Electromagnetic and Structural Coupling Analysis of Hybrid Driven PM Multi-DOF Motor

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This paper focuses on a novel fluid damping based hybrid drive multi-degrees-of-freedom permanent magnet motor. The electromagnetic structural coupling model of the motor coils is established using the electromagnetic and structural analysis tools. The electromagnetic field finite element analysis is performed by FEM, and the magnetic force distribution of coils is obtained which can be imported into static-structural module as a load for the coupling analysis. The structural equivalent stress and the total deformation distribution are obtained. These results show that the dynamic behaviors of a structure with and without a magnetic field are different. The results provide the theoretical and data support for optimization design and control system design of this kind of motors.

Index Terms—**permanent magnet motor, multi-DOF, hybrid driven, electromagnetic structural coupling**

I. INTRODUCTION

In recent years, with the increasing demand for bionic drive and mechatronics, the spacial movement generated by single unit such as multi-DOF motors has attracted more and more attention [1-3]. Most of this kind of motors or actuators usually suffered great stress in the drive force exertion parts when working at rated operation [4, 5]. The stress may cause insulation damage and conducting bar fatigue fracture. When the windings appears in abnormal states such as short circuit, the stress may be 30 times more than that of rated condition, which can cause damage and out of operation. Therefore, it is necessary to carry out the electromagnetic and structure coupling analysis of the motor, and verify the structure of the stator and rotor. Some researchers have carried out the coupling field calculation of the windings of induction motors and turbine generators [6]. While, it is seldom to consider this aspect in multi-DOF motors.

Based on the principle of fluid damping based hybrid drive multi-DOF PM motor, the research background is introduced at first; then the electromagnetic and structural coupling analysis methodology is discussed; finally, the coupling analysis is carried out to derive the results which makes a primary investigation on the design and implementation.

II. MOTOR STRUCTURE AND WORKING PRINCIPLE

The multi-DOF hybrid drive motor mainly includes the rotor, stator coil, damping fluid and rotor shell. The rotor is hollow, whose inner surface is inlaid with permanent magnets. The permanent magnet of the vertical position can complete a large-scale movement, and the permanent magnet positioned at the end can realize an accurate fine tuning. The periphery of the rotor is surrounded by cylindrical stator coil. The gap between the stator and rotor is sealed with liquid to adjust the damping of the rotor movement, which plays an important function in friction loss reducing and positioning accuracy. According to the structure which is mentioned above, the assumption of a modeling process can be shown as following: 1) ignore the magnetic circuit saturation; 2) during the analysis of magnetic field, ignore the eddy current effects caused by magnetic field changes; 3) the magnetic field created by the energized coils only has effects on the rotor magnetic poles which is nearby the coils. The magnetic field has less effects on rotor magnetic poles which is not adjacent to the coils so that the magnetic field can be ignored; 4) the magnetic material is isotropic medium. The structure of the motor is shown in Fig. 1, detailed parameters are listed in Table I.
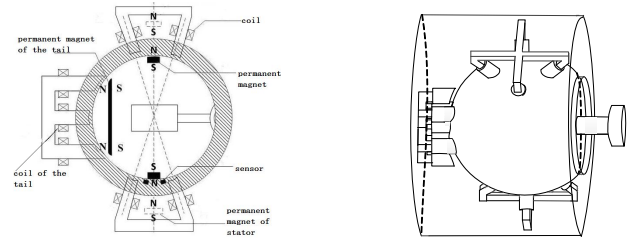

Fig. 1 Schematic diagram of motor structure

TABLE I
MOTOR STRUCTURE PARAMETERS

Name	Value(mm)
Outer diameter of stator spherical shell	60
Inner diameter of stator spherical shell	58.8
Large scale control of permanent magnet outside diameter	55.3
Large scale control of permanent magnet Inner diameter	48.8
Oil film thickness	3
Spherical shell thickness	2
Large range moving core height	30
Stator permanent magnet thickness	6

III. PRINCIPLE OF THE ELECTROMAGNETIC AND STRUCTURAL COUPLING

According to the classical mechanics, the general equation of dynamics of the object is:

$$[M]\{x''\} + [C]\{x'\} + [K]\{x\} = \{F(t)\} \tag{1}$$

where $[M]$ is mass matrix; $[C]$ is damping matrix; $[K]$ is stiffness matrix; $\{x''\}$ is acceleration vector; $\{x'\}$ is velocity vector; $\{x\}$ is displacement vector; $\{F(t)\}$ is static load.

