Study of Magnetic Levitation Spherical Motor Control System

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Abstract

The rotation and suspension of magnetic levitation joint rotor depends on the magnetic levitation force and electromagnetic torque produced after the joint is powered on. This paper presents an idea of differential control strategy. There is only a set of winding in upper or lower stator, and the magnetic levitation force and electromagnetic torque could be controlled by the magnitudes and phases regulating of the winding currents, then which make the motor operate stably. With MATLAB/Simunik software, the simulation of control system is made, and the results are analyzed.

Keywords: differential drive, spherical motor, magnetic levitation, control system, simulation analysis.

1. Introduction

Magnetic levitation spherical motor ^[1,2] is an integrated complex systems, which combines spherical motor^[3] and magnetic levitation technology^[4,5] in a device, and gets the advantages such as compact structure, small volume, convenient control and etc al. There is only a set of control winding adopted on the upper or lower stator, which control the motor torque and levitation force through the real-time adjustment of the current phase and size in the set of winding on the stator, then the bearingless motion of spherical motor is realized.

2. Control Strategy of Magnetic Levitation Spherical Motor

The control of magnetic levitation spherical motor is a core technology which related to the stable suspension and rotation of spherical motor. Because the spherical motor has the same structure of winding as a common motor, the rotation of spherical motor can use the control system as the

traditional motor controlling, and the suspension control problems need to be solved in the new design^[6,7]. a structure of control and drive system along a coordinate direction is presented, as shown in Figure 1.

Fig. 1 the structure of control and drive system

This system uses 2 independent power supply inverters to respectively supply the windings of 2 stators. The control system of inverter is based on a general motor control system, which adds a suspension control loop.

Fig. 2 the control block diagram of the magnetic levitation spherical motor

The function of levitation controller is to control the radial displacement of the spherical rotor in a coordinate direction (such as Y axis), and to achieve the stable suspension in this direction. Figure 2 shows the control block diagram of the magnetic levitation spherical motor. A pair of displacement sensors (such as eddy current sensor) is used to measure the radial displacement of the spherical rotor in their coordinate detection, and convert the

displacement to the differential voltage signal. Then it would be compared with the reference input signal. Finally the error voltage signal of spherical rotor in this coordinate detection is gotten. When the error signal is greater than zero, the spherical rotor has moved up from the balance position along the Y direction. So the levitation controller would adjust the suspension performance according to these error signals. Then the voltage (or current) signal of the control inverter on the stator, which is in the Y direction of spherical rotor moving to, would be reduced, and the three-phase current through the inverter into the corresponding equivalent windings on the stator would be decreased synchronously with the same rate. And the voltage (or current) of the control inverter on the stator, which is in the Y direction of spherical rotor leaving, would be creased, and the three-phase current through the inverter into the corresponding equivalent windings on the stator would be creased synchronously with the same rate. These cause that the current reduction of a stator winding in a coordinate direction is equal to the increase value of another stator winding in this coordinate direction. The differential regulation of these two stator windings would produce a synthesis magnetic pulling force to make spherical rotor return to equilibrium position. At the same time, the current value increase of the two stator windings in the direction is equal to the reduced one, so the electromagnetic total torque, which drives the rotation of rotor around the axis, is invariant. Therefore the levitation control has very little effects on rotation control.

3. The Mathematical Model of Magnetic Levitation Spherical Motor

3.1 Electromagnetic Torque and Magnetic Levitation Force Model of Magnetic Levitation Spherical Motor

Fig. 3 the schematic diagram of a single degree of freedom magnetic suspension motor

The principle structure of a single freedom degree magnetic levitation motor is shown in Figure 3. If the stably suspended rotor has a displacement in the Y direction under the uncertain interference, which is y . In order to bring the rotor back to the original equilibrium position, the controller would reduce the current i_1 of the stator winding, which is near to the reduced gap (the gap is $e_{y1} = g_0 - y \cos \phi_0$), and increase the current i_2 of the stator winding, which is near to the increased gap (the gap is $e_{y2} = g_0 + y \cos \phi_0$).

The magnetic levitation force produced by the magnetic levitation spherical motor in the Y direction of the axis is:

$$F_y = F_{y1} - F_{y2} = \frac{i_1^2 K_f(\psi)}{2(g_0 - y \cos \phi_0)^2} - \frac{i_2^2 K_f(\psi)}{2(g_0 + y \cos \phi_0)^2} \quad (1)$$

Where F_{y1} and F_{y2} are the electromagnetic levitation force respectively on the decreased gap side and increased gap side. i_1 and i_2 are the winding current respectively on the decreased gap side and increased gap side. $K_f(\psi) = \frac{1}{2} \times N^2$

$R^2 \pi \cos \phi_0 \sum_{k=0}^{m-1} \left| f\left(\psi - \frac{2k\pi}{m}\right) \right|$, ψ is the phase difference between the rotor and the stator while the rotor turns around the coordinate axis. N is the winding turns. R is the radius of the spherical rotor. m is the phases numbers of multiphase winding, which drive the rotor. g_0 is the gap between the rotor and the stator while they are concentric. ϕ_0 is the angle between the normal position and the Y axis.

The synthetic electromagnetic torque of the magnetic levitation spherical motor around the Y axis is:

$$M_y = M_{y1} + M_{y2} = \frac{i_1^2 K_m(\psi)}{2(g_0 - y \cos \phi_0)^2} + \frac{i_2^2 K_m(\psi)}{2(g_0 + y \cos \phi_0)^2} \quad (2)$$

Where M_{y1} and M_{y2} are the electromagnetic torque respectively on the decreased gap side and increased gap side.

