Structural optimization design of magnetic Shock absorber based on particle swarm optimization

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Abstract. With the advancement of society and the accelerated pace of people's lives, our pursuit of quality of life is also increasing. The car is not an unattainable luxury for nowadays. Not only that, but we have higher requirements for the comfort and smooth performance of the car. This puts higher demands on the suspension system of the car, and the semi-active suspension emerges as an emerging suspension system. The most used damper in the semi-active suspension system is the magnetorheological damper, because it can adjust the damping force in time as the movement state of the car changes, so that it cannot only satisfy the comfort. Sexual requirements can also meet the requirements for smooth performance. Its emergence has aroused strong repercussions from the academic community and high attention from the industry. The medium of the magnetorheological damper is a magnetorheological fluid. By adjusting the input current, the intensity of the magnetic field is changed, and the consistency of the magnetorheological fluid changes rapidly, that is, between the Newtonian fluid and the solid. Reversible changes, and the response time of this change is only a few milliseconds, very fast. This provides an appropriate damping force in a timely and effective manner. The structure of the magnetorheological damper is simple, easy to operate, fast in response, and low in energy consumption. In this paper, the mechanical model of the double-tube shear valve type magnetorheological vibration reduction, the design, the particle swarm optimization algorithm and other parameters are analysed and discussed in detail.

Key words: magnetorheological damper; optimization; particle swarm optimization.

1. The working principle of the magnetorheological damper

The medium of the magnetorheological damper is a magnetorheological fluid. By adjusting the input current, the intensity of the magnetic field is changed, and the consistency of the magnetorheological fluid changes rapidly, that is, between the Newtonian fluid and the solid. The reversible change, and the response time of this change is only a few milliseconds [1]. This will provide an appropriate damping force in a timely and effective manner. The structure of the magnetorheological damper is simple in design, convenient in operation, fast in response, and low in energy consumption. In this paper, the
optimized design of the double-tube magnetorheological damper based on the mixed working mode is introduced. The working principle of the magnetorheological damper will be introduced below.

The working principle diagram of the double cylinder magnetorheological damper is shown in Figure 1, which is similar to the working principle of the conventional hydraulic double cylinder damper: when the piston 3 moves up and down in the working cylinder 5, along with the magnetic The rheological fluid flows between the upper and lower chambers of the working cylinder 5 or between the working cylinder 5 and the liquid storage cylinder 4, and the piston 3 and the working cylinder 5 gap and the compression valve 7 respectively generate a restoring resistance and a compression resistance, and the compensating valve 6 ensures The magnetorheological fluid flows back and forth between the working cylinder 5 and the liquid storage to ensure that the magnetorheological fluid always fills the working cylinder 5. By changing the current flowing into the coil 2 of the magnetorheological damper piston, the magnetic field is continuously enhanced, and the particles in the magnetic fluid are gradually magnetized. As the magnetic field changes from weak to strong and eventually reaches a critical point, the particles of the entire magnetic fluid will change as follows [2]: First, when the magnetic field strength is small, the dipole chain composed of particles is in quantity. Or the hardness is relatively small; but as the strength of the magnetic field increases, part of the magnetic domain will completely disappear, because some of the original inner magnetic domain rotates outward, unlike the previous stage, the dipole chain at this time is The number or hardness will increase, corresponding to the magnetorheological fluid will not be easily cut; when the magnetic field increases to a certain critical point, the magnetic polarization of the particles in the magnetorheological fluid also reaches the highest value, corresponding to its shear The shear stress also reached the highest value. At this time, the dynamic yield stress of the particles in the magnetorheological fluid also reaches a peak. As a result, the flow properties of the magnetorheological fluid change, which directly causes the pressure difference across the damper channel to change.

