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Mechanical properties of magneto-sensitive shear thickening fluid absorber and application potential in a vehicle

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ABSTRACT

A multifunctional smart material with both shear thickening effect and magnetorheological performance was fabricated by dispersing carbonyl iron powder (CIP) particles into shear thickening fluid, the properties and application potential were tested and analysed. Firstly, the rheological properties of this type of magneto-sensitive shear thickening fluid (MSTF) was tested by a rheometer. Besides, the influence of the current, frequency and amplitude on the mechanical properties of the absorber with MSTF was studied. Finally, the damping force and the variation rules of the Cadillac shock absorber with commercial magnetorheological fluid and MSTF were tested, compared and analysed at different currents and distinct velocities. The influence of the shear thickening effect of MSTF on the damping force in the shock absorber was studied by testing the self-made MSTF and MRF with the CIP fraction from 10% to 70%. This work provided a design idea to improve the shock absorber performance.

1. Introduction

Shear thickening (ST) is a common phenomenon that the viscosity of this kind of materials will increase with the increasing external shear rate. Under normal circumstance, ST materials are relatively soft. Once these materials are subjected to high speed impact, they will become stiff in response to the external loads [1–3]. Interestingly, the materials will return to the initial soft state when the impact or load is removed [4–6]. Due to the nonlinear mechanical properties and continuous reversibility, in recent years, this type of stimuli-sensitive materials has attracting increasing interest worldwide, and has been widely used in the application of damper, personal armour and vibration control [7–12].

According to the distinct carrier, the ST materials involve shear thickening gel (STG) and shear thickening fluid (STF). STG, represented by Silly Putty and D3O, can be effortlessly kneaded into any shape desired under normal conditions and is mainly used as the protective function material [13] and shock transmission unit [14]. While STF was first proposed in 1938 and recently used to improve the protective ability of the fibre, such as Kevlar [15,16], Twaron [17] and ultra-high molecular weight polyethylene [18,19]. Besides, STF also shows the application potential in the fields of crash safety of the battery [20–22], noise reduction [23], polishing [24,25], cutting tools [26], vibration control [27] and impact resistance [28].

Nowadays, in the practical vehicle industry, most of the absorbers in luxury cars are magnetorheological shock absorbers [29–32]. The magnetic particles in magnetorheological fluid (MRF) will transform from a disordered structure to an ordered structure in the presence of an external magnetic field or an electrical field, resulting in the variation of the viscosity of MRF [33,34]. However, the absorber based on the MRF cannot play a role in the vehicle in the event of an electrical failure, the viscosity and property of MRF also cannot be regulated actively in the absence of a magnetorheological field.

STF can passively respond to the external excitation, especially the shear rate, and with the increasing external shear rate, the viscosity of STF shows a rapid increase of 2–3 orders of magnitude [35–37]. Furthermore, due to the reversibility of ST materials and the liquid state of STF under normal conditions, the fatigue of shock absorber in stress is

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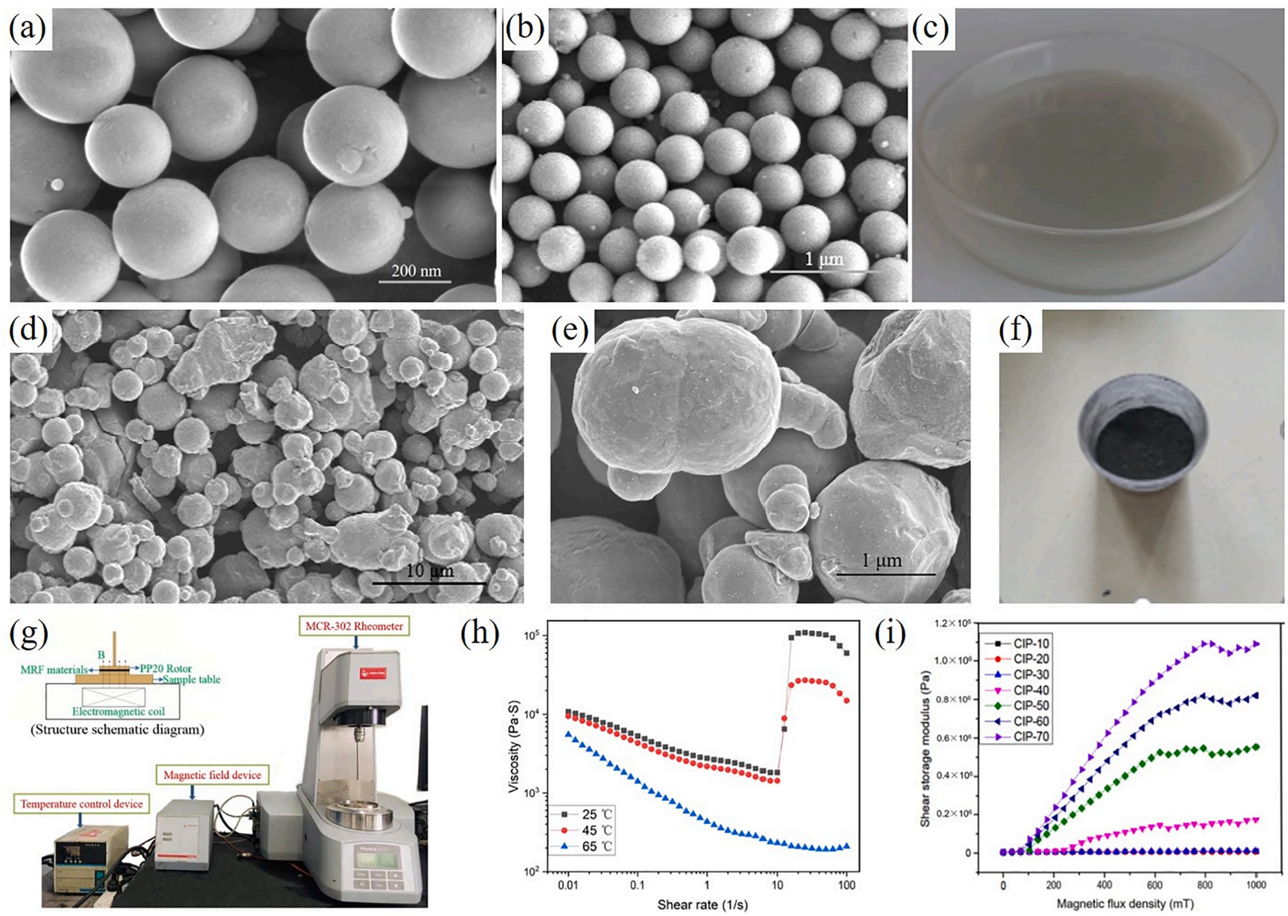

Fig. 1. The (a)(b) SEM micrographs of SiO_2 used in the test, (c) STF prepared, (d)(e) SEM micrographs of CIP particles, (f) CIP particles used in the test, (g) MCR-302 series rheometer, (h) shear thickening effect and (i) magnetorheological performance of MSTF.

reduced [38]. After adding the magnetic particles in the preparation procedure of STF, the mechanical properties of this kind of materials can also be actively regulated in a magnetic field as MRF.

In this work, the magneto-sensitive shear thickening fluid (MSTF) that exhibits both shear thickening and magnetorheological effects was prepared by dispersing carbonyl iron powder into the carrier with ST performance. The rheological properties of MSTF and mechanical properties at different currents, frequencies and amplitudes of the self-made absorber with MSTF were tested. The damping forces of the MSTF magnetorheological shock absorber were measured at distinct velocities of the piston, and the results were also compared with the same type of commercial magnetorheological shock absorber. Finally, the influence of the shear thickening performance on the damping force was studied by testing the same CIP mass fraction of self-made MSTF and MRF.

2. Materials and methods

2.1. Preparation of MSTF

In the preparation procedure of MSTF, the experimental materials include polyethylene glycol (PEG, Sinopharm Chemical Reagent Co., Ltd.), nanoscale spherical SiO_2 particles (Shanghai Bu Micro Applied Materials Technology Co., Ltd.) and the carbonyl iron powder (CIP, Jiangsu Tianyi Ultra-fine Metal Powder Co., Ltd) with an average particle size of 3.50 μm.

The SiO_2 particles were as the dispersed phase, which were added into the PEG200 and then put into a ball mill for 24 h at room temperature. After dispersing a certain amount of CIP into the mixture, the MSTF was finally prepared. Before the magnetic saturation, the magnetorheological effect of MSTF is in direct proportion to the CIP content added in the preparation procedure. The SEM micrographs of SiO_2 and CIP, STF prepared and the machine testing the rheological properties of MSTF are as shown in Fig. 1.

