Three-dimensional Quasi-transient Simulation for Electromagnetic Field by Using Current Vector Calculation and Coil Mesh Generation

Dong-Woo Kang, Sung-Chul Go, Sung-Hong Won, Hyung-Woo Lee,
Jae-Hyuck Kim, and Ju Lee
Hanyang University
Sung-dong Gu, Seoul, 133-791, Republic of Korea
dwkang1222@gmail.com

Abstract — As opposed to conventional cylindrical motors, a spherical motor discussed in this paper generates three-degree-of- freedom (3-DOF) movement in a single drive unit. This 3-DOF movement is due to the spherical shape of the rotor moving like a ball joint. In this regard, the analysis of the electromagnetic field generated by the 3-DOF movement of the motor requires three-dimensional finite element method (FEM). However, three dimensional FEM takes significant amount of computation time leading high computational burden to computer processors. Therefore, this paper discusses a three- dimensional quasi-transient computation method for the spherical motor using current vector and coil mesh, which saves significant computation time.

I. INTRODUCTION

Fig. 1 shows a spherical motor which generates 3-DOF movement along with three axes (x: Pitch, y: Roll, z: Yaw). This motor is desirable for a robot joint or a security camera. In a conventional robot joint system, several motors are required to generate humanlike motion leading the system bulky and heavy. However, it is feasible to implement a joint system using a single 3-DOF spherical motor. In this regard, a spherical motor lends itself to a multi-coordinate motion system with the advantages in terms of the size, weight, and hence cost savings compared to a conventional multi-motor-based joint system [1]-[2].

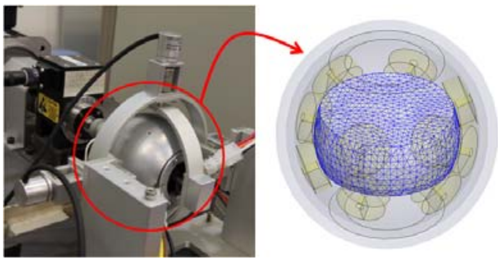

Fig. 1. The spherical motor and simulation model

Due to its inherent spherical shape, the transient electromagnetic field of the spherical motor is calculated using the three-dimensional FEM. However, the three-dimensional FEM takes significant computation time. In order to reduce the computation time, a three-dimensional quasi-transient simulation method based on torque vector is often used for calculation of the electromagnetic field of the spherical motor [3]-[4]. This method computes the electromagnetic field using normalized torque vectors which are generated between the current of a coil and the magnetic field of a permanent-magnet at each defined relative position and twist angle [5].

However, this torque vector-based quasi-transient method is effective only for the spherical motors with round-shaped coils as the motor can generate the same torque vectors in any direction between the coil and the magnet and hence there is no need for multiple calculations to obtain the torque vector in each direction [5]. Fig. 2 shows a novel spherical motor employed in this paper. This motor has doubly rectangular- shaped coils for improved 3-DOF motion control capability. Unfortunately the torque vector-based method is not feasible for this motor because the torque vectors are no longer the same in each direction between the coils and magnets. Thus, to calculate the three-dimensional electromagnetic field of the employed spherical motor, a quasi-transient computation method based on current vector instead of the torque vector along with the coil mesh is discussed in this paper.

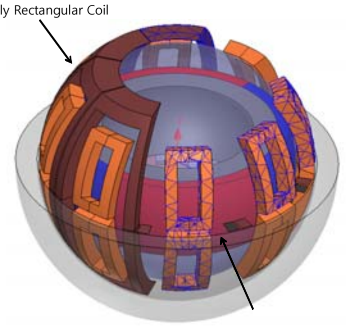

Fig. 2. Spherical motor for improved 3_DOF motion controllability

II. THREE-DIMENSIONAL FIELD COMPUTATION

For computation of a linear or cylindrical motor, the method based on the current vector and the coil mesh in Cartesian or cylindrical coordinate system is utilized. In this paper, the current vector in spherical coordinates is employed for quasi-transient computation.

