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ARTICLE

Trial Production of Heavy-Duty Metal Rubber Based on Predictive Model of Relative Density Mechanics

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Abstract: The predictive model and design of heavy-duty metal rubber shock absorber for the powertrains of heavy-load mining vehicles were investigated. The microstructural characteristics of the wire mesh were elucidated using fractal graphs. A numerical model based on virtual fabrication technique was established to propose a design scheme for the wire mesh component. Four sets of wire mesh shock absorbers with various relative densities were prepared and a predictive model based on these relative densities was established through mechanical testing. To further enhance the predictive accuracy, a variable transposition fitting method was proposed to refine the model. Residual analysis was employed to quantitatively validate the results against those obtained from an experimental control group. The results show that the improved model exhibits higher predictive accuracy than the original model, with the determination coefficient (R^2) of 0.9624. This study provides theoretical support for designing wire mesh shock absorbers with reduced testing requirements and enhanced design efficiency.

Key words: metal rubber; fractal graph; preparation process; mechanical model; properties prediction

1 Introduction

Conventional rubber dampers are failing to meet the increasingly stringent performance requirements of large, specialised vehicles such as mining trucks. Their susceptibility to ageing at high temperatures and becoming brittle at low temperatures limits their engineering performance. Large-load dampers are generally installed on mining vehicles between the engine and body (Fig.1). Metal rubber (MR) is a damping material with a complex spiral network structure. It has the advantages of conventional rubber and can reduce ageing, making it more effective in extreme environments[1]. Compared to other metal porous materials, such as porous metals, foam metal composites and twisted wires, MR exhibits superior flexibility in material type, structural design and density control. However, in engineering design, empirical knowledge and extensive trial-and-error iterations are required[2].

Extensive global research has been conducted on MR dampers. Cao et al[3] investigated the mechanical performance of large-load MR dampers in mining trucks under dynamic conditions. They established a constitutive model for MR based on a hyperelastic model and analysed the damping performance of the damper in three dimensions to study the variations in damping characteristics with stress, strain and strain rate. Yu et al[4] proposed optimization criteria for the structural parameters of MR dampers and provided a rational mechanical model which offers guidance for the design and optimization of dampers. Xue et al[5] assumed that the contact angles between the internal metal wires in MR are normally distributed and introduced a cantilever beam model to study the damping performance of MR dampers.

Conventional design methods are still common in the damper development process which involve iterative cycles of design, manufacturing, testing, analysis and improvement, resulting in lengthy development cycles and high research and development costs. Therefore, it is crucial to use advanced design tools such as computer-aided calculation, design and analysis to accelerate the development of dampers. Shi et al[6] obtained a skeleton model of MR samples using computed

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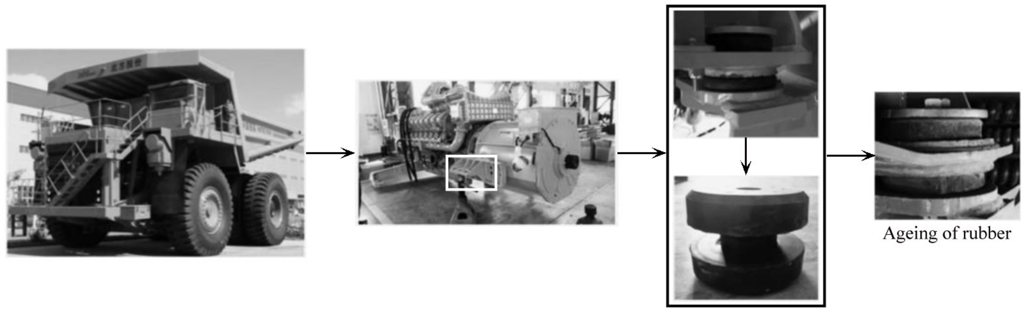

Fig.1 Schematic diagram of rubber damper installation locations on a mining truck

tomography (CT), which can be used to describe the topological features of MR. However, the adhesion between metal wires affects further modelling and simulation results. Rodney[7] and Gadot[8] et al constructed three-dimensional (3D) models of single long-fibre winding materials through X-ray CT, and investigated their internal structure and mechanical properties. Nevertheless, their studies did not consider the influence of material parameters on the structures[9]. Ren et al[10] combined virtual preparation technique to establish constitutive models of macroscopic parameters, such as wire diameter, helix diameter and elastic modulus, with microscopic structural parameters, such as the spatial distribution, contact shape and friction coefficient of metal wires. They also studied the variations in the contact points of the internal metal wires in MR during loading and unloading processes. Results show that virtual preparation technique can construct a 3D model that realistically reflects the macroscopic mechanical properties and microscopic complex structure of MR. However, such models are restricted by the difficulty in establishing a comprehensive material model using the initial modelling method and making reasonable assumptions when setting boundaries. Although a constitutive model can theoretically reveal the nonlinear mechanism of MR, using too many parameters in the quantitative description increases the simulation complexity[11]. Therefore, it is difficult to accurately describe the performance of a vibration absorber through theoretical modelling.

