permanent magnets as shown in Fig. 6. On the other hand, the electro-magnets outside the area are excited to generate the repulsive forces.

By repeating the specification of rotation velocity, the prediction of rotor posture, the generation of excitation pattern of electro-magnets and the excitation of electro-magunets, the rotor rotates in the specified rotation velocity. The rotation velocity can be changed at any time.

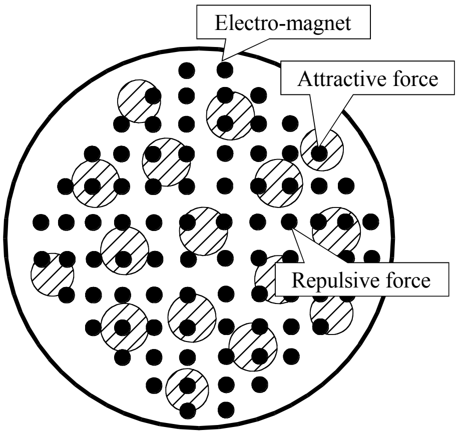


Fig.6. Excitation method of electro-magnets in stator

Rotation Performance of Spherical Stepping Motor

The rotation performance of the stirrer as a spherical stepping motor is first evaluated. Figure 7 shows the set up for evaluation experiments of rotation performance of spherical stepping motor. A string is connected at the top of the rotor. The string hangs a bottle with water through a pulley. Rotation experiments are conducted by changing the mass of water. The maximum mass of water that the rotor rotates at the specified rotation velocity in the direction to lift the bottle for 90 degrees is recorded.

The maximum output torque calculated from the maximum mass of water and the bottle at a specified rotation speed is recorded as an output torque for the rotation speed. The obtained rotation performance is shown in Fig. 8. From the figure, the maximum torque of the spherical stepping motor is about 1.2 [Nm] and the motor can rotate 1 to 9 [rad/sec] depending on the load.

The authors also confirm that the motor rotates under the condition that the rotor is almost full of water. At that time, the mass of water contained in the rotor is 1.5 [kg].

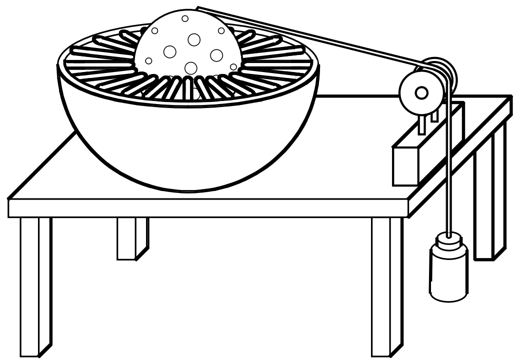


Fig.7. Set up for evaluating rotation performance

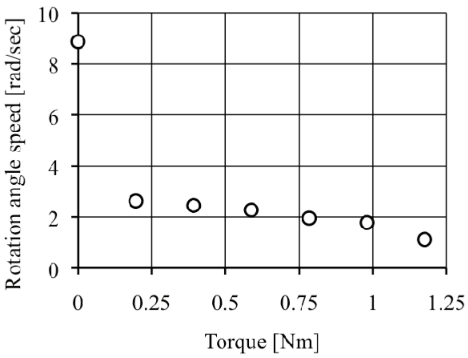


Fig.8. Rotation performance

Evaluation of Stirring Performance

The applicability of the stirrer to material production under the condition of small influence of gravitational force is evaluated by stirring experiments to dissolve the salt of 0.05 [kg] in the water of 0.2 [kg]. The concentration of salt is measured by a salinity refractometer (ATAGO Co., Ltd., MASTER-S28α).

