Performance research and Simulation analysis of magnetorheological torque servo device

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Abstract. This paper expounds the rheological mechanism of magnetorheological fluid and the working principle of magnetorheological moment servo, studies the relationship between excitation current and magnetic field strength, magnetic flux and magnetic flux potential, and analyzes and designs the magnetic circuit. The electromagnetic analysis of the magnetorheological moment servo device was carried out by ANSYS software, and the relevant information such as the distribution of magnetic field lines and magnetic induction intensity was analyzed. The relationship between excitation current and magnetic flux density was obtained by fitting the data under different excitation current. The quantitative relationship between the input current and output torque of the magnetorheological drive device is simulated by matlab software.

Keywords: Magnetorheological fluid; Magnetic circuit design; Torque servo; Simulation analysis.

1. Introduction. Magnetorheological(MR) fluids is a new type of controllable intelligent fluid material that is composed of magnetized suspended phase particles[1] and other materials, including additives, distributed evenly in the base liquid. The rheological property of magnetorheological fluid can change with the change of external magnetic field. Under the action of magnetic field, it can achieve its conversion between solid state and liquid state reversibly and continuously in a very short time[2-3]. When there is no external magnetic field in the Magnetorheological fluid, the internal magnetic particles are arranged in a disordered manner, and the interaction force between them is very small. When the particles move, they are only subjected to the coulomb force between the particles. In this case, the damping force generated by the magnetorheological fluid is the viscous damping force, and its value is very small. Once the magnetorheological fluid is acted on by an external magnetic field, the magnetic particles inside it will be magnetized into magnetic couple particles under the action of magnetic field, attracting each other and condensing into chains. When the shear stress is too large, the old magnetic chain will be cut off, and the new magnetic chain will be formed, thus generating a continuous flow of resistance.
2. The working principle of magnetorheological torque servo device

Magnetorheological torque transmission device is based on magnetorheological effect, make the distribution of MRF in strong magnetic field around, under the influence of impressed current, with the constant change of exciting current, the magnetic induction intensity changes, in order to adjust the shear yield force of magnetorheological fluid, finally realizes the smooth and effective transfer torque, this process can realize the torque output of the infinite change, with short response time and reversible process, no wear characteristics[4].

The mechanical structure of the magnetorheological moment servo device studied in this paper is shown in Figure (a), which is mainly composed of shell (6), drive shaft (7), active rotary plate (5), torque private server (1), excitation coil (3), isolation magnetic ring (4), bolt and screw (2). Drive shaft drive under external driving force source of drive shaft rotation, after electrify, under the action of excitation coil, magnetic particles of magnetorheological fluid is its viscosity increased rapidly, along the direction of the magnetic induction line form chain structure, and has higher shear yield stress, drive torque with private server system, through the torque server system come to the final moment.

3. Magnetic circuit design of magnetorheological torque servo device

Basic principles of magnetic circuit design. The magnetic field of the magnetorheological moment servo device is provided by the excitation coil, and the relationship between the intensity of the magnetic field generated and the input excitation current and the relationship between the magnetomotive force and the magnetic flux can be explained by Ampere's law and Hopkinson's Law. The magnetic circuit model is shown in Figure (2)[5]. Among them, the core of the cross-sectional area of S, L and the length of the magnetic circuit, the coil number of turns for N, the size of the current I, magnetic circuit in the magnetic field intensity H as a uniform distribution.

According to Ampere's law in the magnetic circuit, the integral of the magnetic field strength H in any closed loop is equal to the algebraic sum of the currents of the conductor surrounded by the closed loop. As shown in Formula (1):
\[ \int \vec{H} \cdot d\vec{l} = \sum I \]  

(1)

In the formula, \( \vec{H} \) is the magnetic field strength vector (A/m); \( d\vec{l} \) is line element vector (m). When the magnetic field strength \( H \) of any point on the closed loop \( l \) is equal, and the tangent direction of any point on the closed loop \( l \) is completely the same, formula (1) can be expressed as: \( Hl = \sum I \), and it can be arbitrarily known from the amperes loop law:

\[ Hl = \sum I = NI \]  

(2)

In the formula, \( NI \) is the magnetomotive force of the coil. The magnetic field is formed in the magnetic circuit because of the magnetomotive force. The size of magnetic flux in the magnetic circuit can be expressed by formula (3):

\[ \phi = BS = uHS = u \frac{NI}{l} S = \frac{NI}{l / uS} \]  

(3)

Go to the formula, \( \phi \) for magnetic circuit flux (WB); \( B \) is the magnetic induction intensity (T), and \( u \) is the magnetic permeability of the core material (H/m).

When a magnetic field passes through a magnetic material, the magnetic material impedes the magnetic field. This obstruction is called magnetoresistance and \( R_m \) is expressed in units of 1/H. The size of magnetic flux can be expressed by formula (4):

\[ \phi = \frac{NI}{R_m} \]  

(4)

Formula (4), also known as Ohm's law of magnetic circuit, can be calculated by formula (1.3) and formula (4) as follows:

\[ R_m = \frac{l}{uS} \]

Where, \( l \) is the length of magnetic circuit (m); \( S \) is the cross-sectional area of the magnetic circuit(m²).