Phenomenological models determine their main parameters and rules through statistical analysis of experimental data, with mathematical models derived by fitting functions such as polynomials to experimental data. Although it is relatively easy to fit functions to experimental data, large amounts of data are required. Zou et al[12] studied the dynamic mechanical properties of MR under high-speed impact loads using a split-Hopkinson pressure bar device and established an empirical constitutive model to predict the mechanical behaviour of material. These models are relatively easy to apply to experimental data using function fitting but require a large amount of experimental data without the fundamental structural parameters of MR. Thus, it is difficult to rationally explain its mechanical performance[13].

The present study combines the advantages of virtual preparation technique and phenomenological models in the design of heavy-duty MR dampers for mining trucks. Virtual preparation technique verifies the feasibility of controlling the structural parameters of MR dampers, and the variable transposition fitting method is used to increase the number of experimental specimens. This allows for the establishment of a mechanical performance model, leading to improved design efficiency and reduced testing costs while further optimizing the performance parameters of the damper. Fig. 2 shows an overview of the research process and structure of this study.

2 Design Scheme for Heavy-Duty MR Dampers

Double-sided clasp-type dampers have anti-slip properties and high reliability which are widely used for vibration control in various equipment. The Barry Controls 44005 T-shaped cylindrical barrel clasp rubber damper is commonly used in heavy-duty mining trucks (Fig. 3). It consists of two hollow rubber cylindrical bosses clamped onto both sides of a connecting plate. It is installed and fixed through a bolt of specific length with a hollow steel tube in the middle. The design primarily considers the pressure area and thickness of the rubber blocks to achieve a suitable distribution of damper stiffness.

2.1 Design requirements for MR dampers

MR is a new type of porous metal material. Compared with similar metal materials, such as metal foam, metal fibre sintered felt and braided wire, it can be prepared using a relatively simple production process with lower cost. The preparation process generally includes: (1) selection of wire material; (2) spiral winding, with the winding radius typically

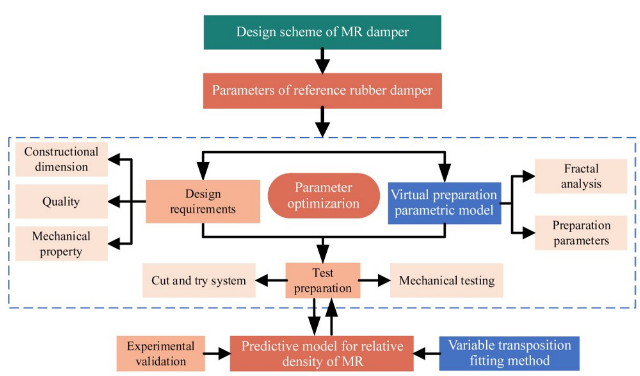

Fig.2 Schematic diagram of research structure and workflow

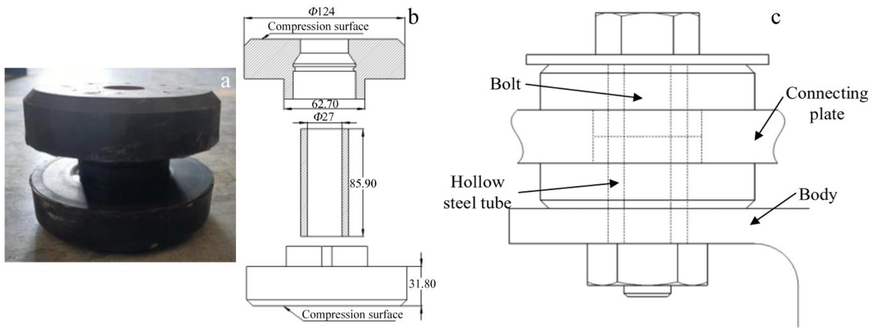

Fig.3 Object drawing (a), dimensional drawing (b), and assembly drawing (c) of rubber damper

5–15 times the wire diameter; (3) pitch stretching, where the pitch is usually approximately equal to the spiral winding diameter; (4) preparation of blanks, with fewer turns of the spiral winding being preferable during blending; (5) cold-stamp forming (single or multiple times); (6) post-processing, such as cleaning and heat treatment. The flowchart for preparing the MR test samples is shown in Fig.4.