The spherical motor stator has no salient pole and the forces on the rotor surfaces can be calculated by Lorentz Force Law in coil elements of the stator:

$$f_e = \Delta_e J_e \times B_e \tag{1}$$

$$T_j = R_j \times F_j = R_j \times \sum f_e = \Delta_e R_j \times \sum J_e \times B_e \tag{2}$$

where f_e is Lorentz force on an element of a coil, T_j is torque on j-th coil, R_j is distance between stator center and j-th coil , f_j is Lorentz force on j-th coil, J_e is current density on an element of coil, and B_e is magnetic flux density on element of coil, respectively.

The Fig. 3 shows the meshed coil elements used for calculating the forces. We only need these meshed coil elements and the flux density field data in the area where the coils are placed. The flux density field data by the rotor permanent magnet can be obtained from just one execution of static three-dimensional FEM [6]-[7].

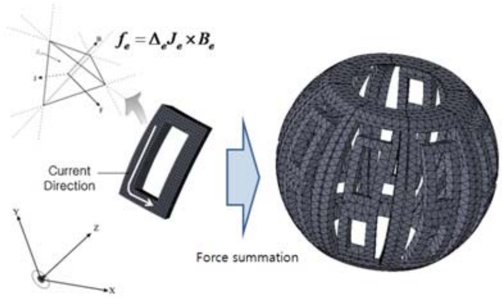

Fig. 3. The current vector and the coil mesh

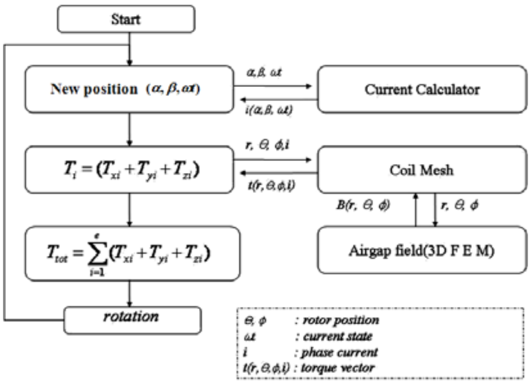

Fig. 4. Transient analysis of the spherical motor

A block diagram of the three-dimensional quasi-transient electromagnetic field computation process is shown in Fig. 4. Therefore the coil model is divided by the tetrahedral element for applying to any coil shape. Total force can be calculated from summed force vector which is multiplied by volume of coil. The current density vector's direction changes according to changes in the coil shape. When the approximated two-dimensional simulation is used, the most important factor is how the coil shape is considered. In this paper, the winding coil mesh is made as its own shape and every element of the mesh has the unit vector of the current following the direction which is used for calculating the Lorentz force vector and back-EMF vector. Even though the motor has several winding coils, just one coil mesh enough because the same coil mesh can be used for another phase coil by rotating the coil mesh.

III. SIMULATION AND RESULTS

The Fig. 5 shows simulation results the proposed current vector-based quasi-transient method for field computation of the spherical motor. From the calculated electromagnetic field, the electromagnetic torque obtained by three-dimensional FEM, the current-vector-based quasi-transient method, and the torque vector-based quasi-transient method are compared. It can be seen that the torque profile of the proposed current vector-based method is quite similar to that of FEM method while the torque vector-based method accuracy of the torque vector method depends on precision of an interpolated torque vector. Therefore the current vector and coil mesh method is much more accurate than the torque vector method.

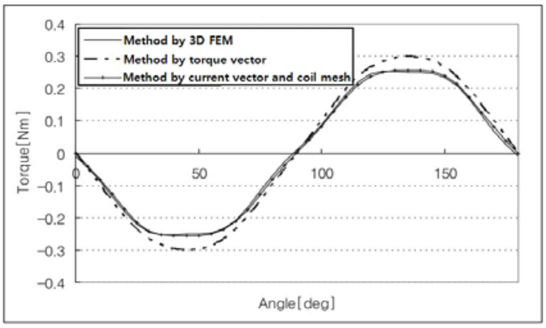

Fig. 5.Comparison of electromagnetic electromagnetic torque computation results

IV. CONCLUSION

This paper presents a three-dimensional quasi-transient simulation method based on the current vector and coil mesh for a spherical motor with non-round shaped coils. With the proposed current-vector-based method, the electromagnetic torque can be obtained without the complete three-dimensional FEM simulation. Computation results on electromagnetic torque using both torque and current vectors are compared with the torque obtained from a complete three-dimensional FEM simulation. Additional simulation results and analytic data will be provided in the final submission.

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