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ARTICLE

Study on Temperature Mechanical Properties of SMA-MR Material Dampers

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Abstract: Against the background of the research on the performance of dampers for a certain type of spacecraft, a new type of shape memory alloy metal rubber (SMA-MR) damper which was made of Ni-Ti alloy wire processed by coil spring, cold stamping and post-treatment was designed. Through theoretical and experimental research on SMA-MR dampers, the equivalent rigidity and energy dissipation coefficient of the damping system in the temperatures range of 20~90 °C were analyzed. The law of mechanical properties of SMA-MR material with temperature was studied. The relationship between equivalent rigidity, energy dissipation coefficient and temperature were analyzed using the experimental results. The results show that the equivalent rigidity of SMA-MR dampers increases with the increase of temperature while the energy dissipation coefficient of SMA-MR dampers decreases. The analysis results provide theoretical basis and data reference for the design of SMA-MR dampers and their application under extreme environment.

Key words: SMA-MR; equivalent rigidity; energy dissipation coefficient; experimental research

During the start-up of the spacecraft, the equipment is subjected to harsh vibration, impact and other disturbances. Research data indicates that about two-thirds of aircraft failures are related to vibration and impact[1]. The important reason for this phenomenon is that the damping properties of pure metal structural materials are usually very limited. Therefore, special damping and damping structures should be installed in some key parts of the spacecraft[2-5]. As a functional structural material, metal rubber offers the potential to be a good damping material at both low and high temperature which makes it a strong candidate for applications in extreme environments[6-9]. What's more, metal rubber made of shape memory alloy which is a kind of metal material with shape memory effect has more special advantages when using in extreme environments[10]. In the present paper, a new type of SMA-MR damper was designed for the vibration reduction requirements of a certain type of spacecraft. By establishing a temperature test system, the relationship between the equivalent rigidity, energy dissipation coefficient of SMA-MR dampers and temperature was studied. At the same time, the temperature mechanical properties between SMA-MR and ordinary MR were compared, and the applicable temperature range and using advantages of SMA-MR damper were analyzed.

1 Structural Design of SMA-MR Dampers

According to the vibration environment and the damping requirements of the spacecraft, the structure of the damper is designed as shown in Fig.1. The edge of the center bracket is the load-bearing position, and the center sleeve is connected to the base. Since one ring-shaped SMA-MR is mounted on the upper and the other one on lower side, there is always damping energy dissipation effect throughout the vibration process. Thereby, the damper gradually reduces the amplitude of the vibration to achieve the purpose of impact and vibration reduction.

The structural parameters of the damper are determined according to the external vibration parameters of the vibration damping system. The SMA-MR component parameters are selected according to the minimum energy dissipation factor.

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The braiding process of spiral winding and lateral curling is selected, and the forming process of the two-way load deformation is performed. In this way, the performance stability and uniformity of the damper are improved while ensuring the damping properties.

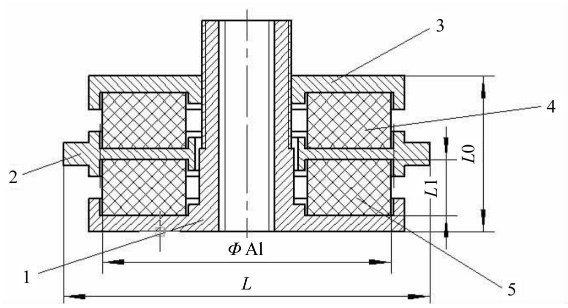
Fig.2 shows the picture of the assembled damper. The hysteresis loop of the damper at different temperatures was measured experimentally.

2 Analysis of Mechanical Properties of SMA-MR Dampers

Fig.3 shows the hysteresis loop of the SMA-MR damping system. ΔW represents the amount of energy dissipated by dry friction damping while W represents the maximum deformation potential energy of the damper during one cycle of loading and unloading. The values can be obtained by step-wise integration of experimental data. Therefore, the energy dissipation coefficient (ψ) of the damping system can be expressed by the following formula:

$$\psi=\frac{\Delta W}{W} \tag{1}$$

In the past, the average rigidity K_s was usually used to analyze the rigidity of a common MR-vibration-damping system. However, the actual rigidity of MR has obvious nonlinear characteristics, which makes the representation method have large errors in analysis. In the present paper, the equivalent rigidity (K_{eq}) concept is adopted and the system energy conservation method is used to calculate it. This calculation