2.2. Methods

2.2.1. Rheological test (shear thickening effect)

The rheological properties of MSTF were tested using the MCR 302 (Anton Paar Co., Austria) series rheometer with cone-plate geometry (25 mm in diameter and 2° in cone angle). All the experiments were tested with a gap size of 0.05 mm at the temperature of 25 ℃, 45 ℃ and 65 ℃. The SEM micrographs were conducted by the ZEISS Gemini SEM 500 (Carl Zeiss Co., LTD, Shanghai, China).

2.2.2. The mechanical properties test (MSTF in self-made absorber)

The self-made absorber is mainly composed of a piston, a piston rod, a shell, an electromagnetic coil, etc. The variation rules of the mechanical properties of the absorber with MSTF were tested using the SDS-500 electro-hydraulic servo fatigue experimental machine. The

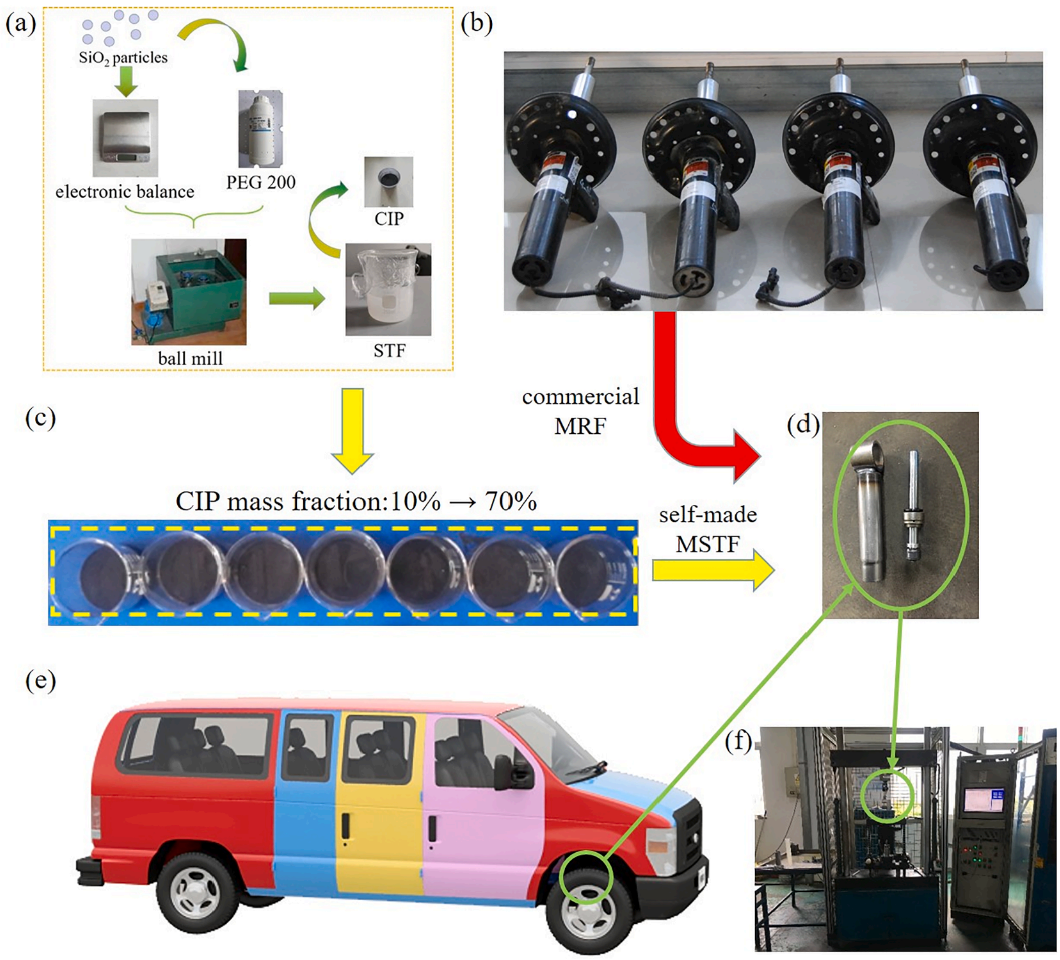

Fig. 2. The (a) preparation procedure of MSTF, (b) Cadillac 36E010 type of the magnetorheological shock absorber, (c) MSTF prepared with different CIP mass fractions, (d) shock absorber used in the test, (e) the vehicle model and (f) test system.

testing system includes a universal testing machine, squeeze and stretch experimental device, temperature sensor and power supply. Several groups of comparison experiments with distinct frequencies, amplitudes and currents were conducted, and the corresponding curves were recorded at the same time.

2.2.3. The damping force test (MSTF and commercial MRF in shock absorber)

The Cadillac 36E010 type of the magnetorheological shock absorber was used to test the damping force at different linear velocities of the piston. The velocity of the piston is set as 0.079, 0.157, 0.314 and 0.520 respectively in the unit of m/s according to the actual velocity of the piston in the shock absorber during the working process of the vehicle. In addition to the velocity, the current is another variable setting as 0 A, 0.5 A, 1.5 A and 2 A. The testing machine used in this experiment is DH-SG-2 type of shock absorber test system. The materials used in the experiment, shock absorber and the test system are shown in Fig. 2.

3. Results and discussion

3.1. The characterization of the self-made absorber with MSTF

A type of self-made shock absorber was manufactured, assembled and the SDS-500 electro-hydraulic servo fatigue experimental machine are as illustrated in Fig. 3. In the working process, the cavity is filled with magneto-sensitive shear thickening fluid, and as the piston moves up and down, the MSTF in the cavity circulates.

To test the mechanical properties of the shock absorber with MSTF, and to study the influence of the frequency, current and amplitude on the damping force of the absorber, the hysteretic loop in each case was tested and analysed, and the results were as shown in Figs. 4-6.

In Fig. 4, the damping forces vary linearly as the amplitude is 1 mm (Fig. 4(a) and (b)), and change nonlinearly (especially at high frequency) when the amplitude is set as 4 mm (Fig. 4(c) and (d)). Furthermore, the damping force–displacement curves obtained at 0.1 Hz, 0.5 Hz, 1.0 Hz and 5.0 Hz are not different significantly, which indicates that the damping force is almost insensitive to the frequency as the amplitude is small, as demonstrated in Fig. 4(b).

At the zero magnetic field, the CIP particles are distributed disorderly in the carrier, the damping force has a wide range of fluctuation due to the free movement of the CIP particles. On the contrary, once the current is set as 3 A, most of the CIP particles are fixed along the magnetic induction line, resulting in a small fluctuation of the damping force, that is, the current can increase the damping force value while reduce its fluctuation.

Through the comparison between Fig. 4(a) and (b), the increase of

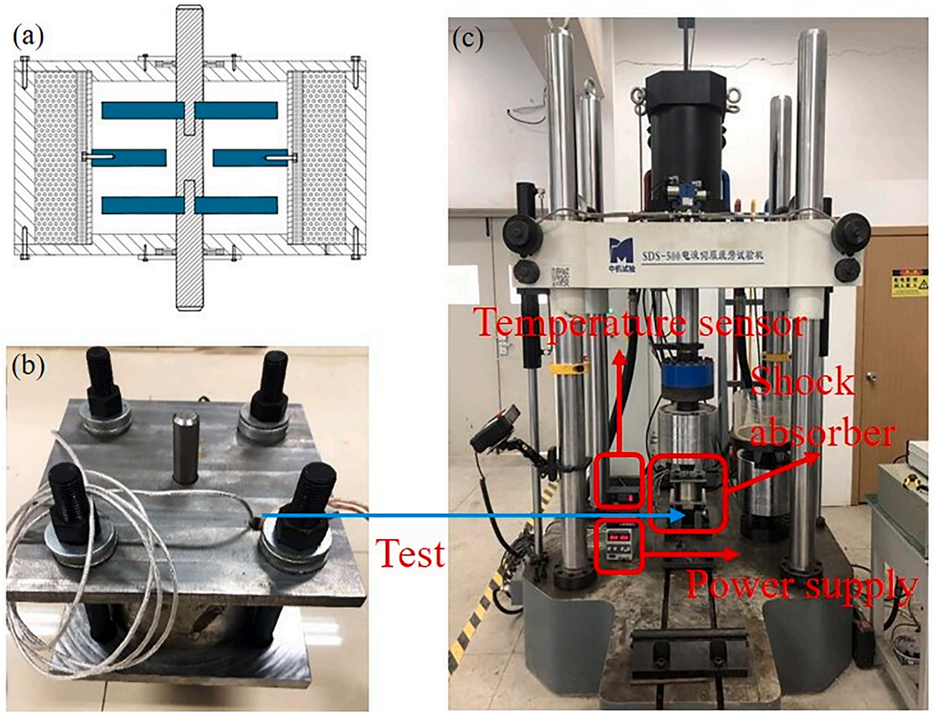

Fig. 3. (a) The schematic diagram the shock absorber, (b) the assembled shock absorber, and the (c) SDS-500 electro-hydraulic servo fatigue experimental machine.