![Figure 1. Schematic diagram of the double cylinder magnetorheological damper](image)

1. Piston rod 2. Coil 3. Piston 4. Reservoir 5. Working cylinder 6. Compensation valve 7. Compression valve

2. The structural parameters of the magnetorheological damper studied in this paper

According to the double cylinder damper [3] of a front suspension, according to the design principle of the magnetorheological damper, some structural dimensions of the damper are retained, and a double model based on the working mode of the shear valve is designed. Cartridge magnetorheological damper. In the structural design of the magnetorheological damper, the selection of the core of the damper piston,
the piston rod, the working cylinder and the like directly affects the performance of the damper. These components are the main force and support components of the damper, meeting their strength and stiffness requirements, and they are also part of the magnetic circuit, but also meet the magnetic properties required for some magnetic properties. The 20# low carbon steel has good comprehensive performance in structural strength, mechanical processing performance and magnetic properties, and meets the selection criteria of structural materials for magnetorheological damper. Therefore, this paper selects 20# low carbon steel as the material of the magnetorheological damper piston, piston rod, and working cylinder. Specific performance parameters [4] are shown in Table 1 and 2.

| Steel number | Density ρ g cm⁻³ | Elastic Modulus E × 10³ MPa | Mechanical properties | Thermal conductivity λ W (m.°C)⁻¹ |
|--------------|------------------|-----------------------------|-----------------------|----------------------------------|
| 20           | 7.85             | 20°C 100°C 300°C 410 MPa    | 210 205 185 410 MPa    | 51.08 100°C 50.24 300°C 48.15 500°C |

Table 1. 20# low carbon steel performance indicators

Table 2. Magnetic properties of 20# low carbon steel

| μᵢ           | μ_max          | Bₛ(T) | Hₑ(A/m) | ρ(Ω m) |
|--------------|----------------|-------|---------|--------|
| 6.9×10⁻⁴     | 2.4×3×10⁻³     | 2.12  | 200-224 | 1.2×10⁻⁷ |

According to the relevant regulations of the People's Republic of China automotive industry standards, the technical conditions of the automobile shock absorber and the test method of the worktable [5], when the stroke is neutral, the relevant performance of the damper is tested. 1000 mm, piston speed V₀ = 0.52 m/s, when the compression damping force is 350 ± 50N, then take PY = 350N, its recovery damping force is 800 ± 200N, take Pf = 1000N. The magnetorheological fluid used in this paper is MRF270 / 50 magnetorheological fluid with a density of 3.07 / ml and an apparent viscosity of 0.27 Pa at 20 °. The constitutive equation is: the rated current is selected as I = 3A, and the coilenameled wire diameter is 0.8 mm. According to the above conditions, according to the design procedure of the magnetorheological damper, when the damping gap H = 1mm, a double-tube magnetorheological damper based on the working mode of the shear valve is designed. The structure is shown in Figure 2. The structure parameters are shown in Table 3.

Figure 2. Structure of the double cylinder magnetorheological damper
Table 3. Structural parameters of double barrel magnetorheological damper (m)

| Structural design parameters                  | Value  |
|-----------------------------------------------|--------|
| Piston rod diameter $D_1$                    | 0.02   |
| Piston rod front end diameter $D_2$          | 0.008  |
| Coil winding diameter $D_3$                  | 0.014  |
| Piston diameter $D_4$                        | 0.029  |
| Working cylinder inner diameter $D_5$        | 0.031  |
| Working cylinder outer diameter $D_6$        | 0.0334 |
| Damping gap $h$                              | 0.001  |
| Effective length of the piston $L$           | 0.081  |
| Coils number $N$                             | 78     |
| Coils coil width $L_1$                       | 0.011  |
| Pilot hole diameter in the piston rod $D$    | 0.003  |

3. The three elements of the magnetorheological damper optimization model

3.1. Objective function

In this paper, the two performance indexes of the dynamic adjustable range $D$ and the dynamic response time $T$ of the magnetorheological damper are selected as the objective function. Thus, the optimization models are established from the two angles of damping force and magnetic circuit. Their expressions are respectively for:

$$ D = \frac{F_c}{F_\eta} = \left[ \frac{4LA_p}{h} + 2bL \right] \tau_s \text{sgn}(v_0) $$

$$ T = \frac{L_m}{R_e} $$

From (2):

$$ R_e = \frac{4\rho N(D_3 + 4\delta)}{\delta^2} $$

$$ L_m = \frac{N_2}{R_m} $$

In equation (3), the resistivity is the diameter of the enameled wire.

