Transient Temperature Field Simulation Analysis of Magnetorheological Grease Torsional Vibration Damper

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Abstract—To reveal the transient temperature distribution pattern inside the magnetorheological grease (MRG) torsional vibration damper and explore the relationship between the current and the internal temperature of the device, the transient temperature simulation analysis of the MRG device was conducted in this paper. Firstly, a theoretical heat transfer model of MRG torsional vibration damper with dual heat source structural feature was established based on the Bingham constitutive model and the temperature-dependent viscosity characteristic of MRG. Then, the transient temperature field model of the MRG torsional vibration damper was developed by the finite element method, and the temperature field distribution and temperature-time variation characteristics of the MRG torsional vibration damper were analyzed. The simulation results show that the temperature rise of MRG in the working domain is the fastest, and the temperature rise rate slows down after the device works for 5.4s. The simulation results reveal the internal temperature distribution and temperature rise characteristics of the torsional vibration damper, which provides a theoretical basis for the structural optimization and control strategy design of MRG torsional vibration damper considering temperature factor.

1. Introduction

In the engine system, the explosive force generated by the instantaneous combustion of combustible gases in the cylinder will lead to torsional vibration of the crankshaft\textsuperscript{[1]}. At present, the reduction of crankshaft torsional vibration is mainly to install silicone oil dampers \textsuperscript{[2]}, rubber dampers \textsuperscript{[3]} and dual-mass flywheel torsional vibration dampers \textsuperscript{[4]}. However, due to the damping is not adjustable, it can only show a good damping effect at a specific resonance frequency \textsuperscript{[5]}. This led to the introduction of MRG smart materials to develop MRG torsional vibration dampers \textsuperscript{[6]}. However, the damping material is silicone oil, MRG and other viscous fluids of the damper will face the problem of heat dissipation and need to ensure that it can not fail due to high temperature.

Research on temperature analysis of torsional vibration dampers and magnetorheological dampers, Homik, W. \textsuperscript{[7]} proposed a thermal fluid dynamics model for viscous torsional vibration dampers. Venczel, M. \textsuperscript{[8]} developed a temperature and shear rate-dependent viscosity model for silicone fluids.
Park, E. J. [9] analyzed the fluid flow and heat transfer system of magnetorheological fluids. Patil, S. R. [10] evaluated the temperature rise of a magnetic fluid due to braking manipulation. So far, most of the studies have been conducted on the temperature aspects of viscous fluid torsional vibration dampers and magnetorheological dampers. There is a lack of temperature analysis of MRG torsional vibration damper. In this paper, the temperature analysis of the MRG torsional vibration damper was carried out based on the temperature rise theory of viscous fluid torsional vibration damper and the temperature analysis of the magnetorheological damper.

In this paper, a theoretical model of the temperature field of MRG was established based on the Bingham mechanical model and the viscous temperature characteristic equation, and the heat transfer system of the MRG torsion damper was analyzed. Secondly, the MRG torsional vibration damper was modeled in three dimensions, the transient temperature field simulation analysis was carried out. The results of the analysis provide the simulation and theoretical basis for the subsequent heat dissipation optimization and temperature compensation control.

2. Mathematical Model and Simulation Model of Torsional Vibration Damper

2.1 Magnetic field properties and temperature properties of MRG
The rheological behavior of MRG is described based on Bingham's intrinsic model, which is Eq. (1)

\[
\begin{align*}
\tau &= \tau_y \text{sgn}(\dot{\gamma}) + \dot{\gamma} \eta_y & |\tau| > |\tau_y| \\
\dot{\gamma} &= 0 & |\tau| \leq |\tau_y|
\end{align*}
\]

(1)

Where: \(\tau\) is the shear stress; \(\tau_y\) is the shear yield stress caused by the applied magnetic field; \(\dot{\gamma}\) is the shear rate; \(\eta\) is the MRG power viscosity independent of the magnetic field.

Considering the viscosity-temperature characteristics of MRG, the viscosity-temperature equation is Eq. (2) [11]:

\[
\eta = \eta_0 e^{-\beta(T-T_0)}
\]

(2)

Where: \(\eta_0\) is the viscosity when the temperature is \(T_0\), \(\eta\) is the viscosity when the temperature is \(T\), \(\beta\) is the viscosity-temperature coefficient, take 0.03/\(^\circ\)C.

2.2 MRG torsional vibration damper simulation model
Considering the damping requirements of the engine crankshaft system under actual operating conditions and the magnetic circuit closure, the structure design is shown in Fig. 1.

