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• LETTER •

Special Focus on Bio-Robotic Systems: Modeling, Design, Control and Perception

Design and experiment of bio-inspired GER fluid damper

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Dear editor,
With the rapid development of industrial robots, the influence of vibration has been considerably increasing. The consequent demand for vibration suppression in robot systems has become increasingly urgent. The effective vibration suppression can remarkably improve the performance of robots such as operation stability, detective and tracking accuracy, and the security of interaction with the human body.

Recently, a growing number of bio-inspired approaches have appeared in the field of vibration attenuation along with the development of the bionics. Mei et al. [1] developed an ultra-precision vibration isolation imitating the woodpeckers' heads. The proposed structure mainly comprised giant magnetostrictive actuators and air-springs. It was observed that the developed isolation system with a 2-dimensional fuzzy active control system performed well in a complex vibration environment. Inspired by the horses' ability to protect themselves in the event of vibration or shock, Wilson et al. [2] studied the mechanism of their legs and found that the damping and stiffness of horses' muscles are adjustable. Thus, the change of damping and stiffness plays a vital role in bionic structures.

Using smart materials such as dielectric-elastomers and magnetorheological fluids is a creative approach to realize bionic structures and have a promising application [3, 4]. Electrorheological fluid (ER fluid) is a type of smart material whose property can vary with the applied electric field. The variation of its viscosity responds within a few milliseconds and is reversible [5]. Its distinguished property of reversibility and controllability is especially similar to biological muscle. Because of this interesting characteristic, ER fluid is widely used in the field of vibration attenuation to improve the performance of mechanical equipment and robot systems.

ER fluid is mostly used in the design of dampers to attenuate vibration. Shear, squeeze and flow modes are the three basic operation modes of ER fluid. Many researchers have performed considerable work on the design of ER dampers. Ehrgott and Masri [6] developed a typical shear mode damper and proposed a mathematic model that predicted the performance of the device. Most ER dampers are designed in shear and flow modes. The squeeze mode is not adequately studied because of its complex mechanical properties in stiffness and damping. Contrary to the flow and shear modes, the squeeze mode has a very similar characteristic to biological muscle.

In this study, a type of a multiple plate electrodes ER damper that operates in the squeeze mode has been proposed. The used ER fluid has

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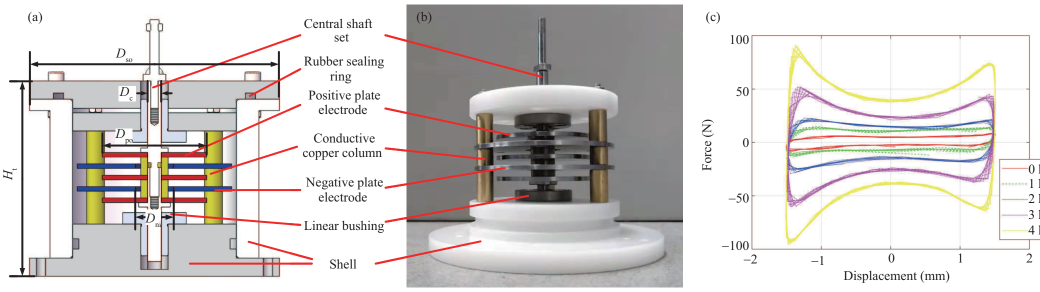

Figure 1 (Color online) Multiple plate electrode GER fluid damper. (a) Schematic; (b) photograph; (c) force versus displacement curves under different electric field.

been provided by the team of Wen [5] which is called giant electrorheological fluid (GER fluid). GER fluid behaves considerably better than the conventional types. This is because the yield stress of GER fluid can mostly reach 130 kPa at 5 kV/mm and the reversible time is less than 10 ms. Experiments are conducted to prove the mechanical properties of the damper. Comparisons are conducted among the same types of dampers and the superiority of the GER fluid damper is observed when applied to vibration suppression system as a biological muscle.

The design of GER fluid damper. The schematic of the proposed device is shown in Figure 1(a). The positive plate electrode can move with central shaft set, while the negative plate electrode is fixed to the shell. The positive and negative plate electrodes are placed in a spaced arrangement. The adjacent positive plate electrodes are separated by conductive copper columns and so are the negative ones. An electric field is generated between the positive and negative plate electrodes when connected to a high voltage power supply. A pair of linear bushings restricts the movement of the central shaft to only the vertical direction. The original gap between a pair of electrodes is 3 mm. This guarantees safety when a high voltage is applied to the device. Some important parameters are specified in Table S1.