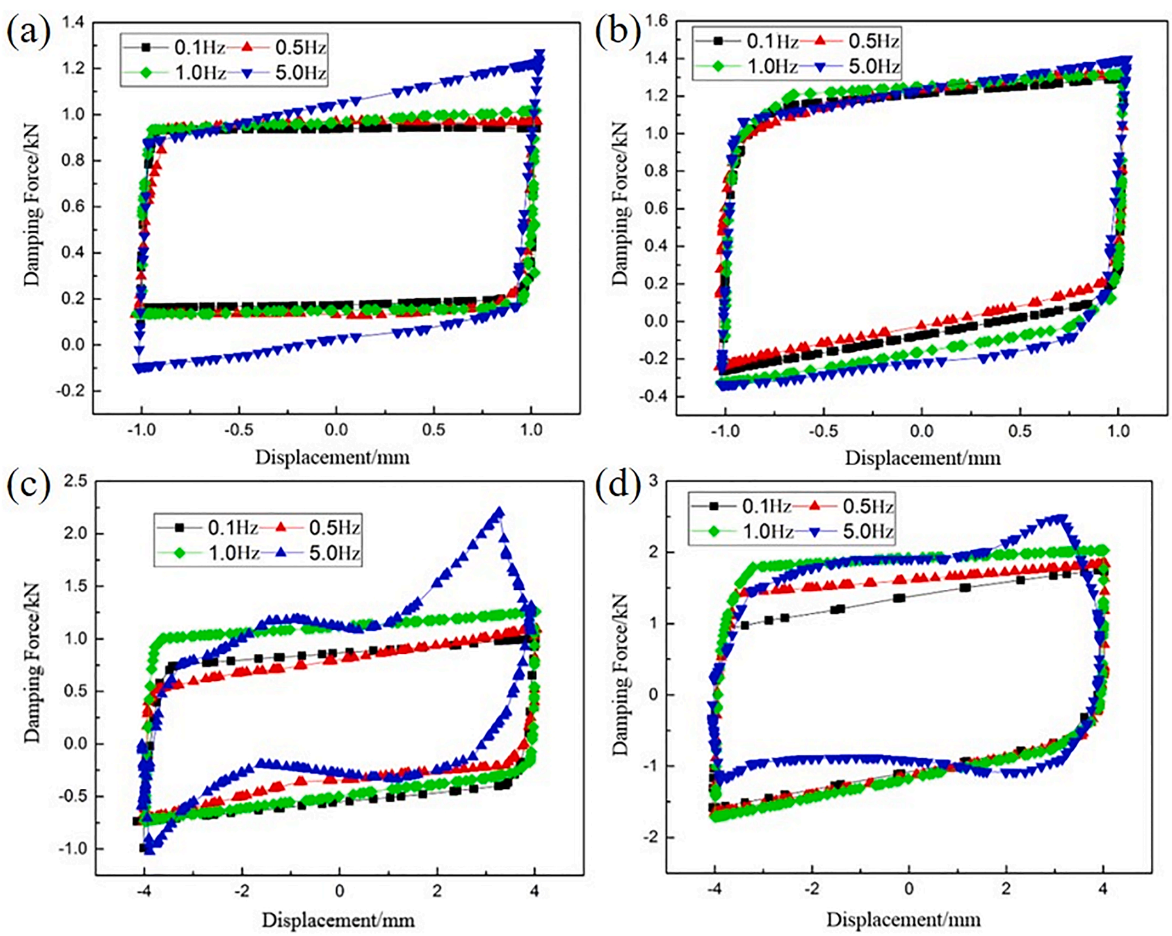

Fig. 4. The damping force-displacement curves of the MSTF self-made absorber at (a) 1 mm amplitude and 0 A current, (b) 1 mm amplitude and 3 A current, (c) 4 mm amplitude and 0 A current and (d) 4 mm amplitude and 3 A current and the relationship curves.

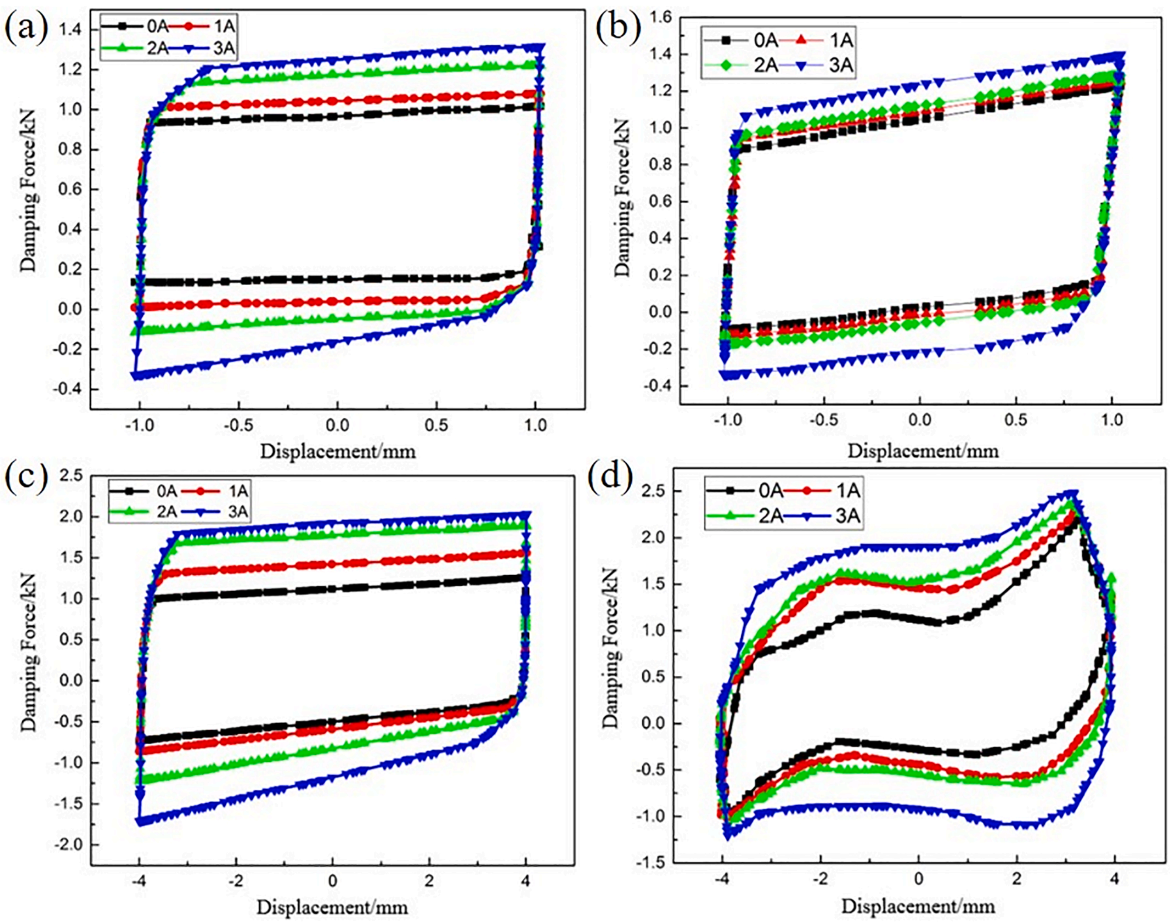

Fig. 5. The damping force-displacement curves of the MSTF self-made absorber at (a) 1 mm amplitude and 1 Hz frequency, (b) 1 mm amplitude and 5 Hz frequency, (c) 4 mm amplitude and 1 Hz frequency and (d) 4 mm amplitude and 5 Hz frequency and the relationship curves.

the damping force can be realized by a more ordered magnetic particle chain, which is similar to the magnetorheological materials. The magneto-sensitive materials can be converted from liquid state to solid state and actively controlled at the presence of an external current or a magnetic field.