1-center sleeve; 2-center bracket; 3-joints; 4,5-ring-shaped SMA-MRs

Fig.1 Structural drawing of the damper

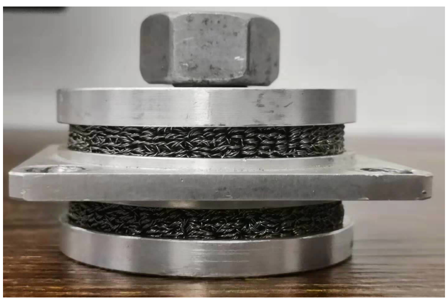


Fig.2 Picture of the SMA-MR damper

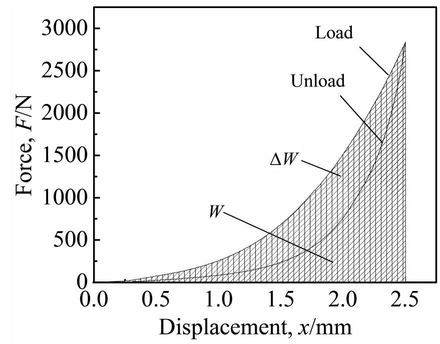


Fig.3 Hysteresis loop of the SMA-MR damping

principle is shown in the following formula according to Fig.4:

$$\int_0^{x_{max}} K_{eq} \cdot x\mathrm{d}x = W - \frac{\Delta W}{2} \tag{2}$$

So, the equivalent rigidity is given by

$$K_{eq} = \frac{2W - \Delta W}{x_{max}^2} \tag{3}$$

3 Experiment

The assembly of the damper is completed according to Fig.1. SMA-MRs with the same wire diameter of 0.2 mm and different relative densities of 0.22 and 0.26 are installed in it. The hysteresis loop of each damper at different temperatures is obtained through experiments. The test device is installed in the temperature box, and the temperature control device supports a certain temperature environment. When the temperature stays at the predetermined value, the corresponding stroke of the loading system is programmed by the computer. The control program includes setting the magnitude and speed of the displacement of the compression. After the power is turned on, the corresponding program is run, and the loading-unloading test is performed at a certain temperature. After the test is completed, the displacement and restoring force data collected by the corresponding sensor are saved. The test is repeated and the corresponding data are processed.

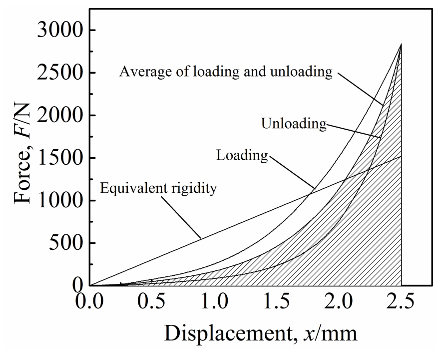


Fig.4 Solution principle of equivalent rigidity curve

The temperatures set in the experiment are 20, 30, 40, 50, 60, 70, 80, and 90 °C. The initial height of the metal rubber used is 10 mm. Considering that the compression amount of the metal rubber cannot be too large, the compression displacement amplitude in the loading-unloading test is set to 2.5 mm, and the loading-unloading speed is set to 1 mm/min. Then, the forces of each damper are measured under different displacements at a certain temperature experimentally.

4 Results and Discussion

After processing the data obtained by the test, the hysteresis loops of the metal rubber dampers of the two materials at different temperatures are plotted as shown in Fig.5 and Fig.6. It is not difficult to find from the figures that the hysteretic curve characteristics of the ordinary stainless steel wire metal rubber are not affected by the temperature, while the SMA-MR's hysteretic curve characteristics have a significant change when temperature changes.

The corresponding energy dissipation coefficient and equivalent rigidity are calculated according to Eqs. (1) and (3), respectively. The equivalent rigidity of the SMA-MR dampers at different temperatures is solved with the help of MATLAB. The calculated results are shown in Fig.7. By fitting the points in Fig.7 to a numerical function, the relationship between the equivalent rigidity of the SMA-MRs and the temperature can

