Simulation Analysis of One Degree of Freedom Motion of Electromagnetic Spherical Joint based on Maxwell

Haoran Wang¹, Fucong Liu¹, sai Lou¹

¹Department of Mechanical Engineering, Tianjin University of Technology and Education, Tianjin, China
Email: chonge@bestbond.top

Abstract. In order to improve the stiffness of the spherical joint of the robot, reduce the difficulty of manufacturing and the complexity of the control system, this paper proposed a method of spherical joint and digital drive of the robot based on the electromagnetic principle. Firstly, introduces the structure and motion principle of the spherical joint of the robot, establishes the mathematical model of the spherical joint and establishes the dynamic model according to the second Lagrange equation. After that, the relationship between the number of turns of the electromagnet on the spherical joint, the attitude Angle of the rotor and the force of the rotor was obtained by simulating the single degree of freedom of the joint based on Ansys maxwell and Matlab, which provided a basis for the realization of the digital drive of the spherical joint.

1. Introduction

With the rapid development of robot technology, robots need to realize more freedom of movement. To achieve this goal, continuous innovation and development of robot joints are needed. The common robot joint drive structures are mainly hydraulic drive system, pneumatic drive system and mechanical drive system on the market. Mechanical drives are the most common, including gear drives, such as RV and harmonic reducers, and servomotor drives. These joints usually can only complete the transmission of a single degree of freedom. The multi-DOF motion can only be compounded through multiple single-DOF joints. This structure not only increases the volume of the mechanical system, but also limits the flexibility of the mechanical system and increases the response time of the machine control system. As a new type of robot joint, permanent magnet spherical joint can simultaneously change three degrees of freedom of robot. It has the advantages of small volume, light weight, simple control system and high precision. Permanent magnet spherical joint has a broad application prospect in robot end-effector and other precision instruments, rockets and satellites.

The model of induction spherical motors was first proposed in the literature by scholars such as F.C. Williams in 1958. In 1987 Tech Vacatsevanos was first proposed by spherical motors applied to robotic joints. In 1994, China's first multi-freedom permanent magnet spherical DC motor was designed by Su Xiaofei and Liu Changshuo of Northwest University of Technology. In 2005, Wang Qunjing of Hefei Polytechnic University and other scholars designed a permanent magnetic spherical motor and studied it deeply. In 2008, Li Hongfeng and Xia Changming proposed a permanent magnet motor based on Halbach array.
In this paper, a robot spherical joint based on the electromagnetic principle is designed. The rotor of the joint is rotated and deflected by the electromagnetic force between the electromagnet and the iron block. At the same time, torque analysis of permanent magnet spherical joint, which is the basis of joint motion and realization. It is of great significance to the structural improvement and control optimization of the joint. Finally, the static simulation of the spherical joint is carried out by using Ansys Maxwell electromagnetic simulation software, which provides the basis for realizing the digital drive control of the spherical joint.

2. Permanent magnet spherical joint structure
The spherical joint structure of the robot designed in this paper, as shown in Figure 1, includes two parts: stator and rotor. The main parts of stator and rotor are made of non-magnetic materials. The stator is composed of a half sphere containing 36 electromagnets. The structure reduces the interference between magnets and magnets to external components. The rotor is a spherical structure mounted with 125 iron blocks, which move through the electromagnetic force between the iron blocks and the electromagnet. The outer spherical shell of the spherical joint and the stator spherical shell form a low ball hinge, so that the joint can complete 360° spin motion and plus or minus 20° deflection motion. This structure improves the rigidity of the mechanical structure of the joint, reduces the difficulty of machining, and is conducive to application in engineering practice. The attitude sensors used for precise position and acceleration detection are installed on the supporting arm and the external arm respectively. The rotor Angle, angular velocity and angular acceleration are monitored in real time and the signals are provided to the control system, so that the precise control of the spherical joint can be realized.

![Figure 1. Permanent magnet spherical motor structure diagram.](image)

The principle of robot spherical joint movement is through the electromagnet into the current, its surrounding on the rotor iron block electromagnetic force. Feedback controller by posture sensor data to change the size of the magnet flux into the current, the number and position of electrified electromagnet, thus changing the direction and the size of the rotor stress vector, spin and deflection control joint movement.