The design requirements for the MR isolators, in terms of structural dimensions, weight and mechanical properties, and with reference to the 44005-type mining truck vibration isolators mentioned in the previous section, are as follows.

(1) Structural dimensions

Considering the difficulty of preparing complex shapes in MR such as protrusions, split the two hollow cylindrical protrusions of the rubber vibration isolator into three hollow cylindrical structures (upper, middle, and lower), as shown in Fig. 5a. The dimensions of the MR isolator must match the installation position and dimensions of the original rubber isolator. Excessive changes may affect the normal operation of other important components and the truck's centre of gravity. Therefore, based on the parameters of the 44005-type isolator, the dimensions of the MR isolator were designed, as shown in Fig.5b.

(2) Quality

Although the porous structure formed by wrapped metal wire reduces the overall mass of MR, it is still denser than conventional polymer materials like rubber. Despite the desirable mechanical performance and stability of MR, its high mass remains a necessary design consideration.

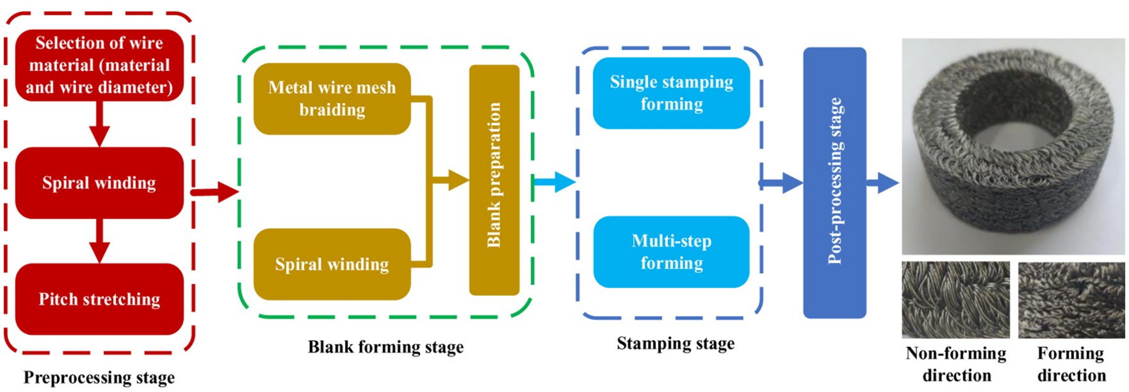

Fig.4 Flowchart for MR preparation process

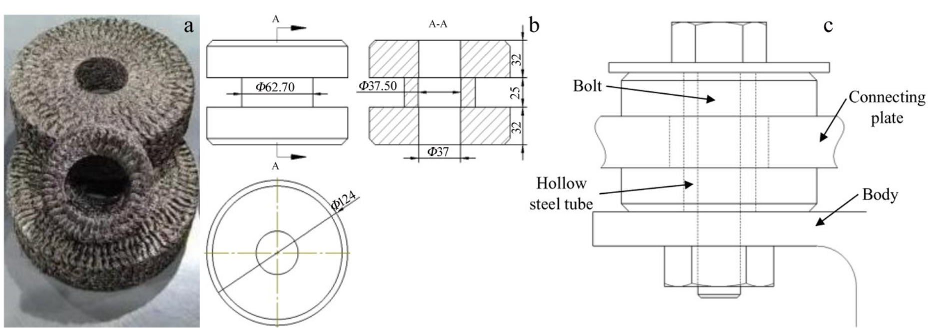

Fig.5 MR damper design: (a) object drawing; (b) dimensional drawing; (c) assembly drawing

3) Mechanical performance

Using MR dampers as alternatives to conventional rubber dampers requires evaluation of their mechanical performance. Quasi-static compression tests can be employed as the primary testing method. By comparing the test curves of MR dampers with those of conventional rubber dampers, feasible design parameters can be determined.