The stirring performance is compared for five stirring methods. In the stirring experiments, the coordinate system is defined as shown in Fig. 4. The rotation methods are

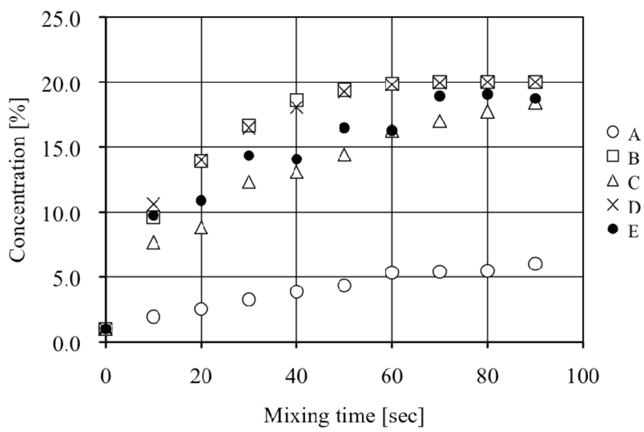
(A) Continuous rotation around z (vertical) axis,
(B) Continuous rotation around x (horizontal) axis,
(C) Rotation in changing the rotation axis between z and x axes in every 5 [sec],
(D) Rotation in changing clockwise and anti-clockwise directions around x axis in every 5 [sec], and
(E) Rotation in changing rotation direction at random in every 5 [sec].

An experiment for a rotation method is composed of ten batches by changing rotation time t from 0 to 90 [sec] as increaseing by 10 [sec]. Three experiments are conducted for each rotation method. A batch is carried out by the following 7 steps.

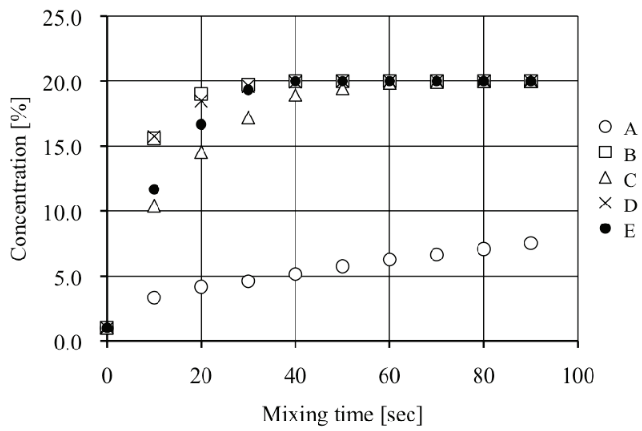
1. Washing throughly the inside of the rotor by water,
2. Putting the water of 0.2 [kg] in the rotor,
3. Putting softly the salt of 0.05 [kg] in the water,
4. Assembling the rotor and setting it on the stirrer in 90 [sec],
5. Rotating the rotor for t [sec] by one of five rotation methods mentioned above,
6. Taking the rotor to pieces within 90 [sec], and
7. Measuring the concentration of salt at 90 [sec] after stopping the rotation.

Figure 9 (a) and (b) show the experimental results in the rotation angle speeds of 2.13 and 5.34 [rad/sec], respectively. The stirring performance at the higher rotation angle speed of 5.34 [rad/sec] is greater than that at the lower rotation angle speed in each rotation method. The continuous rotation around x axis (Method B) gives the highest stirring performance because some fragments of salt move in the water by the gravitational force. On the other hand, the salt seems to rotate slightly at the bottom of the water in the lowest performance case (Method A).

The stirring performance of the method to change the rotation direction at random (Method E) is slightly lower than that of the rotation method B. Because the direction of gravitational force to the salt changes at random by the change of rotation direction, the rotation method E is considered to reduce the influence of the gravitational force. Therefore, the developed stirrer driven by spherical stepping motor can be applied to material production under the condition of small influence of gravitational force.



(a) Rotation speed of 2.13 [rad/sec]



(b) Rotation speed of 5.34 [rad/sec]

Fig.9. Stirring performance

Conclusions

This study applies the spherical stepping motor the authors developed to the driving device of a stirrer and develops a proto-type stirrer. The developed stirrer is composed of a rotor with 91 permanent magnets, a stator with 80 electro-magnets, a control PC, an electric-magnet excitation circuit, and a power supply. The rotor is composed of double spherical shell in order to contain fluid inside the inner spherical shell.

The applicability of the stirrer to material production under the condition of small influence of gravitational force is evaluated by stirring experiments to dissolve salt in water. By comparing the stirring performance of several rotation methods, the rotation method of changing rotation direction at random is confirmed to give high stirring performance.

Future works include to improve the structure and the rotation control method of the stirrer to attain a smooth and mild fluctuation for the application of this type of stirrer to an incubator that does not damage cells.

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