Accelerated lifetime test of vibration isolator made of Metal Rubber material

Hongrui Ao¹, Yong Ma, Xianbiao Wang, Jianye Chen, Hongyuan Jiang

School of Mechatronics Engineering, Harbin Institute of Technology, Harbin 150001
P.R. China

E-mail: HongruiAo@hit.edu.cn

Abstract. The Metal Rubber material (MR) is a kind of material with nonlinear damping characteristics for its application in the field of aerospace, petrochemical industry and so on. The study on the lifetime of MR material is incumbent to its application in engineering. Based on the dynamic characteristic of MR, the accelerated lifetime experiments of vibration isolators made of MR working under random vibration load were conducted. The effects of structural parameters of MR components on the lifetime of isolators were studied and modelled with the fitting curves of degradation data. The lifetime prediction methods were proposed based on the models.

1. Introduction
The Metal Rubber (MR) material is a kind of porous material with the good environmental suitability, long working life-span, and adjustable stiffness. MR material is manufactured by using a special cold pressing technology to metal spiral wires. When it is applied in the vibration condition, it shows nonlinear damping characteristics for its internal dry friction between adjacent metal wires. The features of the vibration isolation of MR material comprise good damping capacity, strong environmental suitability, adjustable stiffness, and so on. Since it is the alternative of the rubber damping material under special working condition, it gains wide application in the fields such as spacecraft, weaponry, and petrochemical engineering [1]. The research on this material concentrated on its vibration performance, mathematical description, and application [2,3]. The researches on the vibration isolation and vibration damping performance of MR mainly comprise the studies in the property of nonlinear deformation, energy dissipation mechanism, and fatigue damage. Li et al testified the effects of shape factor on the mechanical property of material structure, obtained the variation relation of the mechanical property of MR with the changing of structure parameter, and acquired the theoretical equation of the loss factor changing with the material height and balance weight respectively [4]. Jiang et al [5] took the broadband random vibration experiment on the MR vibration isolation system and discussed the influence factors of the vibration isolation system according to the result. Wang et al [6] considered the comprehensive damage factor as the failure criteria of MR components. Zhao et al [7] discussed the relation between the fatigue circulation circles and the stiffness of the parts with soft characteristic, the static loss factor, and the dynamic loss factor respectively through the cyclic loading experiment on MR material.

Usually the MR components work under the random vibration condition. Therefore, for the popularization of metal rubber material, it is meaningful to study the lifetime and reliability of MR vibration isolator based on the random load. The statistical objects of traditional lifetime research and
reliability analysis are the failure time which needs lots of lifetime and accelerated lifetime experiments to obtain the failure data of products. But for the MR isolators with long lifetime and high reliability, the many needed experiments and long time to obtain these data restrict the application of traditional reliability assessment method. Therefore, in this study the analytical method based on the performance degradation is adopted. As a necessary parameter for reliability analysis, the performance degradation can make up the deficiencies of the traditional reliability analysis in analyzing the products with long lifetime and high reliability.

In the experiments, a high level stress is put on the products than the requirement of their normal works to accelerate the failure process and rapidly acquire the failure data without changing the failure mechanism of the products. At present, the accelerated lifetime experiment has already been an important method of reliability assessment. According to the researches, during the disabling process, some important performance may change solely as the time changing, so the disabling process of products can be seen as the process that the performance parameter degrades constantly. For the reliability analysis of products with long lifetime and high reliability, it has been an important method to do the reliability assessment by building up the appropriate model after extracting the failure information from the degradation data.

The reliability model based on the performance degradation amount assumes that the performance degradation data of samples correspond a certain distribution law at the same moment, estimate the distribution parameter by the degradation data, and calculate the reliability of products at each moment according to the definition of reliability function.

Generally, the basic researches mentioned above are helpful to understand the vibration damping principle, the damping effect, and the fatigue damage mechanism. However, currently, the researches on the lifetime forecast, reliability, and other features of MR material are still immature, and the insufficient data accumulation also restricts the wider application of the technology. In this paper, the lifetime of MR isolator was tested experimentally and the mathematic models by the performance degradation data to forecast its lifetime were established.

2. The accelerated lifetime test of Metal Rubber isolator

The fatigue lifetime experiment includes two steps: the sine sweep frequency experiment and the random vibration experiment. The sine sweep frequency experiment can measure the resonant frequency and resonant transmissibility of the MR vibration isolator. Through the random vibration experiment, the MR elements will bear a certain random load, the amount of which is determined by the acceleration stress. The dynamic stress generated inside the metal rubber elements during the random vibration is expressed as

\[ \sigma_d = \frac{ma}{S} = \frac{m}{S} \sqrt{\frac{\pi A f_0 \eta_0}{2}} \]  

(1)

where \( \sigma_d \) is the dynamic stress inside the MR elements (MPa), \( m \) is the mass of the system (kg), \( S \) is the equivalent contact area of the MR element (mm\(^2\)), \( a \) is the accelerated speed response of the random vibration (g), \( f_0 \) is the resonant frequency of the system (Hz), and \( \eta_0 \) is the resonant transmissibility of the system.

According to the equation (1), after the stress condition of the accelerated lifetime experiment is determined, the power spectral density of the random vibration can be calculated as

\[ A = \frac{2\sigma_d^2 S^2}{\pi m^2 f_0 \eta_0} \]  

(2)

It is noted that the Metal Rubber isolators need to be stabilized before the sine sweep frequency experiment.

After the stabilization is completed, the resonant frequency \( f_0 \) and resonant transmissibility \( \eta_0 \) measured from the sine sweep frequency experiment are taken as the original value of the performance
degradation data. The power spectrum density of the random vibration experiment is calculated according to the equation (2), and conduct the fatigue lifetime experiment for a while under the random vibration condition. The resonant frequency and transmissibility were measured through the sine sweep frequency experiment every other certain time to compare with the initial value. When the performance degradation data exceeds the threshold value of initial value, the fatigue lifetime experiment can be stopped.