With the increasing amplitude and frequency, the nonlinearity of the damping force-displacement curves increases significantly even the current is set as 0 A in Fig. 5(d). According to Fig. 5(b), (c) and (d), the nonlinear variation of the damping force is obvious only at high frequency and large amplitude at the same time. Besides, the value of the damping force is increased by 10% ~ 25% approximately for each 1 A current increase in all the groups of tests. In Fig. 5, the variation rule of the damping-displacement curve (linear or nonlinear) tested at the current of 0 A is always consistent with the curve tested at the current of 3 A, which indicates that the changing rule of the shock absorber with MSTF cannot be changed extremely by the different currents.

It is obvious that with the increasing amplitude, there is a remarkable increase in the nonlinearity of the damping force at high frequency, as shown in Fig. 6(b) and (d). As the current increases from 0 A to 3 A, the area surrounded by the force-displacement curve increases slightly as the amplitude is set as 1 mm, 3 mm and 4 mm in Fig. 6(a) and (c). It also can be drawn from Fig. 6(b) and (c) that the nonlinear mechanical performance of the shock absorber with MSTF is more sensitive to the frequency than the current.

It can be drawn from the damping experiments and the changing rules that the nonlinear variation of the damping force of the shock absorber based on the MSTF only occurs at high frequency and large amplitude, especially the damping–displacement curve tested at 5 Hz frequency in Figs. 4(c), (d), 5(d), 6(b) and (d). As a kind of rate-sensitive material, the viscosity of MSTF demonstrates a nonlinear increase with the increasing external shear rate, resulting in the nonlinear variation rules of the damping-displacement curve of the shock absorber with MSTF when the testing velocity is high. As the amplitude is small, the frequency is almost insensitive to the damping force values, however, with the increasing amplitude, the damping force gradually increased by the increase of the frequency. Moreover, the damping force increases by 10% ~ 25% for each 1 A current increase (within the range from 0 A to 3 A), and the fluctuation of the damping force can be reduced by the increasing current when the shock absorber works at a high frequency and large amplitude due to a more regularly arranged magnetic particles in the carrier.

3.2. The application potential of MSTF in magnetorheological shock absorber

3.2.1. The shock absorber with self-made MSTF and commercial MRF

Nowadays, the most used shock absorbers in the suspension system of the vehicle are mainly divided into traditional hydraulic oil shock

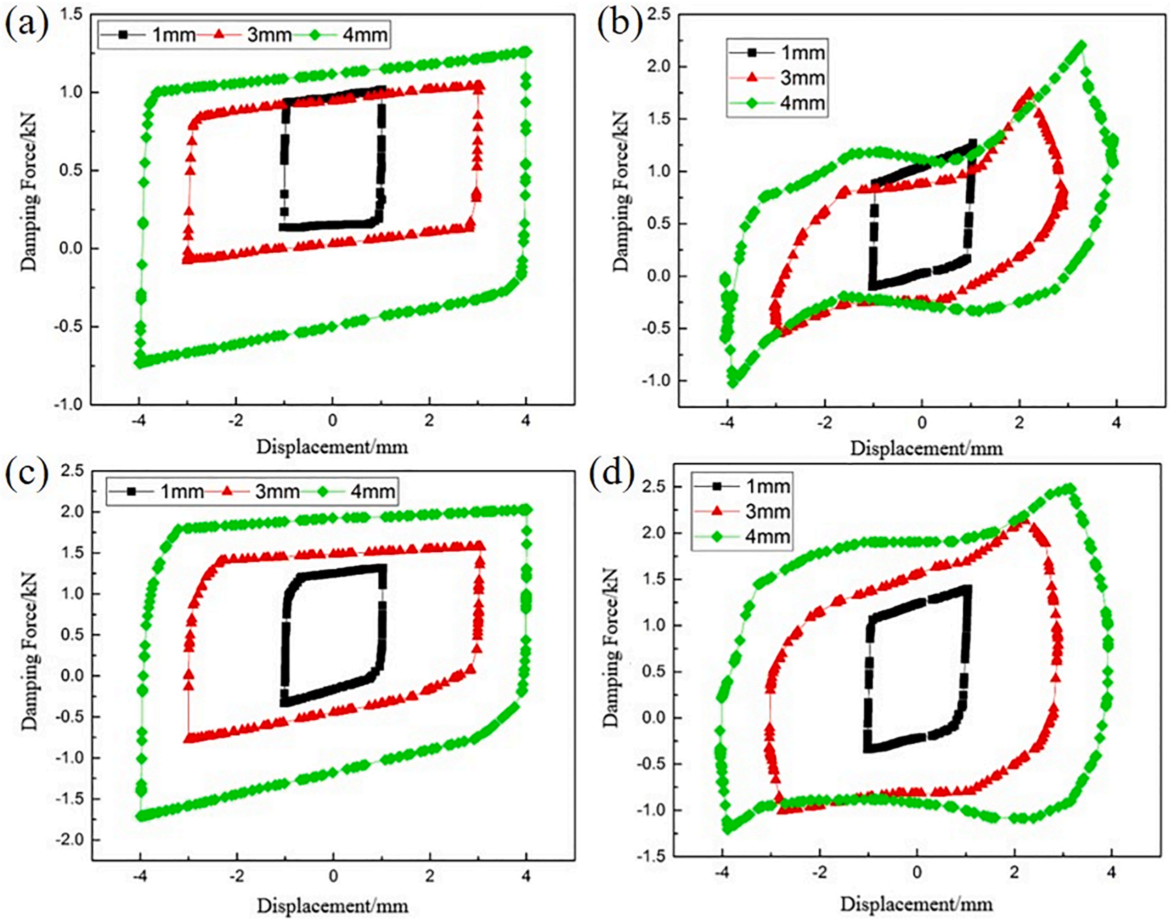

Fig. 6. The damping force-displacement curves of the MSTF self-made absorber at (a) 0 A current and 1 Hz frequency, (b) 0 A current and 5 Hz frequency, (c) 3 A current and 1 Hz frequency and (d) 3 A current and 5 Hz frequency and the relationship curves.

absorber (without the current) and magnetorheological absorber (with the current). The magnetorheological shock absorber is commonly used in the high-end vehicles, such as Ferrari (599 GTB Fiorano, California and 458 Italia), Audi (TT, R8 and A5) and Cadillac (XT6), etc.

In this experiment, the same amount of self-made MSTF and commercial magnetorheological fluid are used as the smart materials. According to the actual velocities during the working process, the linear velocities of the piston of the shock absorber in the test are 0.079 m/s, 0.157 m/s, 0.314 m/s and 0.520 m/s respectively.

In the application of the magnetorheological shock absorber, the changing viscosity of MRF of MSTF is due to the external applied electrical or magnetic field, in addition to being sensitive to the external field, the damping force of the absorber with MSTF differs according to the different linear velocities of the piston. To study the variation rules of the damping force, the shock absorber with self-made MSTF at several groups of currents were tested, and the parts of the results are illustrated in Fig. 7.

In Fig. 7, the abscissa axis in the indicator diagram shows the working stroke in the unit of mm, the ordinate axis represents the force value in the unit of N, including the rebound force (above the 0 axis) and the compression force (below the 0 axis). The area surrounded by the stroke-force curve indicates the energy dissipation ability of the absorber. Clearly in Fig. 7, the symmetry of the indicator diagram is excellent which indicates that the CIP particles disperse uniformly in the carrier with shear thickening performance. The variation rules of the damping forces of the shock absorber with MSTF at distinct velocities and currents are demonstrated in Fig. 8.

The rebound forces of the MSTF absorber are higher than the compression forces under the same testing conditions, and the damping forces can be improved by both the current and the linear viscosity of the piston significantly. However, if the current is too large or the mass fraction of the CIP is too high, the liquidity of the MSTF will be reduced, resulting in the increasing asymmetrical performance of the indicator diagram. The stroke-force curves of the same type of shock absorber with commercial MRF are demonstrated in Fig. 9.

As shown in Fig. 9(c), (d) and (e) (commercial materials), the symmetry and smoothness of the indicator diagrams are better than the diagrams in Fig. 7 (self-made materials). The damping forces and the increase rate of the compression force and rebound force at different velocities and currents are illustrated in Fig. 10.