However, in the current structural analysis, the quantity depends on time will be ignored, so the above formula can be simplified as:

$$[K]\{x\} = \{F\} \tag{2}$$

The equation of the magnetic field of the end winding is shown as follows:

$$\begin{cases} \nabla^2 A = -\mu_0 J \\ B = \nabla \times A \end{cases} \tag{3}$$

where is $A(A_x, A_y, A_z)$ is magnetic vector; $J(J_x, J_y, J_z)$ is current density vector; $B(B_x, B_y, B_z)$ is magnetic induction vector; ∇^2 is laplasse differential operator; ∇ is Hamilton operator. After solved by the method of separation variable, considering inner and outer windings, the expression of magnetic induction intensity is:

$$\begin{cases} B_x^k(x,y,z,t) = G_1^k(x,y,z)\sin wt + G_2^k(x,y,z)\cos wt \\ B_y^k(x,y,z,t) = G_3^k(x,y,z)\sin wt + G_4^k(x,y,z)\cos wt \\ B_z^k(x,y,z,t) = G_5^k(x,y,z)\sin wt + G_6^k(x,y,z)\cos wt \end{cases} \tag{4}$$

where G_i^k is the expression of coordinate function and current density, i=1,2,…6.

IV. COUPLING ANALYSIS AND SIMULATION

The corresponding material properties of the model are given according to the actual material of the motor. The winding material is aluminum, the resistivity is $3.8 \times 10^{-7} \Omega \cdot m$, the resistivity is set with infinite. Take the rear coils as an example, the coils are excited with a loop current of 200 Ampere turns. The magnetic field distribution and magnetic field vector can be obtained, which is shown as Fig. 2. As can be seen from the figure, the maximum value of magnetic induction intensity is distributed in the coil center, and the farther the distance from coils is, the smaller values of the magnetic induction intensity are derived.
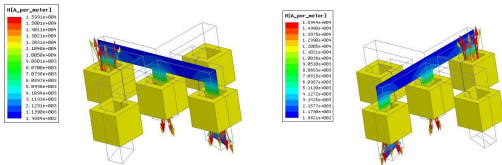

Fig. 2 Magnetic field distribution of XZ and YZ plane

After finishing the magnetostatic analysis, the model is imported into static-structural module, where the force analysis of the winding is obtained. In this step, the electromagnetic force generated in electromagnetic field is selected as a load, which is imported into the structure field to complete the stress coupled calculation, then applying the fixed boundary condition to solve the structure field based on the facts.

The force density image is shown in the Fig. 3, which is mainly around the windings. The total deformation is shown in Fig. 4, as can be seen, the maximum deformation is located at the corner of the support structure which is above the windings. Fig. 5 shows the equivalent stress of the coils. As is shown in the figure, the maximum stress is located at the end of the support structure.
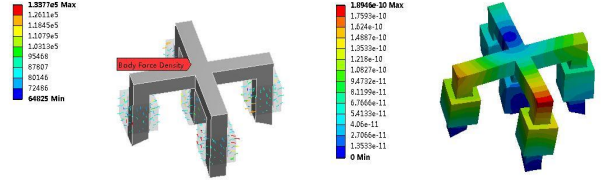

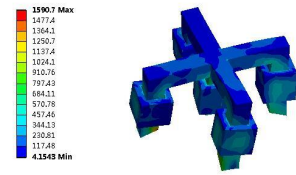Fig. 3 Force density distribution   Fig. 4 Total deformation distribution

Fig. 5 Equivalent stress distribution

V. CONCLUSION

A new type of hybrid driven permanent magnet multi-DOF motot with liquid suspension mode is presented in this paper. The analytical method and the finite element method are used to analyze the air gap magnetic field. The analysis of electromagnetic structural coupling field based on the structure of windings can effectively analyze the actual operation and design problem, and the calculation results have certain guiding significance to the optimization design of this kind of motors or actuators.

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