Study on magnetic rheological mount properties of rough-rolled motor

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Abstract. Magnetorheological mount is an effective semi-active suspension, which is widely used in vibration damping systems for automobiles and aerospace machinery. The magnetorheological mount converts electromagnetic energy into mechanical energy to control and vary the viscous damping and dynamic stiffness of the suspension. In this paper, a new lumped parameter model of magnetorheological mount is established, and on the basis of the total parameter model, the nonlinear mathematical equation of magnetorheological mount bond graph model is established. Finally, its dynamic performance is analyzed and predicted. Results show that under the condition of exciting current from 0-2A, magnetorheological mount damping Angle increases to 38 °, the maximum dynamic stiffness increases by 30%. The current effect significantly affects the dynamic characteristics of magnetorheological mount. The cross section area of inertial channel increases by 20%, the dynamic stiffness increases by 5.3%, and the damping Angle increases by 24%.

1. Introduction

Due to the development of heavy industry, high-power and low-speed roughing motors are widely used in rolling mill equipment. The problem of noise and vibration is always a difficult problem in heavy machinery metallurgy field. As the vibration isolation system of power source, the mount of rough-rolled motor plays an important role in reducing vibration and noise. However, the vibration isolation system needs to be designed in order to control the motor's low speed fluctuation. For controlling the fluctuation of low rotating speed, the large damping character of the mount system has significant effect [1-3]. However, for vibration excitation caused by high frequency unbalance force of motor, it is suggested that the mount system has small damping characteristics. Therefore, it is necessary to design vibration isolation unit of motor mount system. In this paper, the decoupled membrane magnetorheological (M r) mount system is proposed. Meanwhile, the mount structure, state equation, performance parameters and parameter model simulation are studied [4-7]. Semi-active suspension can be divided into two categories: structure parameter control type and performance parameter control type [8]. The semi-active suspension controlled by performance parameters mainly realizes the adjustable dynamic characteristics by changing the damping characteristics of the suspension, and the common ones are electrorheological suspension and magnetorheological suspension, etc. [9]. The semi-active
suspension controlled by structural parameters realizes the adjustable dynamic characteristics by changing the stiffness of the decoupling film and inertial channel parameters (area, length, number) of the suspension. Literature [10] studies the dynamic characteristics and parameter identification of multi-inertia passageway semi-active suspension. In literature [11], a semi-active suspension controlling decoupling film stiffness was studied, and its idle speed damping effect was verified on a real vehicle. In literature [12], on the basis of the establishment of multi-body dynamics model of the whole vehicle, the NVH performance of a double-mode semi-active suspension was simulated and calculated, and the reliability of simulation results was verified by real vehicle experiments. The above research on semi-active suspension with structural parameter control focuses on the analysis of dynamic characteristics and the NVH performance of the vehicle, but there are few literature reports on the structural optimization design of semi-active suspension elements themselves.

2. Basic structure

The damping properties of magneto-rheological (MR) mount are variable, and the damping is correlated with the magnetic flux of the external magnetic field. When excited by external magnetic field, the suspended internal liquid changes from liquid to liquid and solid coupling state, presenting a controllable yield strength [13]. Considering the magneto-rheological characteristics of the mount system, the damped adjustable magneto-rheological mount was designed [14, 15]. The magneto-rheological mount structure designed in this paper is shown in figure 1. The magneto-rheological mount is mainly composed of rubber main spring, liquid chamber, extrusion disc, coil, liquid channel, magneto-rheological liquid, sensor, decoupled film and other structures. Under low frequency excitation, the suspended upper liquid volume changes, the magneto-rheological fluid flows through the variable damping channel, and changes the current size according to the vibration of the suspension active terminal, so as to realize the change of magnetic flux. Adjusting the flow resistance of the liquid channel can adjust the damping characteristics of the suspension. When high frequency excitation occurs, fluid flow through the damping channel increases the liquid energy loss [16], thus controlling the high frequency vibration characteristics.