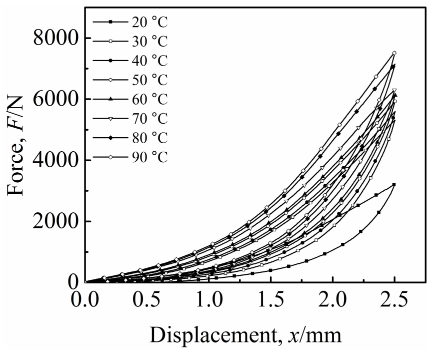


Fig.5 Hysteretic curves of SMA-MR at different temperatures

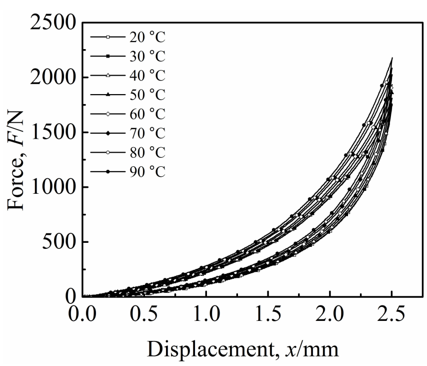


Fig.6 Hysteretic curves of common-MR at different temperatures

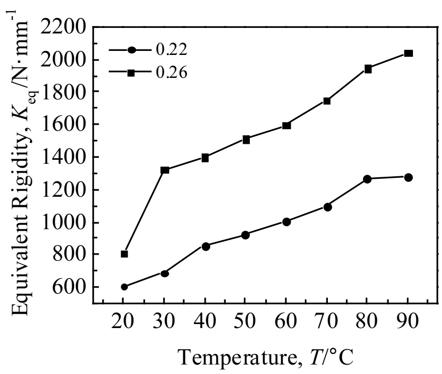


Fig.7 Equivalent rigidity curves of SMA-MR at different temperatures

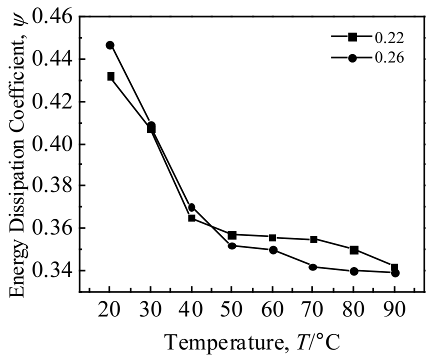


Fig.8 Energy dissipation coefficient-temperature curves of SMA-MR dampers

be obtained. The results are shown in Eqs. (4) and (5):

$$K_{eq}(0.22) = (-0.0005T^4 + 0.010T^3 - 0.755T^2 + 33.563T + 154.654)\ \text{N/mm} \tag{4}$$

$$K_{eq}(0.26) = (-0.0004T^4 + 0.092T^3 - 0.785T^2 + 288T - 2495.663)\ \text{N/mm} \tag{5}$$

where, T is temperature.

The calculated results of the energy dissipation coefficient of the SMA-MR dampers at different temperatures are shown in Fig.8. Eqs. (6) and (7) are obtained by numerically fitting the calculated results.

$$\psi(0.22) = (-1.9\text{e}-8)T^4 + (3.7\text{e}-6)T^3 - (2\text{e}-4)T^2 + 0.001T + 0.465 \tag{6}$$

$$\psi(0.26) = (-5.2\text{e}-9)T^4 + (6.2\text{e}-7)T^3 - (4\text{e}-5)T^2 + 0.007T + 0.568 \tag{7}$$

where, T is temperature and e is Euler number.

It can be seen from Fig.7 that the equivalent rigidity of the two relative density SMA-MR dampers tends to increase with the increase of temperature. When the temperature is 90 °C, the equivalent rigidity reaches the maximum value of 1275.9 N/mm (relative density of 0.22) and 2040.3 N/mm (relative density of 0.26). It can be seen from Fig.8 that the energy dissipation coefficient of both kinds of relative density SMA-MR dampers decreases sharply with the increase of temperature when the temperature is in the range of 20~50 °C. While in the range of 50~90 °C, with the increase of temperature, the energy dissipation coefficient decreases slowly.

5 Conclusions

1) The characteristics of the vibration damping performance of the memory alloy wire metal rubber damper under special working conditions are analyzed, and the mechanical characteristic temperature test system is established. The test results show that the hysteresis loop of ordinary stainless steel metal rubber is almost unaffected by temperature in the range of 20~90 °C, and the hysteresis loop of SMA-MR is significantly affected by temperature.

2) In the range of 20~90 °C, the equivalent rigidity of SMA-MR increases rapidly with the increase of temperature. Meanwhile, SMA-MR has a larger equivalent rigidity with a larger relative density.

3) For both kinds of relative density SMA-MR in the temperature range of 20~50 °C, the energy dissipation coefficient decreases sharply with the increase of temperature and in the range of 50~90 °C, this downward trend is gradually weakened. It provides corresponding theoretical basis and parameter reference for the engineering application of SMA-MR material dampers.

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SMA-MR 材料减振器温度力学特性研究

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摘　要：以某型号飞行器用减振器性能研究为背景，设计了一种由 NiTi 合金丝经卷簧编织、冷冲压成型、后处理得到的新型记忆合金金属橡胶（SMA-MR）阻尼减振器。通过对 SMA-MR 减振器进行理论和试验研究，分析其在 20~90 ℃温度环境下的等效刚度与能量耗散系数的变化情况，研究 SMA-MR 减振器的力学特性随温度变化的规律，利用试验结果，分析等效刚度、能量耗散系数与温度的关系。研究结果表明 SMA-MR 减振器的等效刚度随温度升高而升高，而能量耗散系数随温度升高而降低。分析结果为 SMA-MR 减振器的设计及特种环境下的减振应用提供理论依据与数据参考。

关键词：SMA-MR；等效刚度；能量耗散系数；试验研究

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