**Magnetic circuit separation of magnetorheological moment servo system.** Since the structure of the magnetorheological moment servo system is arranged symmetrically along the centerline of the fixed plate, only half of the structure of the device is considered in the analysis and calculation [6]. Ignore magnetic field to produce bolt and screw link structure in the magnetic resistance, regardless of the leakage magnetic field in magnetic circuit, so the device of magnetic circuit of magnetic resistance part includes: the exciting current in the magnetic resistance from the top and bottom shell of copper produced by the magnetic resistance, magnetorheological fluid in the magnetic resistance from the top and bottom shell of magnetorheological work produce magnetic resistance and damping plate in the magnetic resistance, etc, as shown in the diagram as shown in figure (3): Where \( u_1, u_2, u_3, u_4, u_5, u_6 \) are the permeability of each part; \( L_1, L_2, L_3, L_4, L_5, L_6 \) are the average length of each part; \( r_1, r_2, r_3, r_4, r_5, r_6 \) are the size radius of each part.

Total reluctance in magnetic circuit:

\[ \sum R = R_1 + 2R_2 + R_3 + 2R_4 + R_5 + 2R_6 + R_7 \]

Among them, \( R_1 = \frac{L_1}{\pi u_1 r_1} \); \( R_2 = \frac{\ln r_1}{2\pi u_1 l_2} \); \( R_3 = \frac{\ln(r_2 / r_1)}{2\pi u_2 l_3} \); \( R_4 = \frac{\ln(r_3)}{2\pi u_3 l_4} \);

\[ R_5 = \frac{\ln(r_4 / r_3)}{2\pi u_4 l_5} \] ; \( R_6 = \frac{\ln(r_5 / r_4)}{2\pi u_6 l_6} \); \( R_7 = \frac{L_7}{\pi u_7 (r_6^2 - r_4^2)} \)

According to Ohm's law of magnetic circuit, the magnetic flux in the magnetic circuit is \( \phi = \frac{NI}{\sum R} \).

Where, \( N \) is the number of turns of the coil, and \( I \) is the strength of the current.
4. Finite element analysis of Magnetorheological torque servo device

According to the theory of electromagnetic field, the FINITE element analysis of the magnetorheological moment servo system is carried out with ANSYS finite element analysis software to analyze the distribution of magnetic field lines, magnetic induction intensity distribution and other relevant information[7-8]. At the same time, the relationship between its current and its output torque is obtained. In this paper, MRF250 magnetorheological fluid is selected for magnetic field simulation analysis, its density is 2.72g/ml, the loading source is current density, the ratio of the number of turns of the coil and the cross-section area of the coil is used as the excitation current density, and the magnetorheological fluid is input through the B-H curve of MRF250 magnetorheological fluid. In the process of post-processing, the intensity and distribution of the magnetic field in the torque servo can be checked. The grid division and material display of the simulation model are shown in Figure (4).

When the field current from changes $I = 1A$ to $I = 2A$ the simulation model as shown in figure (5) of the distribution of magnetic field lines torque server model in the lines of magnetic force on the damping plate is non-uniform distribution state, a current strength under the magnetic induction intensity distribution is not very regular, but under different excitation current, the magnetic field distribution trend is consistent. Its trend and magnetic circuit design goal, and passed the damping plate and magnetorheological area, this paper designed the magnetic circuit of the magnetic circuit structure of the magnetorheological torque server and the choice of materials is reasonable, at the same time, can be seen from the graph, with the increase of current, excitation server in the magnetic flux density is also growing.
The correlation between the torque servo output and shear yield stress can be approximated by a linear function. The size of shear yield stress depends on the magnetic induction intensity $B$, which can be controlled by adjusting the current intensity and thereby controlling the output torque of the torque servo. Based on $I = 0.5$ A, 1 A, 1.5 A, 2 A, 2.5 A, 3 A, 3.5 A, 4 A for the variation of the excitation current simulation, the relationship between the field current and magnetic flux density is shown in figure (6).

As can be seen from the figure above, the magnetic induction intensity in the magnetorheological fluid increases with the increase of excitation current, and can be expressed as:

$$B = 1.29I^4 - 7.25I^3 - 37.62I^2 + 505.65I + 10.046$$
The quantitative relationship between the input current and output torque of the Magnetorheological drive device was simulated by MATLAB software, as shown in Figure (7), and a relatively simple fitting formula was obtained:

\[ T = 0.0247I^4 - 0.2515I^3 + 0.8342I^2 - 0.155I + 0.046 \]

Fig.6 The relationship between current and magnetic field

Fig.7 The relationship between current and torque

5. Conclusion

According to the torque servo device studied, the magnetic circuit is analyzed and designed by analyzing and expressing the relationship between excitation current and magnetic field strength, magnetic flux and magnetic flux potential. Based on the finite element analysis and the relevant analytical calculation formula, the relationship between excitation current and magnetic flux density is obtained by fitting the change of magnetic flux density under different excitation current. The quantitative relationship between the input current and output torque of the magnetorheological drive device was simulated by MATLAB software, and a relatively simple fitting formula was obtained, which was convenient for practical application and laid a foundation for its subsequent application on the lathe to analyze and simulate the influence of various factors on its output results.

References

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