2.2 Virtual preparation based on fractal analysis

Fractal curves can simulate complex natural structures and form, which exhibit self-similarity and have been applied to the analysis of surface textures[14] and pores[15]. In the present study, different fractal curves were compared in terms of their dimensions. After considering their relationship with the shape of the MR wire mesh, the Peano curve with planar filling characteristics was selected. Rapid generation of fractal curves was achieved using an iterated function system, as shown in Fig. 6. However, when comparing the microscopic structure of the MR blank (Fig. 7a) with the Peano fractal curve, it is found that the fractal curves intersecte and the generated paths appear disordered. Therefore, the shape of the Peano curve is modified to obtain the shape shown in Fig.7b.

In this study, the MR preparation parameters (such as wire diameter and dimensions) were incorporated into a 3D model of MR. The specific parameters are as follows.

Fig. 8a is a diagram of single layer of metal wire mesh. Several parameters are labelled. θ represents the winding angle, s is the pitch of the metal wire helix, and D is the diameter of the helix.

Fig. 8b shows several layers of metal wire mesh superimposed to form a cuboidal blank, where h denotes the interlayer distance; L and W indicate the length and width of the mesh, respectively; N represents the number of layers.

Fig. 8c shows the metal wire mesh coiled into a cylindrical blank, where H represents the height of the blank, r is the inner diameter of the coiled mesh, R is its outer diameter, and

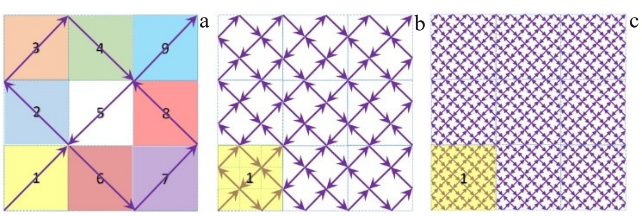

Fig.6 Generation of Peano fractal curves: (a) one iteration; (b) two iterations; (c) three iterations

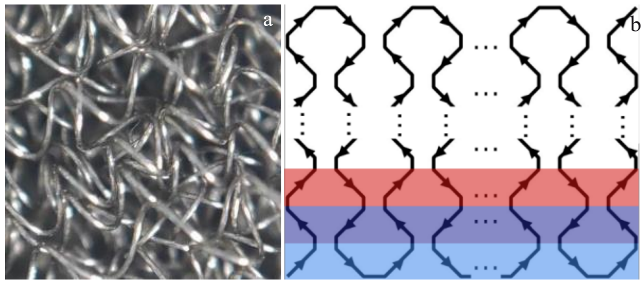

Fig.7 Comparison of metal wire mesh arrangement (a) [16] and corresponding modified Peano curve (b)

P is the interlayer spacing.

Fig. 8 also reveals that, unlike other 3D models of MR, the proposed model uses individual wire strands. This makes it similar to actual MR structures and provides a simplified modelling approach.

The steps used for 3D modelling and parameter calculations are presented below. The parameters are obtained according to the design requirements.

(1) Assume a relative density $\bar{\rho}$ ($\bar{\rho}$ equals ρ_{MR} divided by ρ_{s}, where ρ_{s} is the metal wire density and ρ_{MR} is the sample density), a volume specimen V_{MR}, and a wire diameter d. Then, the volume V_{wire} of the metal wire in the MR sample is:

$$V_{\mathrm{wire}} = \frac{m}{\rho_{\mathrm{s}}} = \frac{m\bar{\rho}}{\rho_{\mathrm{MR}}} = \bar{\rho} V_{\mathrm{MR}} \tag{1}$$

where m is the mass of the MR specimen.

(2) Assuming a fractal curve iteration count n, we can set dimensions L and W of the single-layer metal wire mesh, the winding angle θ, the pitch s, and the helix diameter D. The skeletal line L_{axis} of the single-layer metal wire mesh can be extracted using software. Then, the length L_{lay} of the metal wire spiral coil is given by:

$$L_{\mathrm{lay}} = \frac{L_{\mathrm{axis}}}{s} \sqrt{(\pi D)^2 + s^2} \tag{2}$$

(3) Depending on the design requirements, the MR blank can be prepared by either superposition or coiling. If superposition is used, the number of layers N for the stacked blank is determined as follows:

$$N = \frac{V_{\mathrm{wire}}}{\pi \left(\frac{d}{2}\right)^2 L_{\mathrm{lay}}} \tag{3}$$