2.1. Basic model

The suspended parameter model is shown in figure 2. The parameter Kr represents the stiffness parameters of the spring system. K and B represent the stiffness and damping system of the spring respectively. Parameter C is the volume stiffness of the suspension model, parameter A is a variable area, working mode and principle is to control the flow of liquid by adjusting the aperture of the damping channel. The flow variation of the decoupled film and the throttling disc controls the area of the upper and lower Chambers respectively, thus controlling the flow rate to change the acting force. The control quantity in the mount model includes input excitation X (t) and suspension transmission force F (t).
2.2. Bond graph model

The bond graph structure was proposed by Professor Paynter H in 1950. Subsequently, Karnopp D.C. and Rosenberg R.C developed its theory based on the theory of statistical energy. It is a dynamic analysis method of complex subjects which can be quantified and modularized. Due to the intuitionistic nature of this method, it has been widely used in the design of magneto-rheological (MR) mount. According to the bond graph structure, the bond graph model of magneto-rheological (MR) mount was obtained, as shown in figure 3.

According to the bond graph structure theory, the nonlinearity of the volumetric stiffness of the liquid chamber can be simplified. In this paper, we consider only the nonlinearity of the magneto-rheological fluid yield limit and magnetic flux intensity. Where, the liquid resistance of the variable flux of magneto-rheological rheological is expressed as $R_m = R_{m0} + R_r(r_y(B))$. The dynamic equation of magneto-rheological suspension is derived as follows:
\[ F(t) = K_r X + B_r \dot{X} + (A_p - A_m + A_t)P_t + (A_m - A_t)P_1 \]  
\[ C_i \dot{P}_i = Q_i - (A_m - A_p - A_t)\dot{X} \]  
\[ C_i \dot{P}_1 = (A_m - A_t)\dot{X} - Q_i - Q_m - Q_d \]  
\[ C_2 \dot{P}_2 = Q_m + Q_d \]  
\[ P_1 - P_t = I_1 \dot{Q}_t + R_i Q_i \]  
\[ P_1 - P_2 = I_m \dot{Q}_m + R_m Q_m \]  
\[ P_1 - P_2 = I_d \dot{Q}_d + R_d Q_d \]

The above mentioned kinds of Laplace transforms are derived and the magneto-rheological suspension stiffness is:

\[ K^s(s) = \frac{L(F(t))}{L(X(t))} = K_r + B_r s + (A_p - A_m + A_t)f_1(s)/C_t + (A_m - A_t)f_2(s)/C_1 \]

Among them:

\[ f_1(s) = \frac{a_0 + a_1s + a_2s^2 + a_3s^3 + a_4s^4 + a_5s^5}{b_0 + b_1s + b_2s^2 + b_3s^3 + b_4s^4 + b_5s^5} \]
\[ f_2(s) = \frac{c_0 + c_1s + c_2s^2 + c_3s^3 + c_4s^4 + c_5s^5}{d_0 + d_1s + d_2s^2 + d_3s^3 + d_4s^4 + d_5s^5} \]

The correlation coefficient \( a_i, b_i, c_i \) and \( d_i \) \((i=0,1,2,3,4,5)\) can be represented by set parameters. Make \( s = j\omega \),

\[ K^s(j\omega) = K_1 + jK_2 \]

Where: K1 is the energy storage stiffness of the system; K2 is the system loss stiffness.

3. Fluid resistance performance

In order to obtain the nonlinear liquid resistance \( R_m \) of magneto-rheological mount, this paper USES the electro-hydraulic coupling law of finite element method to identify. Under different current excitation, the magneto-rheological magnetic induction intensity and magnetic flux were calculated by finite element method, and then identified by liquid resistance formula. The dimension parameters of magnetic
The core structure of magneto-rheological mount are marked as shown in figure 4. The calculation formula of nonlinear liquid resistance $R_m$ can be deduced as follows:

$$R_m = \frac{6\eta (2L + b)}{\pi R_1 (R_2 - R_1)} + \frac{6\tau_y (B)L}{(R_2 - R_1) |Q_m|} \quad (11)$$

Where, $Q_m$ represents the liquid flow rate of magneto-rheological mount. $\rho$ is magneto-rheological mount liquid density; $\tau_y$ is the yield stress of magneto-rheological fluid.