With the increasing piston velocity, the increase rates of the damping forces of the absorber with MSTF from 0.079 m/s to 0.520 m/s range

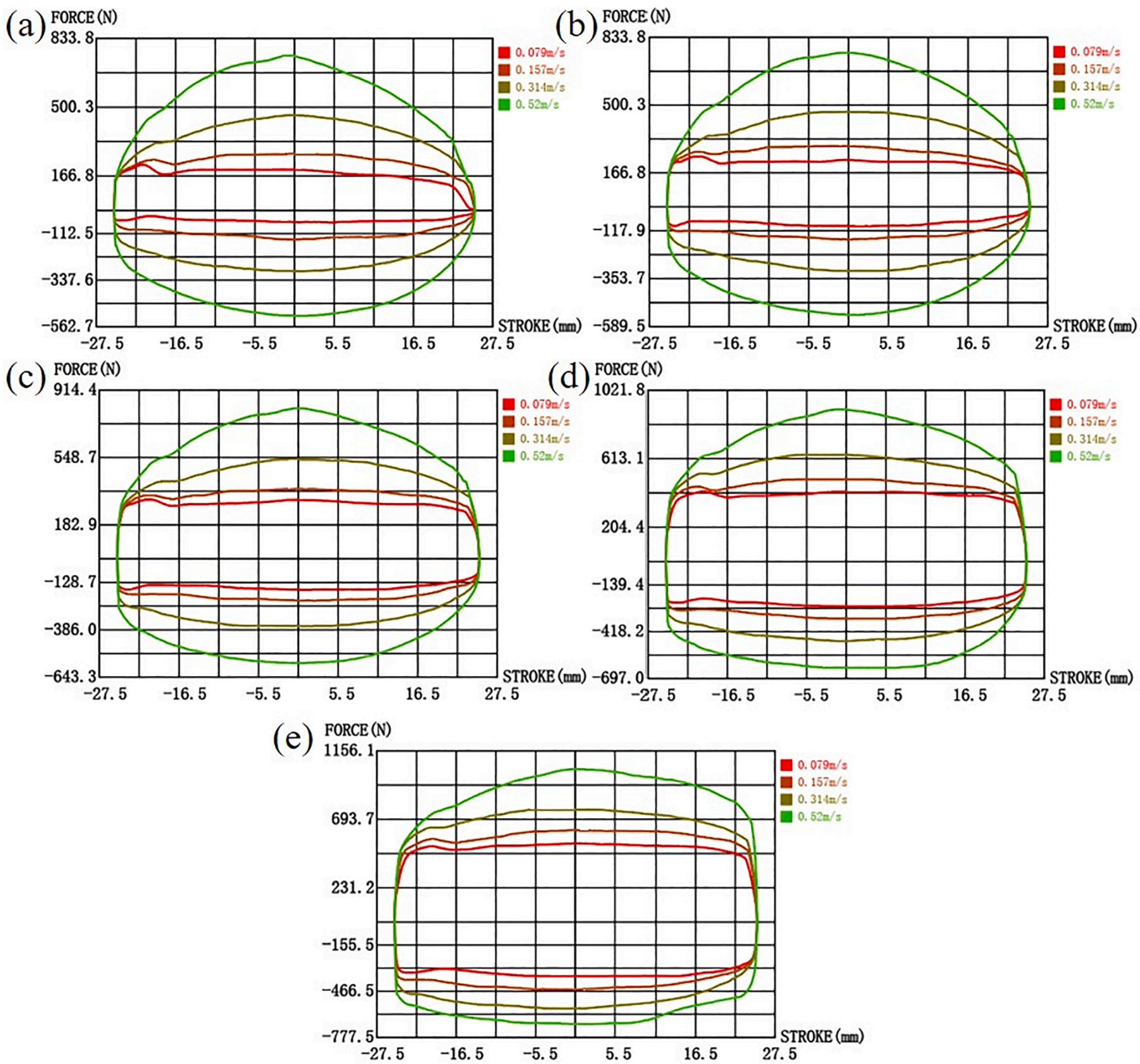

Fig. 7. The indicator diagram of the shock absorber with self-made magneto-sensitive shear thickening fluid at distinct velocities and at (a) 0 A, (b) 0.5 A, (c) 1.0 A, (d) 1.5 A and (e) 2.0 A.

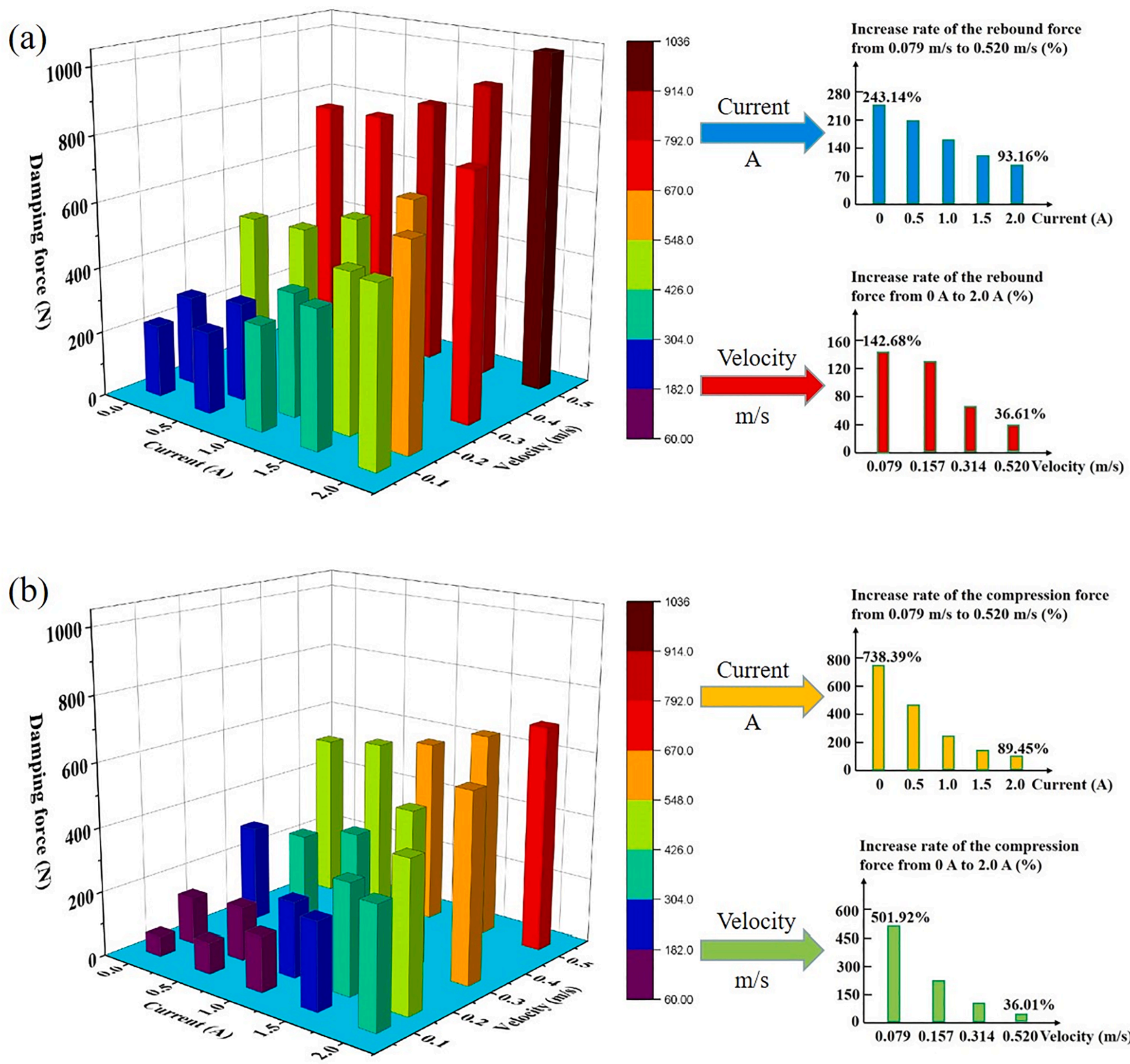

Fig. 8. The changing rules and the increase rate of the (a) rebound force and (b) compression force from 0.079 m/s to 0.520 m/s of the shock absorber with MSTF at distinct velocities and different currents.

from 93.16% to 243.14% (rebound force) and 89.45% to 738.39% (compression force). For the commercial MRF absorber, the increase rates of the forces are 57.05% to 393.19% (rebound force) and 40.66% to 132.09% (compression force) respectively. With the same testing conditions, the increase rate of the damping force of the MSTF absorber is obviously higher than the commercial MRF absorbers. It is due to that in addition to the current, the damping force of the absorber can be increased by the increase of the viscosity with the rising linear piston velocity from 0.079 m/s to 0.520 m/s.