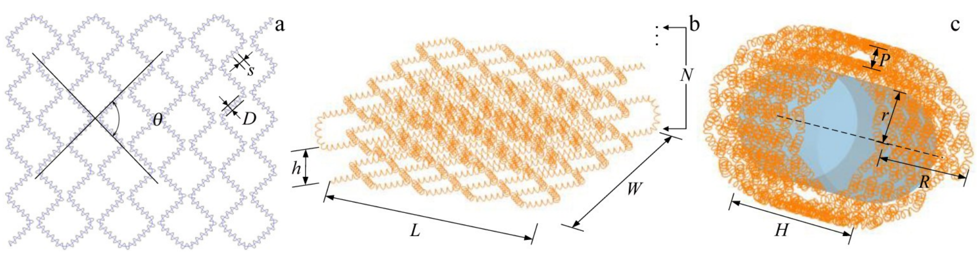

Fig.8 Schematic diagrams of stages of MR blank preparation: (a) single layer of wire mesh; (b) stack of wire mesh layers; (c) coiled stack of mesh

If coiling is chosen, the inner diameter r and the interlayer spacing P of the metal wire mesh coil are set. According to the mathematical formula of the Archimedean spiral, we set the Archimedean spiral coefficient a (distance from the starting point to the polar coordinate origin). Then, the polar angle θ_1 of the starting position for coiling is given by:

$$\theta_1 = \frac{2\pi(r-a)}{P} \tag{4}$$

When coiling the metal wire mesh, the coordinates in the metal wire mesh model should satisfy the arc length formula of the Archimedean spiral:

$$L_i = \frac{1}{2b}\left[(a+b\theta_2)\sqrt{(a+b\theta_2)^2+b^2}-(a+b\theta_1)\sqrt{(a+b\theta_1)^2+b^2}\right]+\frac{b}{2}\left[\ln\left(a+b\theta_2+\sqrt{(a+b\theta_2)^2+b^2}\right)-\ln\left(a+b\theta_1+\sqrt{(a+b\theta_1)^2+b^2}\right)\right] \tag{5}$$

where θ_2 denotes the polar angle corresponding to the metal wire mesh, b represents another Archimedean spiral coefficient (indicating the increase in polar radius for each unit increase in spiral angle), and L_i signifies the distance of a coordinate point in the metal wire mesh model from the starting edge of the coiled spiral.

The outer diameter R of the metal wire mesh coil is equal to the polar radius corresponding to the polar angle obtained when the arc length L_i is equal to L.

4) Utilizing modelling software, drew a spiral line with the MR blank framework wire as the axis to obtain a 3D blank model of the MR.

5) Based on the designed height of the test piece, stamping simulation was performed on the 3D blank model. The feasibility of the design parameters was evaluated by analysing the contact relationships between wires under different design parameters. The virtual preparation process of a MR cushion ring model is shown in Fig.9.

2.3 Preparation and mechanical testing of MR damper prototype

Relative density is not only a key parameter characterizing the damping performance of MR, but also related to the mass of the material. On the one hand, an overly dense sample will have poor damping performance and vibration reduction. On the other hand, if the relative density is too low, the sample becomes soft and unable to withstand heavy-loads, consequently reducing its service life. Based on the reference dimensions of rubber vibration isolators, the design requirements and virtual preparation method mentioned earlier, four sets of MR vibration isolators were prepared. Grade 304 austenitic stainless steel (06Cr19Ni10) wire was used to create annular samples with relative densities of 2.5, 3.0, 3.5 and 4.0 g·cm^{-3}. The material parameters for the coiled metal wire are presented in Table 1.

Experiments were conducted using a static electronic universal testing machine (Tianchen WDW-200). Quasi-static compression tests were performed on the four groups of samples with different relative densities (Fig.10).

The force-displacement curve of a conventional 44005-12 rubber damper lies between those of the MR dampers prepared with relative densities of 2.50 and 4.00 g·cm^{-3} (Fig. 11). This indicates that, in terms of mechanical performance, these dampers can substitute for the specified conventional damper, which provides a reference for the design and optimization of damper performance.