The solid-liquid coupling model of suspended magnetic core component and magneto-rheological fluid was established by using finite element software. The magnetic core module uses 2-dimensional units, and the magneto-rheological liquid is simulated by one-dimensional units. The current density is loaded at the position of the magnetic coil of the model. Under the action of magnetic field, the magnetic flux and induction density of the magneto-rheological liquid can be obtained. When the allowable value of excitation current is 2.0A, the magnetic field intensity distribution of part of the magnetic core is shown in figure 5.
Figure 5. Magnetic field intensity distribution under excitation current of 2.0A

The remaining parameters in the suspension parameters can be identified by solid-liquid coupling and electromagnetic coupling methods, which are described in literature [4, 5]. The identified suspension parameters are shown in Table 1.

| Related parameters | Calculated value |
|--------------------|------------------|
| $K$ (N/mm)         | 100              |
| $C_1$ (m/s/N)      | $3.1 \times 10^6$|
| $C_2$ (m/s/N)      | $1.1 \times 10^4$|
| $R$ (N/sm$^2$)     | 3118             |
| $I$ (kg/m$^4$)     | 1156             |

4. Dynamic characteristics

4.1. Influence of excitation current
Under low frequency excitation, the magneto-rheological fluid moves from the lower decoupling film to the upper decoupling film, which is interrupted by the baffle at the lower decoupling film. The dynamic equation is simplified and the low-frequency characteristic curve of nonlinear model with current variation is obtained by combining with the simulation results of electrical coupling, as shown in figure 6, 7. As can be seen from the dynamic characteristic curve, the dynamic characteristic curve changes significantly before and after the control current is applied. With current intensity with the increase of degree, the dynamic stiffness peak of the low frequency region increases. From 220 N/mm at zero current 285 N/mm at 2A, an increase of nearly 30%; the frequency corresponding to the peak dynamic stiffness is also affected by the current intensity, from 18 Hz at 0.2a to 15 Hz at 2A. Damping peak Angle increases with increasing the strength of the current, increased by 32 ° to 38 °. The peak damping Angle decreases from 16 Hz at zero current to 7 Hz at 2A. It can be seen that by adjusting the current intensity applied to the electromagnetic coil, not only the peak value of suspension stiffness and
damping Angle can be controlled, but also the peak frequency can be adjusted to ensure that it falls within the effective vibration isolation frequency band.

![Dynamic stiffness curves under different current excitation conditions](image1)

**Figure 6.** Dynamic stiffness curves under different current excitation conditions

![Damping Angle under different current excitation conditions](image2)

**Figure 7.** Damping Angle under different current excitation conditions

4.2. **Influence of inertia channel**

It can be seen that when the cross-sectional area of the inertial channel increases by 20% on the basis of the original parameters, the maximum dynamic stiffness increases accordingly the corresponding frequency of the peak value is basically unchanged, and the minimum dynamic stiffness decreases from 118\( \text{N/mm} \) to 115\( \text{N/mm} \), with a reduction of 2.5%. In addition, the dynamic stiffness on the left side of the intersection point between the dynamic stiffness curve and the corresponding curve under the
original parameters decreases. The damping angle curve moves to the upper right with the increase of the width of the inertial channel by 20%, that is, the damping angle peak increases by 24% and the corresponding frequency increases by 2hz, which is similar to the change of dynamic stiffness. The damping angle curve slightly reduces the left damping angle at the intersection point of the corresponding curve under the original parameters. The width of inertial channel decreases with the hour. It can be seen that the cross-sectional area of inertial channel has a great influence on the dynamic characteristics, especially the damping lag angle.

*Figure 8. Influence of cross-sectional area of inertial channel on dynamic stiffness*

*Figure 9. Influence of cross-sectional area of inertial channel on damping Angle*
5. Conclusion
In this paper, a new mechanical model of magnetorheological mount of motor is established, and the dynamic characteristics of mount caused by different current excitation conditions and changes in cross-sectional area of inertial channel are analyzed. Analysis results show that: (1) when the current increases to 2, a magnetorheological suspension has good dynamic stiffness and damping characteristics, dynamic stiffness increased by 30%, damping Angle increases with the increase of current, maximum damping Angle is 38°. (2) with the increase of the cross-sectional area of the inertial channel, the magnetorheological suspension stiffness and damping increase to varying degrees, the dynamic stiffness increases by 5.3% and the damping Angle increases by 24%. This paper provides a good material for the design of magnetorheological mount performance parameters.

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