For these two objective functions, we hope that the larger the adjustment range $D$, the better, and the smaller the dynamic response time, the better. Therefore, our optimization goal is to select the optimal
structural parameters to maximize the adjustment range while having the minimum response time. Therefore, the objective function of the optimization model is defined as:

\[
\min \left\{ f_1(x) = -D = -\frac{F_T}{F_\eta}, \quad f_2(x) = T = \frac{L_m}{R} \right\}
\]  

(5)

### 3.2. Design Variables

In this paper, four structural parameters are selected as design variables, which are the effective length \( L \) of the piston, the inner diameter \( D_5 \) of the working cylinder, the radial height \( h \) of the damping gap and the number \( N \) of the coil.

### 3.3. Constraints

According to the actual structural limitation of the selected front suspension magnetorheological damper, the effective length of the piston is between \( L_{\text{min}} \) and \( L_{\text{max}} \), and \( L_{\text{min}} \) depends on the length of the original piston damping channel. \( L_{\text{max}} \) depends on the damper. Stroke and length of the working cylinder, \( L_{\text{min}}=0.02 \text{m}, \ L_{\text{max}}=0.1 \text{m} \) in this paper; so, \( 0.02 \text{m} \leq L \leq 0.1 \text{m} \);

According to the size requirements of the cylinder between the cylinders, the inner diameter of the cylinder is \( 0<D_5<0.0334 \text{ m} \);

According to relevant design experience, the damper piston damping clearance value range: \( 0.0005 \text{m} \leq h \leq 0.002 \text{m} \);

We require that the response speed of the magnetorheological damper should not be too slow, so the magnetic circuit response time should be: \( T \leq 0.2 \text{s} \);

When the coil is selected, the rated current \( I_{\text{max}} \) is also determined. In order to prevent the electromagnetic coil from being burnt, the excitation current in the circuit should be less than or equal to the rated current \( I_{\text{max}} \). \( I_{\text{max}}=3 \text{A} \) is selected in this paper, so \( I \leq 3 \text{A} \).

The above constraints can be divided into linear constraints and nonlinear constraints, where the linear constraints are:

\[
0.02 \leq L \leq 0.1 \\
0 < D_5 < 0.0334 \\
0.0005 \leq h \leq 0.002 \\
0 < N \leq 300
\]

The nonlinear constraint is:

\[
\frac{\pi^2 \times 10^{-5} (D_5 - 2h)NL}{7 \left( D_5 - 2h - \frac{2 \times 10^{-3}}{11} N - 2 \times 10^{-3} \right) h} \leq 0.2
\]

(6)

\[
L_n \left[ 1 - \frac{2.3}{64.72 \left( \frac{\pi L (D_5 - 2h)^2 - 0.02^2}{h} + 2(D_5 - h)\pi L + 3.26 \pi \times 10^{-7} N \right)} \right] \times h \leq 3
\]

(7)
4. Multi-objective optimization of magnetorheological damper based on particle swarm optimization

4.1. Principles of Particle Swarm Algorithm
The advantage of the PSO algorithm lies in the optimization function of its algorithm, which is derived from the information sharing and cooperation between different particles in the particle population. Constant search between each different particle to get the optimal solution.