3.2.2. The shock absorber with self-made MSTF and self-made MRF

In order to eliminate the influence of the different kinds of magnetic particles in self-made MSTF and commercial MRF, the self-made MSTF and MRF with distinct CIP mass fractions from 10% to 70% were prepared and tested. Before pouring the same amount of MSTF and MRF into the tube, the magnetorheological effect of MSTF and MRF were tested by the rehometer, and the results are illustrated in Fig. 11.

In recent studies, the magnetorheological effect of material is always evaluated by the relative magnetorheological effect (RMRE) and absolute magnetorheological effect (AMRE) [39–41], the performance indexes are as shown in (Eq. (1)) and (Eq. (2)):

$$RMRE = \frac{G_{max} - G_{min}}{G_{min}} \tag{1}$$

$$AMRE = G_{max} - G_{min} \tag{2}$$

where G_{max} is the maximum shear storage modulus at magnetic saturation and G_{min} is the initial zero field shear storage modulus.

As the CIP mass fraction is more than 30%, the RMRE and AMRE increase significantly for these two types of materials. Besides, during the increasing CIP mass fraction from 10% to 70%, the MSTF shows a better magnetorheological performance than MRF.

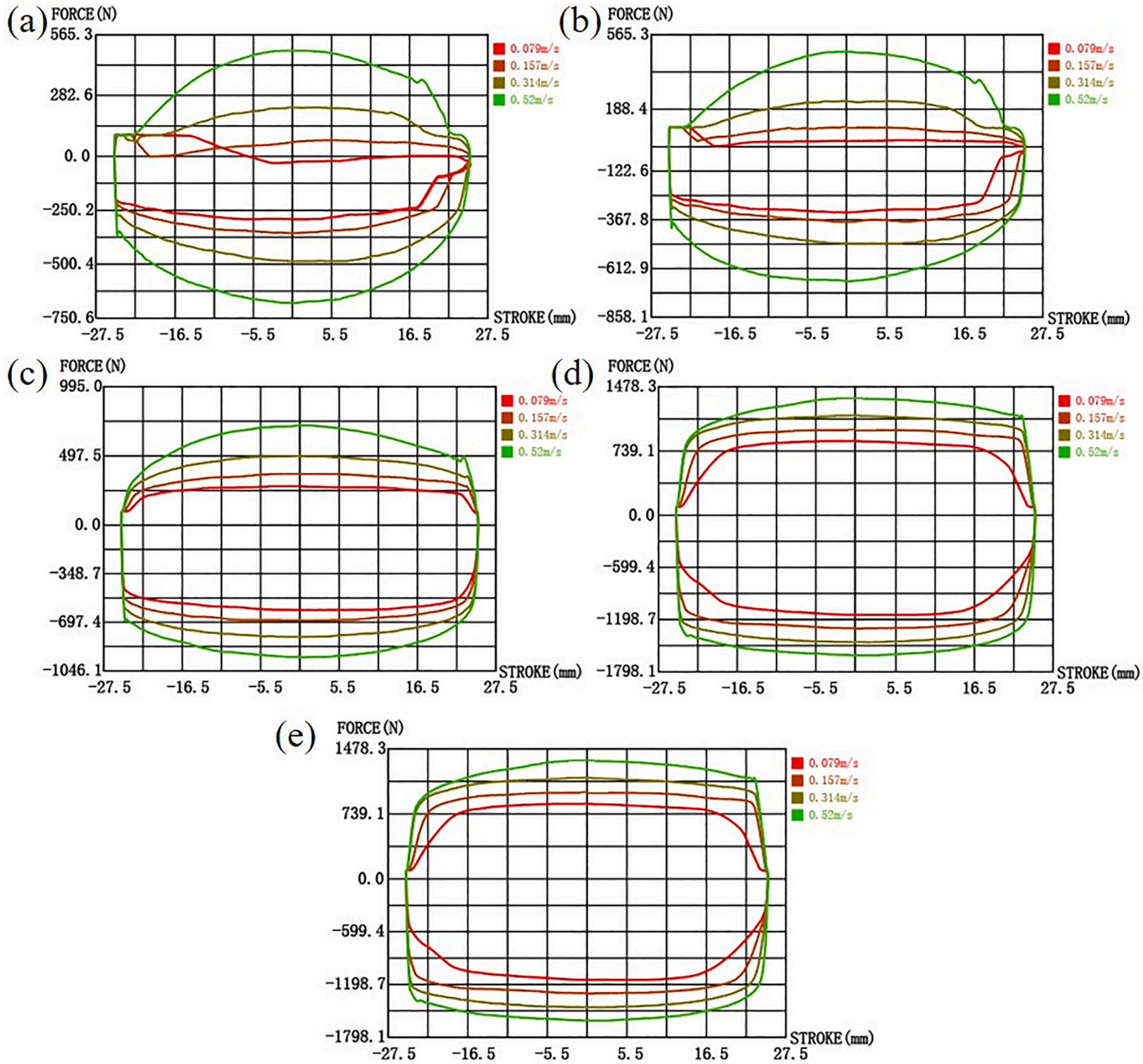

Fig. 9. The indicator diagram of the shock absorber with commercial magnetorheological fluid at distinct velocities and at (a) 0 A, (b) 0.5 A, (c) 1.0 A, (d) 1.5 A and (e) 2.0 A.

To evaluate the increase rate of the damping force, the self-made MSTF and MRF with the CIP mass fraction from 10% to 70% were prepared and tested. The average increase rates which are the mean values of the damping force increasing from 0.079 m/s to 0.157 m/s, 0.157 m/s to 0.314 m/s and 0.314 m/s to 0.520 m/s are as shown in Fig. 12.

There is an obvious tendency in Fig. 12 that the average increase rates of the damping force of these two kind of materials decrease with the increasing CIP mass fraction. Besides, the growth rate of the materials tested at 2 A current is slightly lower than the materials tested at 0 A. It can be also concluded that in the experiment, the increase rate of the MSTF damping force is higher than the MRF in all the groups, which indicates that as the CIP mass fraction of the materials and the testing conditions are the same, the energy dissipation capacity of MSTF obtained by dispersing the magnetic particles into shear thickening fluid increases more rapidly than that of MRF due to the increasing viscosity of MSTF.

4. Conclusions

In this paper, the magneto-sensitive shear thickening fluid was prepared by dispersing the magnetic particles into the fluid with shear thickening performance. The results of the mechanical tests showed that the damping forces were increased steadily by the increasing current, and the influence of the frequency on the damping force increased by the increasing amplitude. If the amplitude was small, the frequency was insensitive to the forces. The self-made MSTF and commercial MRF were poured into the same type of shock absorber and the damping force-displacement curves were tested and recorded. The results demonstrated that the increase rate of the damping force from 0.079 m/s to 0.157 m/s, 0.157 m/s to 0.314 m/s and 0.314 m/s to 0.520 m/s of MSTF absorber were higher than that with commercial MRF due to the