3. Dynamics analysis of spherical joint of robot
3.1. Mathematical Modeling of Spherical Joint of Robot
To establish the dynamic model of the spherical joint of the robot. First, the coordinate system XYZ of the stator is determined, which is the static coordinate system. The XOY plane is the horizontal plane, and the direction opposite to gravity is the z-axis direction. The rotor coordinate system DQP is established on the basis of the stator coordinate system. The rotor coordinate system is a moving coordinate system. When the rotor is not rotating, the rotor coordinate system and the stator coordinate system coincide. According to the possible motions of the rotor in the permanent magnet spherical
joint, three generalized Euler angles are defined to describe the motions of the rotor: $\alpha$ about the X-axis of the stator coordinate system, $\beta$ about the Y-axis, and $\gamma$ about the z-axis. Use $C_x$ to represent the matrix rotating Angle $\alpha$, use $C_y$ to represent the matrix rotating Angle $\beta$, use $C_z$ to represent the matrix rotating Angle $\gamma$. Here:

$$
C_x = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos \alpha & \sin \alpha \\
0 & -\sin \alpha & \cos \alpha
\end{bmatrix} \quad C_y = \begin{bmatrix}
\cos \beta & 0 & -\sin \beta \\
0 & 1 & 0 \\
\sin \beta & 0 & \cos \beta
\end{bmatrix} \quad C_z = \begin{bmatrix}
\cos \gamma & \sin \gamma & 0 \\
-\sin \gamma & \cos \gamma & 0 \\
0 & 0 & 1
\end{bmatrix}
$$

(1)

Suppose the rotor completes its motion by first rotating $\alpha$ about the x-axis, then $\beta$ about the y-axis, and finally $\gamma$ about the z-axis. At this time, the coordinate relation before and after rotor rotation is:

$$
\begin{bmatrix}
X \\
Y \\
Z
\end{bmatrix} = C \begin{bmatrix}
X_i \\
Y_i \\
Z_i
\end{bmatrix}
$$

(2)

Here:

$$
C = C_z C_y C_x = \begin{bmatrix}
\cos \beta \cos \gamma & \cos \alpha \sin \gamma + \cos \gamma \sin \beta \sin \alpha & \sin \gamma \sin \alpha - \cos \gamma \sin \beta \cos \alpha \\
-\sin \gamma \cos \beta & \cos \gamma \cos \alpha - \sin \gamma \sin \beta \sin \alpha & \cos \gamma \sin \alpha + \sin \gamma \sin \beta \cos \alpha \\
\sin \beta & -\sin \alpha \cos \beta & \cos \beta \cos \alpha
\end{bmatrix}
$$

After three coordinate rotation transformations, the rotor’s moving coordinate system DQP is obtained. The pre- and post-rotation coordinate system is shown in Figure 2.

**Figure 2.** coordinate transformation diagram of stator and rotor.

### 3.2. Dynamics Modeling of Spherical Joint of Robot

In the coordinate transformation of the spherical joint of the robot, the generalized Euler angles of rotation of the rotor coordinate system are $\alpha$, $\beta$ and $\gamma$. Take the first derivative. The angular velocities of the rotor in each axis of the moving coordinate system DQP are obtained. The components of the rotor angular velocity $\omega$. The angular velocity of the rotor is expressed as:

$$
\omega = \dot{\alpha} + \dot{\beta} + \dot{\gamma}
$$

(3)
The components of the angular velocity of the joint rotor on each axis can be expressed as \( \omega_x \), \( \omega_y \), \( \omega_z \). And if we convert this to a static coordinate system we can express it as:

\[
\begin{pmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{pmatrix}
= C \begin{pmatrix}
\alpha \\
\beta \\
\gamma
\end{pmatrix}
\]

Expand it to obtain the transformation relation of angular velocity:

\[
\begin{align*}
\omega_x &= \alpha \cos \beta \cos \gamma + \beta \sin \gamma \\
\omega_y &= -\alpha \cos \beta \sin \beta + \beta \cos \gamma \\
\omega_z &= \alpha \sin \beta + \gamma
\end{align*}
\]

To obtain the dynamics model of permanent magnet spherical motor, Lagrange's second equation was used to derive:

\[
\frac{d}{dt} \left[ \frac{\partial E}{\partial q_i} \right] - \frac{\partial E}{\partial \dot{q}_i} = Q_i \quad (i = 1, 2, 3 \ldots k)
\]

Where \( E \) is the kinetic energy of the particle, \( q_i \) is the generalized coordinate, \( q_1 = \alpha \), \( q_2 = \beta \), \( q_3 = \gamma \). \( Q \) is generalized moment. \( Q_1 \), \( Q_2 \) is rotor load torque and \( Q_3 \) is frictional torque.

The kinetic energy of the rotor may be expressed as:

\[
E = \frac{1}{2} I \dot{\omega} \cdot \dot{\omega} + \frac{1}{2} J \omega \cdot \omega
\]

where \( I \) is the moment of inertia of the rotor.