Fig.1 3-D model of MRG torsional vibration damper

The MRG torsional vibration damper is simulated with fluid-solid coupling, and the effects of bearings, conductor tubes, etc. are ignored to shorten the simulation time when carrying out multi-physics field coupling simulation. The fluid properties of MRG are shown in Table 1.
Table 1 Fluid properties

| Parameter                  | Value | Unit     |
|----------------------------|-------|----------|
| Initial viscosity          | 12    | Pa · s   |
| Density                    | 2.68  | g/cm³    |
| Reference pressure         | 101.325 | KPa     |
| Thermal conductivity       | 1     | W/(m · k) |
| Constant pressure heat capacity | 1000 | J/(kg · k) |

To distinguish the temperature characteristic of MRG in the different domains, the internal overall MRG domain is divided into the Working domain Fig. 2(a) and the Non-working domain Fig. 2(b).

![Classification of MRG fluid domains](image)

2.3 Magnetic field simulation analysis

![Magnetic excitation line distribution](image)

![B-d change curve](image)

Fig. 3(a) shows the magnetic excitation line distribution inside the MRG torsional vibration damper. In which, the MRG domain with the outermost ring and higher magnetic excitation line density is defined as the 'Working domain of MRG'; the MRG domain with less magnetic excitation line density inside is defined as the 'Non-working domain of MRG'. The magnetic field distribution through the route of Fig. 3(a) is shown in Fig. 3(b), and $B$ decreases as the distance $d$ between the measurement point and the left endpoint increases.

2.4 Thermal conductivity system analysis

The MRG inside the torsional vibration damper will transform the slip energy and torsional vibration energy into internal energy, the heat will be transferred to the Shell through the Magnetically conductive ring, and the Shell will be forced to convect heat with the external air, dissipate the heat.
The resistance heat generated by the coil is first forced to convect with the surrounding MRG, the temperature of the Working domain of MRG is transferred to the Non-working domain of MRG by liquid heat transfer. The heat transfer process is shown in Fig. 4.

In the right-angle coordinate system, the micro-element parallel hexahedron is chosen in the MRG torsional vibration damper, in the thermal conductivity process, according to Fourier's law the micro-element body thermal conductivity differential equation is shown in Eq. (3).

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + \Phi$$  \hspace{1cm} (3)

Where: $\Phi$ is the intensity of the internal heat source, $\rho$ is the density, and $c$ is the specific heat capacity.

2.5 Convection heat transfer

The control energy generated by the coil resistance heat (coil power consumption $N$) can be expressed by Eq. (4) as:

$$N = I^2 R_W$$  \hspace{1cm} (4)

Where: $I$ is the current, $R_W$ is the wire resistance. During the torsional vibration damper operation, forced convection heat transfer between the resistive heat generated by the coil and the surrounding MRG. convection heat transfer formula according to Eq. (5) Newton’s law of cooling:

$$\Phi = hA \frac{dT}{dx}$$  \hspace{1cm} (5)

Where: $\Phi$ is the heat flow rate; $A$ is the contact area; $dT/dx$ is the temperature gradient; $h$ is the convective heat transfer coefficient.

3. Transient Temperature Field Simulation Results Analysis

Fig. 5 Transient temperature distribution of the MRG torsional vibration damper

(a) $t=0$ s  \hspace{1cm} (b) $t=0.8$ s  \hspace{1cm} (c) $t=4$ s  \hspace{1cm} (d) $t=10$ s
According to Fig. 5, Fig. 6, When 1A current is applied to the coil, the magnitude and rate of temperature rise in the working domain of MRG are the greatest due to the higher viscosity, higher slip and smaller working gap of this domain. The temperature rises rapidly from the initial 20 °C to 51.42 °C. As the temperature increases, the degree of fluid friction is reduced due to the slowing of the increase in the slip difference and the viscosity-temperature properties of MRG, the temperature rise rate slows down after 5.4s. In the process 1 stage of Fig. 6, the coil is fed with 1A current, generating resistance heat and forced convection heat transfer with the surrounding MRG. In the process 2 stage, after 1.6s, the temperature starts to increase due to the heat transfer from the Working domain of MRG to the vicinity of the coil through the MRG. The temperature of the MRG at the coil domain is indicated in the 'Coil domain' of Fig. 6. While for the temperature at the Non-working domain of the MRG, the temperature rise amplitude and rate are the lowest due to MRG with low viscosity and large working clearance, the less intense fluid friction.

The same simulation analysis is performed for five current conditions of 0A, 0.5A, 1A, 1.5A and 2A, the temperature peaks of the five different currents are fitted to explore the relationship between the current and the internal temperature rise of the device, as shown in Fig. 7. According to the simulation and fitting results, the temperature rise amplitude is maximum when 0.852A current is passed to the coil.
4. Conclusion
In this paper, the transient temperature field simulation analysis was performed for MRG torsional vibration dampers. According to the simulation results, the internal temperature distribution pattern of the device is that the temperature rise in MRG working domain is the highest and the fastest. The temperature of both end surfaces gradually increases from the center of the circle along the radial direction. Determine the current at the maximum temperature rise amplitude by using the current-temperature curve. The results provide some guidance for the optimization of heat dissipation considering temperature factors.

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