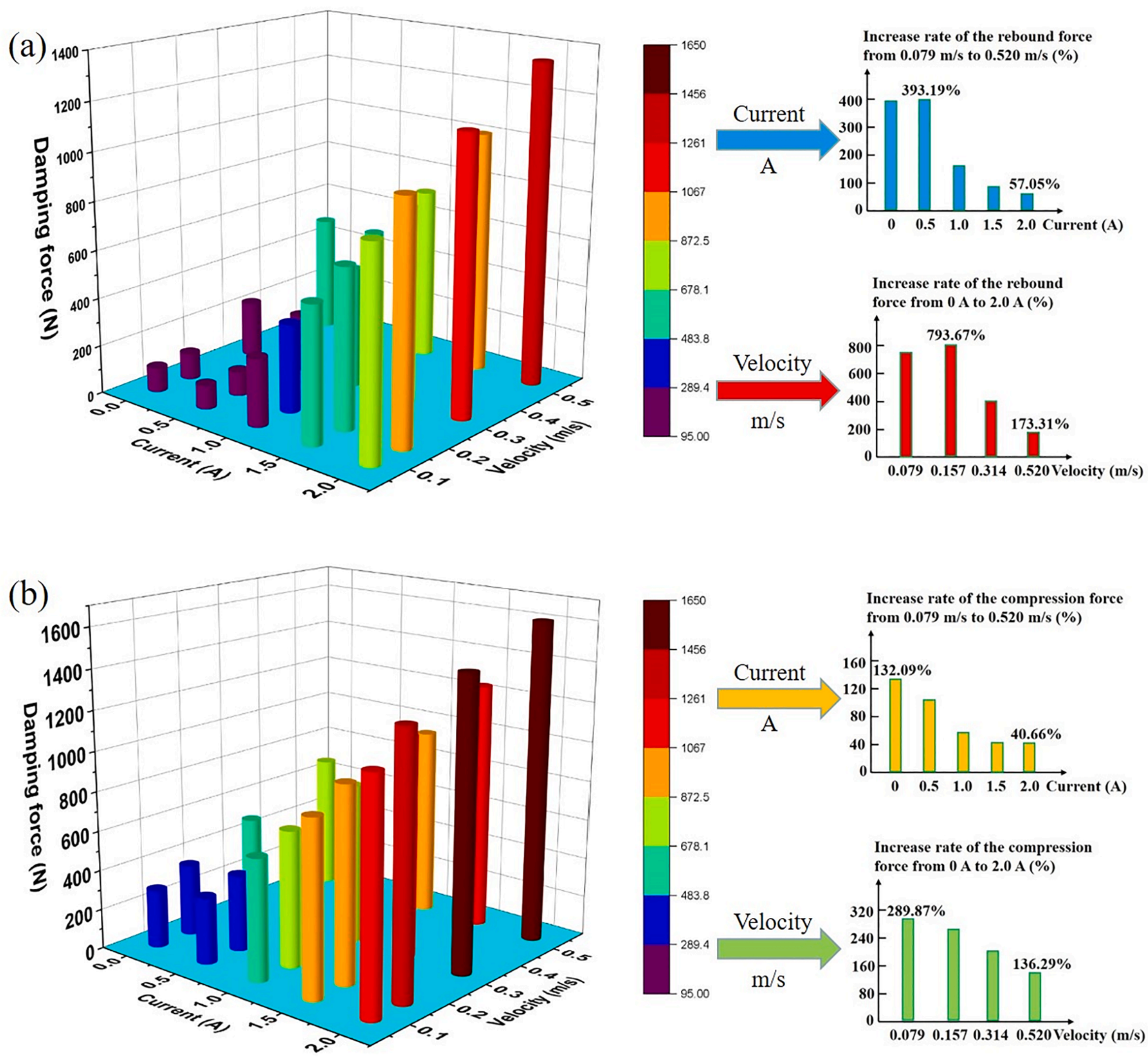

Fig. 10. The changing rules and the increase rate of the (a) rebound force and (b) compression force from 0.079 m/s to 0.520 m/s of the shock absorber with commercial MRF at distinct velocities and different currents.

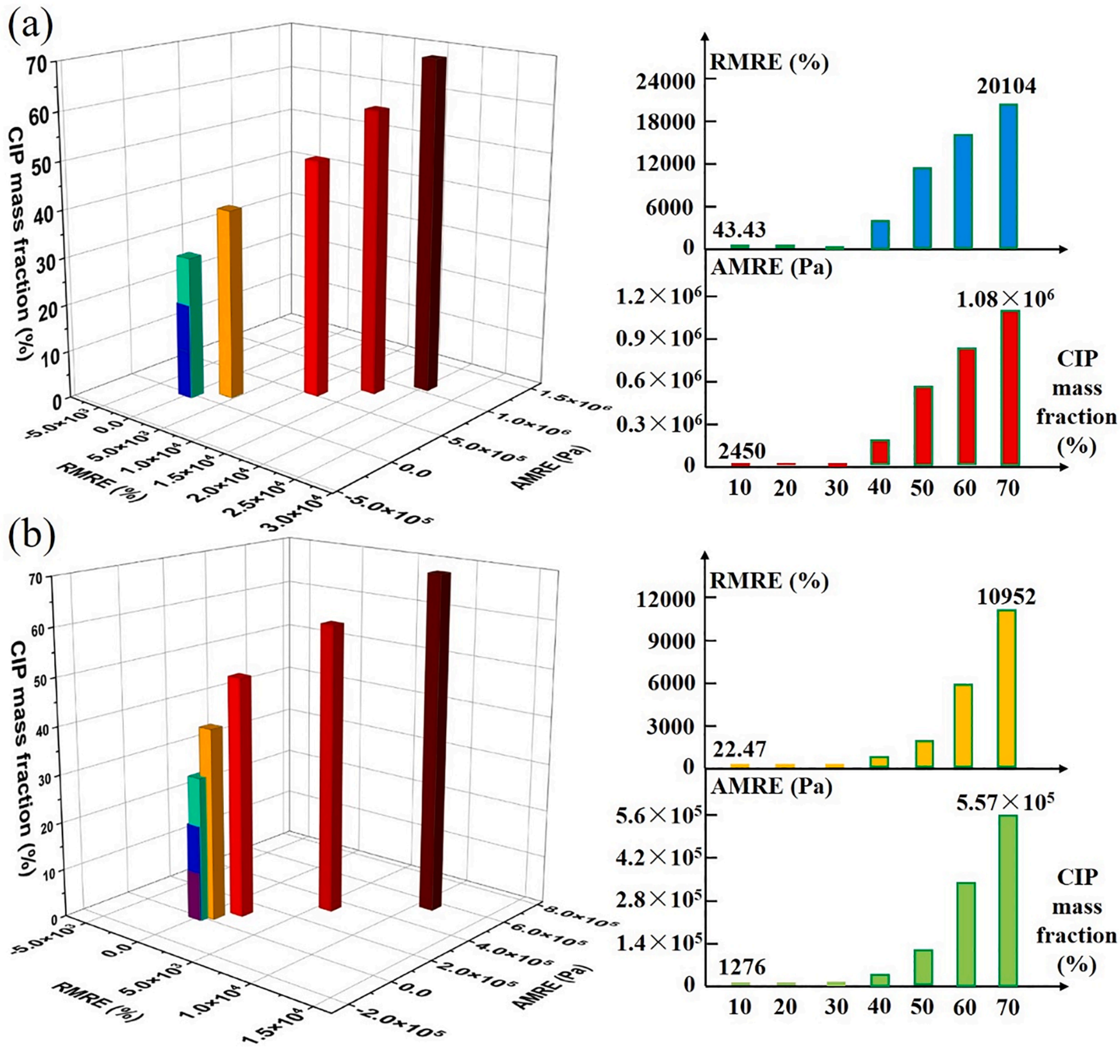

Fig. 11. The RMRE and AMRE of self-made (a) MSTF and (b) MRF with the CIP mass fraction from 10% to 70%.

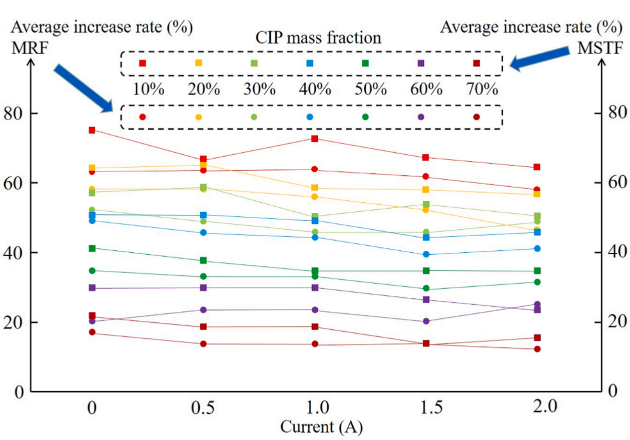

Fig. 12. The average increase rate of the damping force of the MRF and MSTF shock absorber with the CIP mass fraction from 10% to 70% at different velocities and currents.

increasing viscosity of the MSTF with the increasing velocity. Besides, from the CIP mass fraction from 15% to 70%, the increase rate of the damping force of the shock absorber with self-made MSTF is also higher than that with the self-made MRF.

