Development of Electric Machine for Robot Eyes by Using Analytical Electromagnetic Field Computation Method

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***Abstract*—This paper proposes an electromagnetic field computation method by using the interpolation method with the sigmoid functions. This method is useful for approximating and developing of a 3 dimensional electromagnetic field model, because computation time can be reduced. Especially, we are developing an electric machine named spherical motor for operating robot eyes. Because the spherical motor has complicated coil structure, the electromagnetic field computation by using interpolation method is very convenient tool in order to predict torque characteristic. Finally we evaluate accuracy of the method with experimentation results of motor performance.**

***Index Terms*—Computational electromagnetic, Interpolation, Approximation methods, Electric machines, Humanoid robots.**

I. Introduction

When robots look at things, they usually move their head or operate their eyes, like human. The direct driving system of robot eyes is required characteristics of low energy consumption for the battery power system, small size appropriate space and precise movement for tracking objects. In this paper, motor system of robot eyes is introduced which is named spherical motor. The spherical motor has operating range from 0 degree up to 36 degrees as 2 degree-of-freedom and from -180 degrees to 180 degrees as 1 degree-of-freedom. Therefore, as shown Fig. 1, robot eye can be controlled by using one spherical motor.[1]-[3]

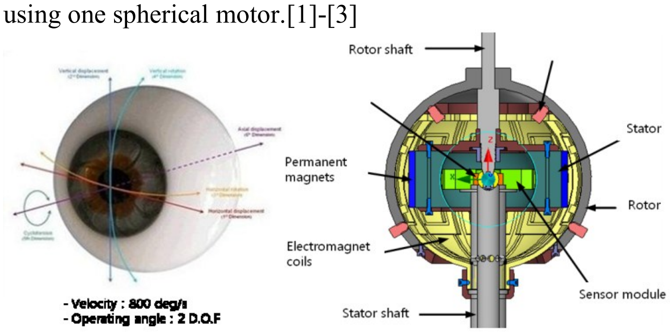

Fig. 1. Robot eyes and spherical motor

II. Operating Mechanism And Torque Computation

A. Operating Mechanism

The coil structure of spherical motor has different shape unlike conventional cylindrical motor`s winding coils. Because the rotor of spherical motor has to be able to move up and down, the coil structure consists of several coil segments which are separated up and down on a stator surface. The electromagnet coil structure is shown in Fig. 2.

The controllable electromagnetic fields are produced by flowing currents in coils. Then attractive or repulsive force is generated between the fields and surrounding permanent magnet on the rotor surface. Therefore the rotor is able to be moved by combining electromagnetic forces. The characteristic of rotor movement is affected by shape of coils. In this paper, we research into two shapes of coils as cylindrical and rectangular type.

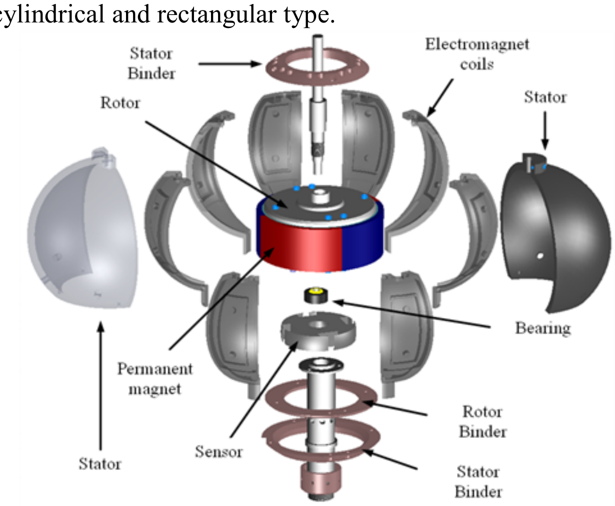

Fig. 2. Exploded view of multi-degree of freedom spherical motor

B. Torque Formulation & Interpolation

We consider a design where the rotor poles of the spherical motor are permanent magnets and the stator poles are coils wound on non-ferromagnetic cores as cylindrical or rectangular shape in order to reduce cogging torque like Fig. 3. The torque acting on the rotor can be approximated as a linear combination of stator currents and distance between coil and permanent magnet. In order to compute rotating torque, orientation vectors in spherical coordinates with angles are defined in Fig. 4. The subscripts “s” and “r” denote the stator and rotor respectively. The subscript “R” denotes radius of coils and magnets. Position angles are denoted the subscripts “α”, “β” and “δ”.