$K_m(\psi) = N^2 R^2 K \pi \sum_{k=0}^{m-1} \left| \int_{\phi_1}^{\phi_2} \sin \phi \sin 2(\phi + \psi - \frac{2k\pi}{m}) d\phi \right|$, ϕ is the range of the corresponding central angle on the width correspondence of the stator pole envelope spherical ring. K is the constant of magnetic permeance.

3.2 Rotor Motion Model for Magnetic Levitation Spherical Motor

According to newton's second law, the equations of motion and rotation of a spherical rotor along the y axis are obtained.

$$\begin{cases} M \cdot \frac{d^2 y}{dt^2} = \frac{i_1^2 K_f(\psi)}{2(g_0 - y \cos \varphi_0)^2} - \frac{i_2^2 K_f(\psi)}{2(g_0 + y \cos \varphi_0)^2} + F_d \\ J \cdot \frac{d^2 \psi}{dt^2} = \frac{i_1^2 K_m(\psi)}{2(g_0 - y \cos \varphi_0)^2} + \frac{i_2^2 K_m(\psi)}{2(g_0 + y \cos \varphi_0)^2} + M_d \end{cases} \dots (3)$$

Where: J , M are respectively the rotary inertia and mass of the spherical rotor. M_d and F_d were respectively the torque and disturbing force imposing on the spherical rotor except the electromagnetic levitation force (torque).

3.3 The Voltage Model of Magnetic Levitation Spherical Motor

The instantaneous inductance of the windings can be obtained from the air gap magnetic energy.

$$L(e, \psi) = \frac{N^2 R^2 \pi}{2e} \sum_{k=0}^{m-1} \left| K(\psi - \frac{2k\pi}{m}) \right| \quad (4)$$

Where e is the radial gap between the stator and the salient pole magnetic surface on rotor, which is related to the radial displacement of the rotor: $K(\psi) = \int_{\varphi_1}^{\varphi_2} [1 + K \cos(2(\varphi + \psi))] \sin \varphi d\varphi$.

The inductance in the Y direction is:

$$\begin{cases} L_{y1} = \frac{N^2 R^2 \pi}{2(g_0 - y \cos \varphi_0)} \sum_{k=0}^{m-1} \left| K(\psi - \frac{2k\pi}{m}) \right| \\ L_{y2} = \frac{N^2 R^2 \pi}{2(g_0 + y \cos \varphi_0)} \sum_{k=0}^{m-1} \left| K(\psi - \frac{2k\pi}{m}) \right| \end{cases} \quad (5)$$

The relationship between the current i and the voltage u in the winding could be gotten according to the law of electromagnetic induction.

$$\begin{cases} u_1 = Ri_1 + L_{y1} \frac{di_1}{dt} + i_1 \left(\frac{\partial L_{y1}}{\partial y} \frac{dy}{dt} + \frac{\partial L_{y1}}{\partial \psi} \frac{d\psi}{dt} \right) \\ u_2 = Ri_2 + L_{y2} \frac{di_2}{dt} + i_2 \left(\frac{\partial L_{y2}}{\partial y} \frac{dy}{dt} + \frac{\partial L_{y2}}{\partial \psi} \frac{d\psi}{dt} \right) \end{cases} \quad (6)$$

4. the Radial Levitation Simulation results Analysis of Magnetic Levitation Spherical Motor

The simulation of magnetic levitation system is done with MATLAB/Simulink software. When the rotor of spherical motor is basically stable, the radial displacement curve of spherical rotor from 0.3s to 1.4s after the disturbance was intercepted, which is shown in Figure 4. As can be seen from Figure 4, when the spherical motor is basic stability, the rotor displacement of spherical motor in

y direction is less than $50\mu m$. Therefore, the rotor is approximately in the center of equilibrium at this time, and the motor has realized the stable levitation.

Fig. 4 the radial displacement curve (in y direction) of rotor after the stator is stable

In order to intuitively analyze the response of the radial levitation force control system of the magnetic levitation spherical motor, a simulation of force condition on the rotor is done. The relationship between radial levitation force and displacement is shown in Figure 5.

Fig. 5 the relationship between radial displacement curve of the rotor after the stator is basically stable

The following can be seen from Figure 5. When the motor is started, the offset for the rotor is maximum. in order to return to equilibrium rapidly, the radial levitation force on rotor is maximum. When the spherical motor to reach the equilibrium position, because of the inertia effect, the rotor cannot be immediately stopped at zero position, and run over at this time, then a completely opposite direction force is imposed on the rotor. After this kind of repetition, the rotor of spherical motor would shake with small amplitude at the center, and the radial levitation force on rotor would change in a very small range. So we think that the rotor is basically stable.

5. Conclusions

The differential control strategy of magnetic levitation

spherical motor is presented based on its characteristics, which can effectively control the magnetic torque and levitation force of motor. Then the mathematic model of magnetic levitation motor is obtained based on the control strategy, which provides a basis for the deeper research.

Acknowledgment

Thank the China Natural Science Foundation for this project, Item Number: 51375427, 51475409. Thank the Jiang Su Natural Science Foundation for this project, Item Number: BY2014117-08, BY2015061-04. Thank the Yangzhou city - Yangzhou University of Science and Technology Cooperation Program Funds, Item Number: SXT20140041, YZ2016244, YZ2016255. Thank the Research Project of State Key Laboratory of Mechanical System and Vibration, Item Number: MSV201810.

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