CRediT authorship contribution statement

Bing Liu: Conceptualization, Data curation, Investigation, Software, Validation, Visualization, Writing - Original Draft. **Chengbin Du:** Methodology, Funding acquisition. **Huaxia Deng:** Investigation, Formal analysis. **Ziyang Fan:** Materials prepared. **Junshuo Zhang:** Investigation. **Fanang Zeng:** Experiment. **Yankai Fu:** Formal analysis. **Xinglong Gong:** Supervision, Project administration, Resources, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Hoffman RL. Discontinuous and dilatant viscosity behavior in concentrated suspension. I. Observation of a flow instability. Trans Soc Rheol 1972;16:155–73.
[2] Lee YS, Wagner NJ. Dynamic properties of shear thickening colloidal suspensions. Rheol Acta 2003;42:199–208.
[3] Barnes HA. Shear-thickening (dilatancy) in suspensions of nonaggregating solid particles dispersed in Newtonian liquids. J Rheol 1989;33:329–66.
[4] Hoffman RL. Discontinous and dilatant viscosity behavior in concentrate suspensions. II. Theory and experimental tests. J Colloid Interface Sci 1974;46: 491–506.
[5] Brown E, Jaeger HM. Shear thickening in concentrated suspensions: phenomenology, mechanisms and relations to jamming. Rep Prog Phys 2014;77: 046602.
[6] Jiang WF, Gong XL, Xuan SH, Jiang WQ, Ye F, Li XF, et al. Stress pulse attenuation in shear thickening fluid. Appl Phys Lett 2013;102:101901.
[7] Lee DY, Wereley NM. Quasi-steady Herschel-Bulkley analysis of electro-and magneto-rheological flow mode dampers. J Intel Mat Syst Str 1999;10:761–9.
[8] Lin XG, Guo F, Du CB, Yu GJ. The mechanical properties of a novel STMR damper based on magnetorheological silly putty. Adv Mater Sci Eng 2018:2681461.
[9] Zhang SS, Wang S, Hu T, Xuan SH, Jiang H, Gong XL. Study the safeguarding performance of shear thickening gel by the mechanoluminescence method. Compos Part B-Eng 2020;180:107564.
[10] Zhao CY, Wang YP, Cao SS, Xuan SH, Jiang WQ, Gong XL. Conductive shear thickening gel/Kevlar wearable fabrics: a flexible body armor with mechano-electric coupling ballistic performance. Compos Sci Technol 2019;182:107782.
[11] Haris A, Goh BWY, Tay TE, Lee HP, Rammohan AV, Tan VBC. On the effectiveness of incorporating shear thickening fluid with fumed silica particles in hip protectors. Smart Mater Struct 2017;27:015021.
[12] Wang YP, Gong XL, Xuan SH. Study of low velocity impact response of sandwich panels with shear thickening gel cores. Smart Mater Struct 2018;27:065008.
[13] Wang YP, Wang S, Xu CH, Xuan SH. Dynamic behavior of magnetically responsive shear-stiffening gel under high strain rate. Compos Sci Technol 2016;127:169–76.
[14] Liang J, Zhang XH. Rheological properties of SP in shock transmission application. J Mater Civil Eng 2014;27:04014250.
[15] Talreja K, Chauhan I, Ghosh A, Majumdar A, Butola BS. Functionalization of silica particles to tune the impact resistance of shear thickening fluid treated aramid fabrics. RSC Adv 2017;7:49787–94.
[16] Guler ES. Rheological behaviours of silica/water, silica/PEG systems and mechanical properties of shear thickening fluid impregnated Kevlar composites. B Mater Sci 2018;41:112.
[17] Baharvandi HR, Heydari MS, Kordani N, Alebooyeh M, Alizadeh M, Khaksari P. Characterization of the rheological and mechanical properties of shear thickening fluid-coated Twaron (R) composite. J Text I 2017;108:397–407.
[18] Asija N, Chouhan H, Gebremeskel SA, Singh RK, Bhatnagar N. High strain rate behavior of STF-treated UHMWPE composites. Int J Impact Eng 2017;110:359–64.
[19] Liu XF, Li MQ, Li X, Deng XB, Zhang XH, Yan Y, et al. Ballistic performance of UHMWPE fabrics/EAMS hybrid panel. J Mater Sci 2018;53:7357–71.
[20] Veith GM, Armstrong BL, Wang H, Kalnaus S, Tenhaeff W, Patterson M. Shear thickening electrolytes for high impact resistant batteries. ACS Energy Lett 2017;2: 2084–8.
[21] Ding J, Tian TF, Meng Q, Guo ZP, Li WH, Zhang P, et al. Yang WR Smart multifunctional fluids for lithium ion batteries: enhanced rate performance and intrinsic mechanical protection. Sci Rep 2013;3:2485.
[22] Shu KW, Wang CY, Li WH, Bussell T, Ding J. Electrolytes with reversible switch between liquid and solid phases. Curr Opin Electroche 2020;21:297–302.
[23] Han H, Li SJ, Guo L, Wu QW. Numerical investigation on suppressing high frequency self-excited noises of armature assembly in a torque motor using ferrofluid. Shock Vib 2017:4251320.
[24] Span J, Koshy P, Klocke F, Müller S, Coelho R. Dynamic jamming in dense suspensions: surface finishing and edge honing applications. CIRP Ann- Manuf Techn 66:321–4.
[25] Gürgen S, Sert A. Polishing operation of a steel bar in a shear thickening fluid medium. Compos Part B-Eng 2019;175:107127.
[26] Gürgen S, Sofuoğlu MA. Integration of shear thickening fluid into cutting tools for improved turning operations. J Manuf Process 2020;56:1146–54.
[27] Gürgen S, Sofuoğlu MA. Smart polymer integrated cork composites for enhanced vibration damping properties. Compos Struct 2020;258:113200.
[28] Sheikhi MR, Gürgen S. Anti-impact design of multi-layer composites enhanced by shear thickening fluid. Compos Struct 2021;279:114797.
[29] Ruan XH, Xuan SH, Zhao J, Bian HT, Gong XL. Mechanical performance of a novel magnetorheological fluid damper based on squeeze-valve bi-mode of MRF. Smart Mater Struct 2020;29:055018.
[30] Wang MK, Chen ZB, Wereley NM. Magnetorheological damper design to improve vibration mitigation under a volume constraint. Smart Mater Struct 2019;28: 114003.
[31] Sohn JW, Oh JS, Choi SB. Design and novel type of a magnetorheological damper featuring piston bypass hole. Smart Mater Struct 2015;24:035013.
[32] Carlson JD, Chrzan MJ. Magnetorheological fluid dampers. US Patent 1994: 277–81.
[33] Sun SS, Yang J, Li WH. Development of a novel variable stiffness and damping magnetorheological fluid damper. Smart Mater Struct 2015;24:085021.
[34] Lee TH, Choi SB. On the response time of a new permanent magnet based magnetorheological damper: experimental investigation. Smart Mater Struct 2019; 28:014001.
[35] Zhang JS, Wang Y, Zhou JY, Zhao CY, Wu YX, Liu S, et al. Intralayer interfacial sliding effect on the anti-impact performance of STF/ Kevlar composite fabric. Compos Appl Sci Manuf 2021;145:106401.
[36] Manukonda BH, Chatterjee VA, Verma SK, Bhattacharjee D, Biswas I, Neogi S. Rheology based design of shear thickening fluid for soft body armor applications. Period Polytech-Chem Eng 2020;64(1):75–84.
[37] Cao SS, Chen Q, Wang YP, Xuan SH, Jiang WQ, Gong XL. High strain-rate dynamic mechanical properties of Kevlar fabrics impregnated with shear thickening fluid. Compos Appl Sci Manuf 2017;100:161–9.
[38] Dimock GA, Yoo JH, Wereley NM. Quasi-steady Bingham biplastic analysis of electrorheological and magnetorheological dampers. J Intel Mat Syst Str 2002;13 (9):549–59.
[39] Wang Q, Sun R, Yao M, Chen M, Feng Y. The influence of temperature on inter-yarns fictional properties of shear thickening fluids treated Kevlar fabrics. Compos Part A Appl S 2019;116:46–53.
[40] Liu B, Du CB, Yu GJ, Fu YK. Shear thickening effect of a multifunctional magnetorheological gel: the influence of cross-linked bonds and solid particles. Smart Mater Struct 2020;29:015004.
[41] Wang S, Jiang WQ, Jiang WF, Ye F, Mao Y, Xuan SH, et al. Multifunctional polymer composite with excellent shear stiffening performance and magnetorheological effect. J Mater Chem C 2014;2(34):7133–40.