3 Predictive Model of MR Dampers According to Relative Density

3.1 Function fitting

To reflect the mechanical behaviour of the MR dampers and their real deformation more accurately during loading, the experimental data were transformed into true stress-strain curves according to Ref.[17]. The least squares method was employed to fit the experimental data with a double

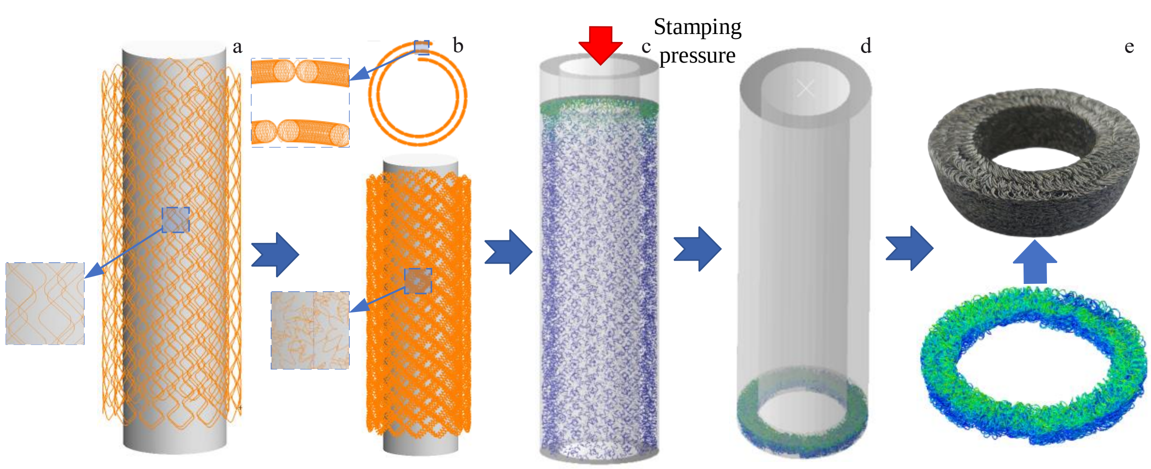

Fig.9 Generation process of a MR numerical model: (a) baseline, (b) spiral coil, (c) stamping initial, (d) holding pressure, and (e) stamping end

Table 1 Material parameters of spiral coil

Material	Diameter/ mm	Pitch/ mm	Wire diameter/ mm	Wire density/ $g·cm^{-3}$
06Cr19Ni10	3.0	3.0	0.3	7.93

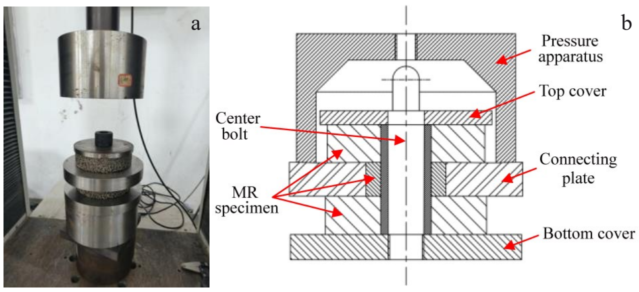

Fig.10 Quasi-static compression testing of MR dampers: (a) experimental diagram; (b) structural diagram

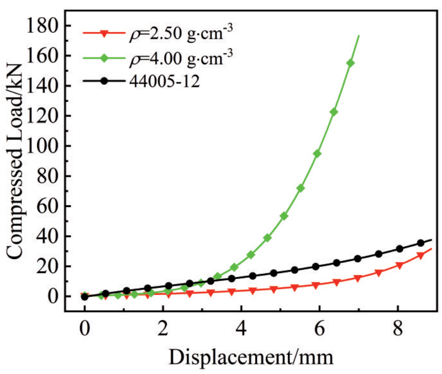

Fig.11 Comparison of compressed load-displacement curves of conventional rubber dampers and MR dampers with relative densities of 2.50 and 4.00 $g·cm^{-3}$, respectively

exponential function of $f(x)=ae^{bx}+ce^{dx}$. The resulting function coefficients for each test group are presented in Table 2.

To better observe the mechanical performance of MR dampers, the true stress-strain curves of the four groups were introduced into a 3D coordinate system with relative density represented on one of the axes, as shown in Fig. 12a. Subsequently, surface fitting using the Griddata interpolation method was used to build the prediction model, as illustrated in Fig. 12b. As can be seen from Fig. 12b, directly fitting the surface using the stress-strain curves of the four experimental groups results in abnormal convex or concave shapes. This may be due to the limited amount of experimental data available and the relatively large differences in relative densities.

3.2 Variable transposition fitting method

Fig. 12b shows the true stress-strain curves obtained at different relative densities fitted onto a surface. Relative density was considered to be the primary variable and the true stress and strain were the two secondary variables. To improve the accuracy of surface fitting, a variable transposition fitting method was employed. By exchanging the primary and secondary variables, true strain could be treated as the primary variable while relative density and true stress were the secondary variables. Curve fitting was conducted on the relative density and true stress at different true strains. This method effectively increases the number of data points and improves the accuracy of the fitted surface. The steps of this method, based on the Matlab programming language, are as follows.