Let the first particle position in the population generated by the algorithm be, and the velocity be. In the algorithm, the particle will track two target positions, one is the extreme value currently found by the particle itself, recorded as. An extremum currently found for the entire population, recorded as. In this formula, d is the number of independent variables, which can be any natural number; and is a constant in the process of acceleration. The right side of Equation 8 includes: “Inertia”, “Cognitive Part”, “Social Part”. These three parts represent different meanings: the first part is the particle habit; the second part represents the particle's recall of the previous activity; the third part represents the information sharing process between the particles. In general, the acceleration constants are 2, and are different in different functions and spaces.

\[
v_{id}(t+1) = v_{id}(t) + c_1 \cdot rand_1 \cdot (p_{id}(t) - x_{id}(t)) + c_2 \cdot rand_2 \cdot (p_{gd}(t) - x_{id}(t)) \\
x_{id}(t+1) = x_{id}(t) + v_{id}(t+1)
\]

In this formula, d is the number of independent variables, which can be any natural number; and is a constant in the process of acceleration. The right side of Equation 8 includes: “Inertia”, “Cognitive Part”, “Social Part”. These three parts represent different meanings: the first part is the particle habit; the second part represents the particle's recall of the previous activity; the third part represents the information sharing process between the particles. In general, the acceleration constants are 2, and are different in different functions and spaces.

4.2. Particle Swarm Algorithm Flow
The flow of the algorithm is as follows [6]:

1. The original state of the particle group, the size of the group, the location and speed of the particle
2. Fitness values of different particles
3. Compare the fitness value and the extreme value of the individual particles, taking the larger of the two
4. Compare the fitness value and global value of individual particles, taking the larger of the two
5. Calculate the particle velocity and location (based on Equations 2-1 and 2-2)
6. If the result meets the conditions, it ends. If it does not meet the conditions, return to step (2) and recalculate.

Can be seen from the above optimization results that when the evolutionary algebra reaches 200 generations, the results have basically converged. The final multi-objective optimized Pareto solution is: the effective length of the piston rod is 0.0874 mm, the inner diameter of the cylinder of the working cylinder is 0.0332 mm, the radial height of the damping gap is 0.0010 mm, and the number of coil turns is 78. The dynamic adjustment range of the objective function is 4.0580, and the dynamic response time is 0.1981s. Compared with the optimization results in [3], the results of the dynamic adjustment range of target 1 are better than the optimization results of 3.2266 in the literature [3]. The optimization result of target 2 dynamic response time is better than the optimization results of 0.4430s in [3]. Therefore, the optimization method described in this paper is feasible and effective.
4.3. Optimization results analysis
We construct the fitness function as, where \( f_1 \) and \( f_2 \) are the two objective functions, respectively. 
\[
q = 100 \times \text{abs}\left[\min(3 - q, 0)\right].
\]

**Figure 3.** PSO algorithm flow chart

**Figure 4.** Population size 2000 fitness function diagram  
**Figure 5.** Population size 3000 fitness function diagram
Figure 6. Change of population size 2000 adjustment range

Figure 7. Change of population size 3000 adjustment range

Figure 8. Variation of population size 2000 response time. Figure 9. Change of population size 3000 response time

5. Conclusion
In this paper, the design and optimization of the structure of the magnetorheological damper for the vehicle are studied. The magnetorheological theory is applied to a certain type of damper, and the magnetorheological damper in the double-tube mixing mode is designed and optimized. A mechanical model of magnetic flow damping is established. The particle swarm optimization algorithm and multi-objective game algorithm are used to optimize the multi-objective parameters of the four important parameters of the magnetorheological damper. The optimal design method combining particle swarm optimization algorithm and multi-objective optimization algorithm is used. According to the calculation model of the previously established magnetorheological damper, the MATLAB is used for programming, and the particle swarm is used for screening to obtain an optimal set of structural parameters. The optimization results are compared with the results in [3]. The results of the target 1 adjustment range are better than those in the literature [3], and the results of the target 2 dynamic response time are better than those of the literature [3]. The optimization method described herein is feasible and effective.
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