Transform (8) into matrix form to obtain the dynamic equation:

\[
H(q) \ddot{q} + C(q, \dot{q}) \dot{q} = \tau
\]
Whereis $C(q, \dot{q})$ the Coriolis matrix, where each element is:

$$C(q, \dot{q}) = \begin{bmatrix}
(J_p - J_n) \dot{\beta} \sin \beta \cos \beta & (J_p - J_n) \dot{\alpha} \sin \beta \cos \beta + \frac{1}{2} J_p \dot{\beta} \cos \beta & \frac{1}{2} J_p \dot{\beta} \cos \beta \\
(J_p - J_n) \dot{\alpha} \sin \beta \cos \beta - \frac{1}{2} \dot{\gamma} \cos \beta & 0 & -\frac{1}{2} J_p \dot{\alpha} \cos \beta \\
\frac{1}{2} J_p \dot{\beta} \cos \beta & \frac{1}{2} J_p \dot{\alpha} \cos \beta & 0
\end{bmatrix}$$

4. Simulation analysis of spherical joint of robot

As the 3D electromagnetic design and analysis software, Ansys Maxwell has the advantages of simple and convenient interface operation, high analysis accuracy. It has adaptive subdivision technology and fast and accurate post-processing ability. It can analyze and automatically calculate the overall characteristics of power loss, impedance, force and torque of electric motor, magnet, coil and other electromagnetic components. At the same time, the B-H distribution, magnetic field lines and energy density of the analyzed components are obtained.

In this paper, the tangential forces of the rotor on the spherical joint of a robot are simulated by means of the Ansys Maxwell 3D. The feature points of the equatorial part of the spherical joint were selected for analysis, as shown in Figure 3. Adjust the attitude of the iron block on the rotor in Maxwell. Change the current flowing into the electromagnet. The force conditions of the electromagnet in different energized conditions and the iron block in different postures are obtained.

![Figure 3. Selection of feature points.](image)

According to the simulation results obtained by Maxwell and imported into Matlab for fitting, the linear relation diagram of rotor attitude angle-rotor force is obtained, as shown in Figure 4.
Figure 4. Rotor attitude - rotor force diagram

Figure 5. Relationship diagram of ampere-turns - rotor attitude Angle - rotor force.

The data obtained from the simulation was imported into Matlab for fitting. The relation diagram of electromagnet ampere turns - rotor attitude Angle - rotor force is obtained, as shown in Figure 5.

According to the relationship between the number of ampere-turns of the electromagnet, the attitude Angle of the rotor and the force of the rotor, the torque equation of the joint is combined. The current of the electromagnet required to force the rotor in each posture is obtained when the rotor moves in a single degree of freedom. The digital drive control between the electromagnet current into the spherical joint and the rotor motion attitude is realized.

5. Summary

This paper proposed a spherical joint of robot based on electromagnetic principle which adopts low pair ball hinge to realize joint motion transmission. It solves the problem of small rigidity and difficult processing and the problem of interference between magnets and external components replacing the stator coil with an electromagnet. The relationship between the number of ampere-turns of the electromagnet on the spherical joint, the attitude angle of the rotor and the force of the rotor was obtained based on the static analysis of rotor single degree of freedom movement by using Ansys maxwell and Matlab, which provided a basis for the realization of the digital drive of the spherical joint.

References

[1] F C Williams, E R Laithwaite, J F Eastham. Development and design of spherical induction motors, in Proceedings of the IEEE—Part A: Power Engineering, 1959, pp. 471–484.

[2] G Vachtsevanos, K Davey, K M Lee. Development of a novel intelligent robotic manipulator. IEEE Control Syst. 1987, Vol. 7, pp. 9–15.

[3] K Davey, G Vachtsevanos, R Powers. The analysis of fields and torques in spherical induction motors. IEEE Trans. 1987, Vol. 23, pp. 273–282.

[4] SU Zhongfei, LIU Changxu, WEI Pingshun, et al. Three-DOF Spherical DC Servo Motor for Robot Joint [J]. High Technology Communications, 1994(08): 16-18.

[5] Wang Qunjing, Li Zheng, Xia Kun, et al. Calculation and Analysis of Structural Parameters and Torque Characteristics of a New Type of Permanent Magnet Spherical Stepper Motor [J]. Proceedings of the Csee, 2006(10): 158-165.

[6] Wang Qunjing, Yong Aixia, Chen Lixia, et al. A Method for rotor position detection of permanent magnet spherical stepper motor [J]. Proceedings of the Csee, 2006(22): 92-96.
[7] Wang Qunjing, Xia Kun, Li Zheng. Stable position calculation of permanent magnet multidimensional spherical stepper motor [J]. *Journal of Hefei University of Technology (Natural Science Edition)*, 2006(12):1592-1596.

[8] Xia Changliang, Li Hongfeng, Song Peng, et al. Magnetic field of permanent magnet spherical motor based on halbach array [J]. *Transactions of China Electrotechnical Society*, 2007(07):126-130.

[9] Li Hongfeng, Xia Changliang, Song Peng. Three-dimensional finite element analysis of torque of halbach array permanent magnet spherical motor [J]. *Journal of Tianjin University*, 2009, 42(11):952-958.

[10] Qiao Yuanzhong. Inductance modeling and magnetic field analysis of resistive spherical motor [D]. *Anhui University*, 2020.