(1) Set the range of values for the primary variable, such as real strain, with parameter values from linspace (0, 0.21, 100).

(2) Input the primary variable into the equation of the real stress-strain curve of each experimental group and set the corresponding relative density as a constant to form a 3D coordinate matrix (four 100×3 matrices).

(3) Recombine all 3D coordinate matrices using cell arrays. Extract the secondary variables (such as relative density and real stress) that correspond to the same primary variable (i.e., real strain) to form a cell, with each cell containing a two-dimensional (2D) coordinate matrix (4×2, totalling 100). Fit each set of data in each cell using a function (such as a Fourier function).

(4) Set the range of values for the secondary variable—relative density with linspace (2.5, 4, 50). Input it into the corresponding fitted equation for each cell and obtain a 2D coordinate matrix (50×2, totalling 100).

(5) Unroll the cell array and input the corresponding primary variable (such as real strain) to obtain a 3D coordinate matrix (50×3, totalling 100), which represents the fitted surface for the relationship between relative density and real stress, as shown in Fig.13.

(6) Finally, use the grid data interpolation method for non-linear surface fitting.

3.3 Experimental verification

To validate the reliability and accuracy of the predictive model established for surface fitting, MR dampers with the same external dimensions and a relative density of 3.75 $g·cm^{-3}$ were prepared as a control group for quasi-static compression tests. Fig. 14 compares the curve of the control group and the fitted surface of the predictive model.

To further validate the accuracy of the predictive model, its results before and after applying the improved method were

Table 2 Function coefficients fitted to experimental data of each group

Relative density/$g·cm^{-3}$	*a*	*b*	*c*	*d*	Root mean square error, RMSE
2.50	0.0736	11.1700	0.0039	26.5700	0.0302
3.00	2.5970	26.6420	−2.5474	26.6876	0.0656
3.50	26.0481	33.6195	−25.9691	33.6308	0.0743
4.00	4.7070	37.6731	−4.6553	37.7170	0.1008

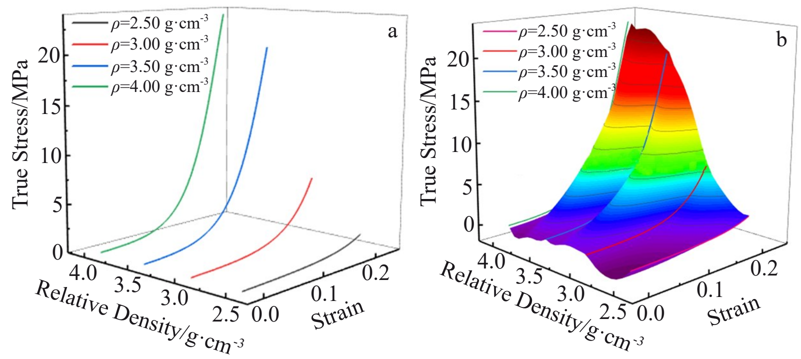

Fig.12 Fitted true stress-strain curves (a) and surfaces (b) of MR dampers

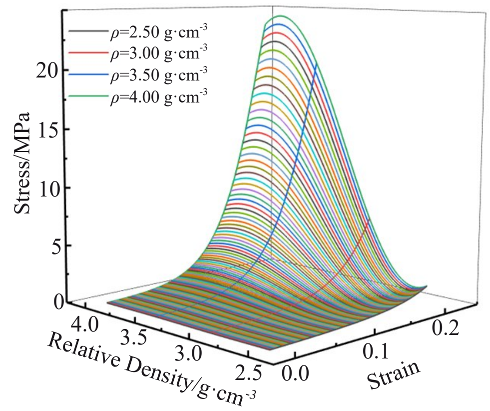

Fig.13 Fitted curves using improved method

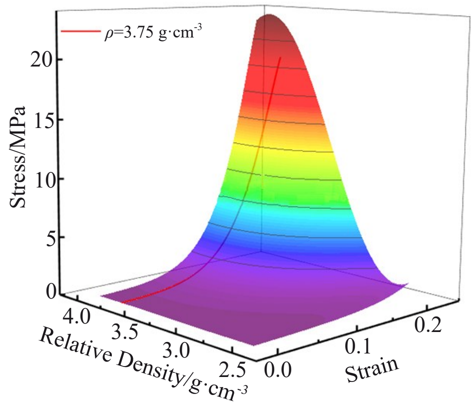

Fig.14 Comparison between experimental curve and fitting surface of improved predictive model

compared with the experimental results at a relative density of 3.75 g·cm^{-3}, as shown in Fig.15.