The GER fluid fulfills the shell and its properties vary with electric field. As the central shaft set moves vertically, the fluid between plate electrodes is compressed so that a damping force is generated. Because the fluid is incompressible, the venting hole is designed to compensate the change in fluid volume. Also, rubber sealing rings are set in the shell to prevent the leakage of GER fluid.

Experiment and results. As illustrated in Figure S1, the GER fluid damper is tested on the MTS Acumen. Voltage needed in experiments is supplied by a Dongwen DC power which optimizes to 5 kV. Different voltages are applied to the GER fluid damper to explore its characteristic both on stiffness and damping. Experiments under different excitation conditions are conducted to demonstrate the relationship between the performance of the damper and the external excitation.

Figure 1(c) depicts experiments conducted under a frequency of 10 Hz and an amplitude of 1.5 mm. The applied voltage ranges from 0 to 4 kV with a linear change. The maximum voltage is decided by the type of GER fluid and the mechanical design. This is done to avoid dielectric breakdown of the GER fluid. The area enclosed by the curve during one period represents the amount of energy dissipation. As seen in Figure 1(c), the energy dissipation during one period grows with an increasing voltage. This shows that the damping performance improves with the rising voltage. The equivalent stiffness is employed in discussing the relationship between the damper and the applied voltage. Here, the equivalent stiffness is adopted to calculate the slope of the line connecting the maximum and minimum force points. This points out the reason that the stiffness of the damper blows up with a hike in the applied voltage. The GER fluid used in experiments has a higher yield stress than the conventional ones thus it has a significant change in its stiffness properties. An enhancement in the applied voltage results to a raise in the damping and stiffness. According to a previously done study [2], animals like horses have a unique muscular work in their legs to mitigate the harm when galloping. The horses' ability to adjust the damping and stiffness in spite of different vibration conditions, owing to their tunable muscles, is indeed an excellent inspiration for dampers' design. From this point of view, the GER fluid damper with a wider tunable range of damping and stiffness is more flexible and closer to the biological systems just like animal muscles.

To explore the influence of excitation conditions, data are collected. This is done under various excitation conditions. The amplitude of the excitation a is 1.5 mm, with an excitation frequency f ranging with a linear change from 1 to 15 Hz. To examine the influence of excitation amplitude, the frequency is set at 10 Hz, while its amplitude is allowed to range from 1.0 to 2.0 mm with some alteration in linearity. Both sets of the experiments are conducted when the applied voltage is 3 kV. From Figure S2(a), it can be observed that the energy dissipation increases slightly with a hike in excitation frequency. In the study of the relationship between the energy dissipation and the damping coefficient $c = \Delta W/2\pi^2 a^2 f$, the damping coefficient decreases with a growth in excitation frequency. Thus, the excitation frequency has a little effect on damping coefficient. The damping characteristic behaves obviously as a nonlinear damping and has a potential application in the field of vibration suppression. In these sets of experiments, the change of stiffness among different conditions of frequencies is not obvious. This means that the influence of the excitation frequency on the stiffness is insignificant. As illustrated in Figure S2(b), the damping is enhanced with a corresponding increase in amplitude. This time, a change in the stiffness is observed. Consequently, the excitation amplitude has great impact on both the damping coefficient and the stiffness.

In terms of physical parameters and the properties of the damper, the proposed damper was compared with those reported in [7–9] as shown in Table S2. The comparison shows that the proposed GER fluid damper has an advantage of a large stress. This implies that the proposed damper can provide a larger force than the others when the dimension comparatively limited. This is an important benefit to the practical application especially in robot systems where the dimension of the design is strict.

Conclusion. In this study, a multiple plate electrodes GER fluid damper has been designed. The mechanical properties were demonstrated by experiments and compared with the same types of dampers. The distinguished controllability in stiffness and damping made it appropriate to work in robot systems as a biological muscle. In the future, we will focus on building a matched mathematical model for more accurate control of the damper. Additional experiments will be conducted with specific applications.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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