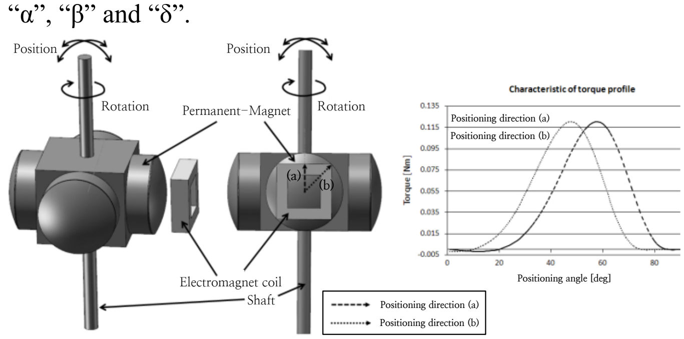

Fig. 3. Torque profile of rectangular shape of electromagnet coils

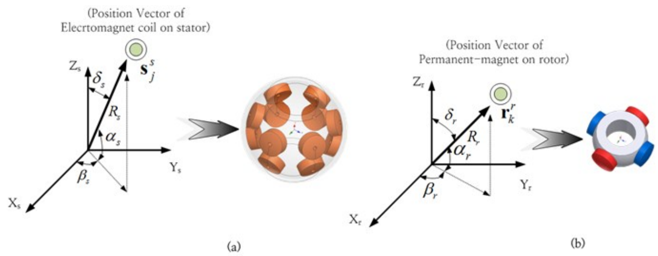

Fig. 4. Coordinates of stator and rotor of the spherical motor

The torque is a result of the interaction between the stator poles and rotor poles. Therefore the torque is able to be computed by using distance and angle between stator pole and rotor pole.[4]-[6] We use the Z-Y-Z Euler angles for transforming the coordinates system.[7].

The magnetization axis of the permanent magnets is defined mathematically by the position vector : s_j^s. Similarly, the magnetization axis of the electromagnet coils is defined mathematically by the position vector : r_k^s. Because the torque T_{jk} is a result of interaction between permanent magnet and electromagnet coil, the equation is defined by (1).

$$T_{jk} = \begin{cases} 0 & \text{if } \left|s_j^s \times r_k^s\right| = 0 \\ u_{rk} u_{sj} \hat{f}\left(\varphi_{jk}\right) \frac{\left(s_j^s \times r_k^s\right)}{\left|s_j^s \times r_k^s\right|} & \text{if } \left|s_j^s \times r_k^s\right| > 0 \end{cases} \quad (1)$$

$\hat{f}\left(\varphi_{jk}\right)$ is torque characteristic function decided by distance and angle between stator poles and rotor poles. Therefore the torque T_{jk} can be calculated by $\hat{f}\left(\varphi_{jk}\right)$ which is approximated. We use two types of interpolation function as exponential and sigmoid function like (2), (3) respectively.

$$\hat{f}_E\left(\varphi_{jk}\right) = \sum_{n=1}^{n_{ef}} \alpha_n \exp\left(-\lambda_n \varphi_{jk}^2\right) \quad (2)$$

$$\hat{f}_S\left(\varphi_{jk}\right) = \frac{k_1}{1 + c_1 e^{-b_1 \varphi_{jk}}} + \frac{k_2}{1 + c_2 e^{b_2\left(\varphi_{jk} - \pi/2\right)}} + k_3 \quad (3)$$

The subscript "n" denotes number of interpolation function. And φ_{jk} is angle between stator pole and rotor pole defined the stator coordinates. The method using the sigmoid functions can be interpolated more delicately, although it needs fewer numbers of functions than exponential interpolation method.

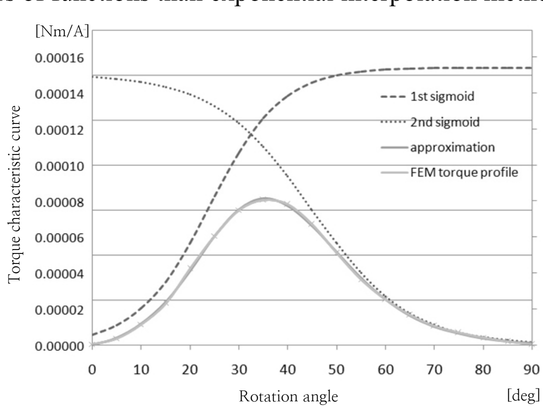

Fig. 5. Torque characteristic interpolation by using sigmoid function

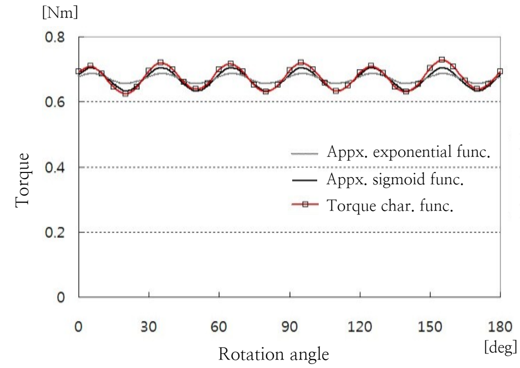

Fig. 6. Approximation error comparison : torque computation

III. Experimentation & Results

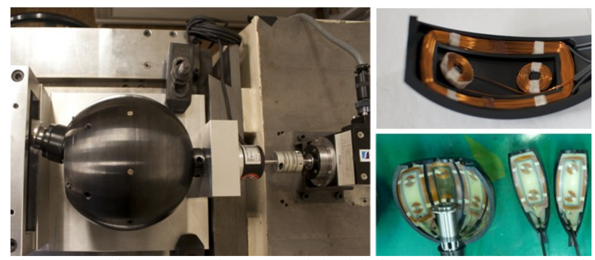
Fig. 7. Non-ferromagnetic core and double layer electromagnet coils

The spherical motor is design by using this sigmoid interpolation method for calculating torque. Finally we made prototype of spherical motor using double coil winding and experimented like Fig. 7.

IV. Conclusion

In order to design of complicated structure electric machines, it needs a 3 dimensional electromagnetic field computation by using the finite element method normally. However it spends much time for calculating the electromagnetic torque and force. Therefore the interpolation method by using sigmoid functions is useful for reducing electromagnetic field computation time. The spherical motor for robot eyes will be improved with newly coil structure which is designed by using this method.

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