To avoid experimental errors caused by factors such as measurement accuracy and white noise, and to effectively estimate the accuracy of the proposed model, residual analysis was conducted on the theoretical predictions. Residual analysis is an effective method for evaluating the accuracy of a model. It examines the differences between the experimental results and the predicted values. The coefficient of determination R^2 is commonly used to measure the

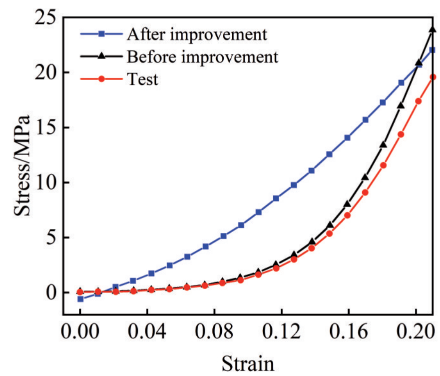

Fig.15 Comparison of experimental results at a relative density of 3.75 g·cm^{-3} and predictive results before and after model improvement

effectiveness of the model, with higher values indicating a greater predictive accuracy.

$$\mathrm{RSS} = \sum_{i}^{n}(y_i - \hat{y}_i)^2 \tag{6}$$

$$\mathrm{TSS} = \sum_{i}^{n}(y_i - \bar{y}_i)^2 \tag{7}$$

$$R^2 = 1 - \frac{\mathrm{RSS}}{\mathrm{TSS}} \tag{8}$$

where RSS represents the residual sum of squares, TSS denotes the total sum of squares, n is the specimen size, y_i stands for experimentally observed values, $\hat{y}_i$ indicates the model-predicted value, and $\bar{y}$ represents the mean of the observed values. The residual analysis results for the MR damper samples are shown in Table 3.

The curves obtained from the predictive models before and after improvement show consistency, as shown in Fig.15 and the residual analysis results in Table 3. The proposed surface-fitting predictive model enhanced by the variable transposition fitting method shows greater accuracy than the original model.

Table 3 Residual analysis results for the MR damper

Parameter	RSS	TSS	R^2
Before improvement	2228.4507	4527.3206	0.5078
After improvement	161.6025	4293.2265	0.9624

4 Conclusions

1) By analysing the structure and performance parameters of traditional rubber shock absorbers under heavy-loads, the relevant design requirements for MR shock absorbers are summarized in terms of structural dimensions, quality and mechanical properties. This saves design time and cost.

2) Fractal curves are employed to describe complex structures, enabling the construction of a numerical model that accurately represents the microstructural characteristics of MR rubber. This opens up new avenues for research in this field.

3) Virtual preparation techniques are utilized to create a finite element model that can evaluate various parameters of MR based on its process parameters. This allows for quick assessment of design feasibility, reduces testing requirements and enhances the overall efficiency of designing MR products.

4) Through trial production tests of MR vibration isolators, a variable inversion fitting method is proposed, which adds data points to the relative density mechanical prediction model to improve its accuracy without increasing testing costs or time consumption. This approach highlights the importance of using flexible adjustment strategies during data analysis, expecially when dealing with complex multivariate relationships. This holds significance for the engineering design and optimization of MR devices.

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基于相对密度力学预测模型的大载荷金属橡胶构件试制

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摘　要：针对大载荷矿用车动力总成悬置系统，研究了大载荷金属橡胶减振器的设计与预测模型。通过基于分形图学描述金属橡胶的微观结构特征，并利用虚拟制备技术建立数值模型，提出了金属橡胶构件的设计方案。试制了4组不同相对密度的金属橡胶减振器，并通过力学试验建立了基于相对密度的预测模型。为进一步提高预测精度，提出了一种变量转置拟合法对预测模型进行改进。通过与对照组试验结果对比，用残差分析定量验证。结果显示，改进后的模型具有较高的预测精度，决定系数R^2达到0.9624。这项研究为金属橡胶减振器设计提供了理论支持，可减少试验次数并提高设计效率。

关键词：金属橡胶；分形图学；制备方案；力学模型；性能预测

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