During the fatigue lifetime experiment, the variation quantity of the threshold value of stopping the experiment need to be 12%, which is determined by the requirements of the customers. The prediction accuracy and the rationality of the models are verified by the repetition of the experiments.

3. The experiment results and analysis

The control variable method is adopted in the fatigue experiment which means to successively change influential factors of MR elements including the relative density, metal wire diameter, and height, and obtain the performance degradation data of different stress condition under each influential factor. By the lifetime forecast model based on the Bayes theory mentioned to deal with the performance degradation data, the lifetime forecast value of the MR vibration isolation under the single influential factor can be obtained.

Figure 1 shows the fatigue lifetime curve of the MR vibration isolation with different metal wire diameter under the condition that the relative density, $\rho$, defined as the ratio of the density of MR components and the density of the steel, is equal to 0.23 and the height of MR component is $h=1.5\text{mm}$.

It can be seen from the Figure 1 that the magnitude of load of random vibration experiment has great influence on the fatigue lifetime of MR vibration isolator. Under the different stress condition, the fatigue lifetime differs a lot. The fatigue lifetime is expressed in a logarithm way and fitted linearly as

$$\ln(T) = -2.377\sigma + 5.408$$ (3)

Figure 1. The fatigue lifetime curve of the MR elements with different metal wire diameters.

In a similar way, the relation between the logarithm value of fatigue lifetime and the stress value received by the MR with different diameters of metal wire, relative densities, or heights of the MR can be obtained. It can be seen from Figure 1 that the fatigue lifetime of MR elements increased with the increasing of the metal wire diameter under the same stress condition.

Then, the coefficient function is adopted to deduce the relation between the fatigue lifetime and metal wire diameter of MR vibration isolation. Taking the lifetime curve of the MR elements of $\bar{\rho} = 0.23, d_w = 0.1\text{mm}, h = 1.5\text{mm}$ as the standard, the forecast model is established as following:
\[ \lg(T) = -2.377\alpha_1(d_w)\sigma + 5.408\alpha_2(d_w) \]  

(4)

In the formula, \( \alpha_1(d_w) \) and \( \alpha_2(d_w) \) are the coefficient function related to the metal wire diameter. Because the standard of lifetime forecast model is the lifetime curve of MR elements of \( d_w = 0.1 \text{mm} \), so \( \alpha_1(0.1)=1, \alpha_2(0.1)=1 \). For the coefficient function value of \( d_w=0.08\text{mm} \) and \( d_w=0.12\text{mm} \), the calculation method corresponds with the coefficient specific value between fitting formula and standard formula. It is:

\[ \alpha_1(0.08) = -2.72 / (-2.337) = 1.144, \alpha_2(0.08) = 5.329 / 5.408 = 0.985, \]

\[ \alpha_1(0.12) = -2.229 / (-2.377) = 0.936, \alpha_2(0.12) = 5.458 / 5.408 = 1.01 \]

According to the above coefficient function value, the coefficient function obtained from the least square fitting is as follows

\[
\begin{cases}
\alpha_1(d_w) = 100d_w^2 - 25.2d_w + 2.52 \\
\alpha_2(d_w) = -6.25d_w^2 + 1.875d_w + 0.875
\end{cases}
\]

(5)

Then, the lifetime forecast formula about the metal wire diameter of the fatigue lifetime can be obtained as

\[ \lg(T) = -2.377(100d_w^2 - 25.2d_w + 2.52)\sigma + 5.408(-6.25d_w^2 + 1.875d_w + 0.875) \]

(6)

Figure 2 shows the relationship between the fatigue lifetime of MR vibration isolators and different relative density under the condition that \( d_w=0.1\text{mm} \) and \( h=1.5\text{mm} \). Similarly, based on the lifetime curve of MR elements of \( \bar{\rho}=0.23, d_w=0.1\text{mm}, h=1.5\text{mm} \), the fatigue lifetime about the relative density can be predicted as follows

\[ \lg(T) = -2.377(-83.2\bar{\rho}^2 + 41.37\bar{\rho} - 4.114)\sigma + 5.408(-40.8\bar{\rho}^2 + 21.11\bar{\rho} - 1.697) \]

(7)

Figure 3 is the fatigue lifetime curve of MR vibration isolators with different heights under the condition that the metal wire diameter of MR elements is \( d_w=0.1\text{mm} \) and the relative density is \( \bar{\rho} =0.23 \). Under the same stress condition, the fatigue lifetime of MR isolators increases with the increase of the MR component heights.
Using the same method discussed above, the forecast formula of fatigue lifetime about the height of MR elements can be obtained

\[
\log(T) = -2.377\left(1.798h^2 - 6.429h + 6.598\right)\sigma + 5.408\left(0.446h^2 - 1.519h + 2.275\right)
\]

(8)

The above three formulas are respectively the lifetime forecast formulas obtained under the condition of single influential factor. But in the practical usage, the three factors must be used together and affect the lifetime of MR. After the further exploration in that if the three factors have dependency, the lifetime forecast formula of multi-factor coupling can be obtained on this foundation.

4. Conclusion

Dynamic experiments under random vibration loads are conducted to test the lifetime of MR isolator for the description of its performance degradation. An exponential mathematic model was put forward based on the degradation data. The influencing factors, including the relative density, the diameter of metal wires, and the preloaded deformation of MR components, on the lifetime of isolator were studied. The fitting method for the lifetime fitting formula of the MR vibration isolators based on the single factor was discussed. These approach are beneficial to the further theoretical study and practical application of Metal Rubber vibration isolation system.

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