Experimental study of high/low temperature effects on the dynamic performance of rubber spring for railway vehicles

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Abstract. For the layer rubber spring of a high-speed bogie, lab tests were conducted to obtain the dynamic parameters under extremely high and low temperatures (-60℃~60℃) to obtain the nonlinear stiffness and damping parameters relevant to the frequency, amplitude and temperature changes. It starts from introducing the rubber element dynamic parameter test equipment, test plan and test methods. The applied loads and the temperatures are discussed. Then both the static and dynamic tests were performed for the layer spring of axle box, along the axial and radial directions. It shows that the common results can only reflect frequency- and amplitude-dependent characteristics of rubber, but the corresponding parameter change associated with each frequency and amplitude is highly dependent on the temperature. This phenomenon is quite severe in the low and extremely low temperature cases. Therefore, it is essential and necessary to carry out environmental temperature tests as well as basic theory study and simulations on all rubber components in order to know the parameter variation domain of the suspension system of a railway vehicle.

1. Introduction
Many passenger lines in North China are subject to the extremely cold climate, enduring temperature difference as large as eighty or ninety Celsius degrees, challenging the dynamic performance of bogies and vehicles. The performance of the rubber elements, such as the layer rubber spring of axle box, is sensitive to the temperature, which is critical to the ride comfort. Field test of high speed EMU was carried out under low temperature conditions which can be as low as -30℃. Parameter test and fatigue test of the rubber elements were also carried out in lab under environmental temperatures -40℃~40℃. However, both the field test and lab test have not taken the extreme cases into account, for example the -60℃ and 60℃ cases. Related literatures are also rare. Thus, it would be of great importance to study the influence of extremely high/low temperature on the dynamic performance of rubber element of the bogie and carry out related experiment.

Lab tests show that the stiffness of layer rubber spring could increase by 30%~100% in -40℃ case compared with normal temperature cases, which would significantly increase the wheel-rail contact force and deteriorate the ride comfort [1]. The vibration of a Japan passenger train doubled because of the aging of the rubber element [2], which indicates the dynamic performance of rubber element should be maintained to ensure ride comfort, as well as in extreme temperature cases [3]. The low temperature rebound test of a few rubber parts, which belong to different species, showed that the tensile strength and elongation are quite different in low temperature cases and alternating temperature cases compared
to that of the normal temperature cases [4]. The stiffness and phase angle could be changed by 2–9.4 times when the rubber bushing of auto suspension is tested within a -40–80℃ temperature range, and under a load with 0.05–1.0mm amplitude and 5–100Hz frequency, which suggests that it is necessary to fully consider the low temperature characteristics of the rubber element when adjusting the performance of the vehicle [5]. Dynamic simulation shows that the stochastic variation of stiffness and damping of suspension elements and its variation domain have significant influence on the dynamic performance of high speed train, and affect the accuracy of wheel wear prediction [6, 7].

An experimental test of the dynamic performance of layer rubber spring for the 350km/h standard EMU was carried out to study the nonlinear characteristic of stiffness and damping under extremely low temperature, reveal the correlation and influence mechanism between frequency-dependent characteristics, amplitude dependent characteristics and temperature dependent characteristics, and obtain the variation range of the key parameters.

2. The layer rubber spring of axle box
The layer rubber spring of axle box is shown in Fig.1. The laminated rubber spring and the steel spring provide vertical support and vibration isolation, bearing the preloading load and dynamic load.

Figure 1. (a) bogie of a high-speed railway vehicle, (b) The layer rubber spring of axle box

3. Test rig and test procedure
3.1. Test temperature
The main varieties of vibration damping rubber for railway vehicles suitable for -40℃ and lower temperature environment are natural rubber, and modified rubber, made by mixing natural rubber and butadiene rubber or other rubber. Rubber brittleness and crystallization in low temperature conditions will cause the loss of elasticity and working ability, therefore, the low temperature resistance of rubber mainly depends on the brittle temperature and crystallization.

The three temperature-related phase of the rubber are shown in Fig. 2, and the test temperatures are set to -60℃, -50℃, -40℃, -30℃, -20℃, -10℃, 0℃, 23℃, 40℃ and 60℃ respectively.

Figure 2. The elastic modulus of rubber under different temperatures
3.2. Test rig

![Test rig diagram]

(1-base. 2-bearing. 3-lower layer rubber spring. 4/5-joint of the actuator. 6-upper layer rubber spring. 7-lateral fix plate. 8-vertical fix plate)

Figure 3. The dynamic parameter test rig for the layer rubber spring of axle box

The test rig used is shown in Fig.3. A hydraulic system is used to apply excitation on the sample, and the displacement and force signal are collected by the displacement sensor and force sensor of the actuator. The force range is ±100 kN, the precision is 0.1% F.S, and the displacement range is ±150mm, the precision is 0.1 %F.S. The temperature box, with a volume ≥1.5 m³, digital controllable temperature range -70~70℃, is used. Before the test, the tested elastic element is placed in the temperature box for more than 24 hours, and the parameter test is carried out after specified test temperature is reached [8, 9].

3.3. Test procedure

Each test follows the same procedure.

1) The static stiffness test must be carried out before the test to meet the static stiffness requirements.

2) before the test, put the rubber pad specimen in the temperature box, set the test temperature, and maintain more than 24 h.

3) parameter test. When doing tests for one specimen, room temperature tests are carried out firstly, then the high temperature tests, and finally the low temperature tests. The tests are arranged in such an order to avoid the rubber crystallization effect caused by low temperatures.

4. Test results

The data processing method used for calculating the stiffness and damping coefficients are based on load-deflection hysteresis curve, and the average processing of multiple data samples is also employed.

4.1. static performance

The temperature-dependent characteristic curve of the static stiffness is shown in Fig. 4. The axial and radial stiffness decrease with the rise of temperature in each load case, and increase with the drop of temperature, which is approximately linear. The axial stiffness changes by 0.06 MN/m and the radial stiffness changes by 0.03 MN/m when the temperature drops by 10℃.
4.2. The effects of temperature on dynamic stiffness

The axial stiffness is highly dependent on the amplitude and frequency of load as shown in Fig. 5. Table 1 shows the high/low temperature characteristics of the axial and radial stiffness (-60 ~ 60 °C). The trends of the frequency- and amplitude- dependent characteristics of the dynamic stiffness are basically the same at different temperatures. Compared with high temperature cases, the effects of low temperature on the stiffness are more significant, which is due to the transition of rubber from rubber phase to glass phase. The axial stiffness increases by 160% ~ 313% (0.5 mm), 79% ~ 163% (1 mm), while the radial stiffness increases by 209% ~ 308% (0.5 mm) and 127% ~ 206% (1 mm) at -60 °C, which indicates that the stiffness increases significantly at extremely low temperatures by up to three times.

Table 1. High/low temperature characteristics of dynamic stiffness of laminated rubber spring

| load case | 23°C (kN/mm) | -60°C rise (%) | 60°C drop (%) | 23°C (kN/mm) | -60°C rise (%) | 60°C drop (%) |
|-----------|--------------|----------------|--------------|--------------|----------------|--------------|
| 0.5mm-1Hz | 4.1          | 160            | 17           | 1.6          | 209            | 13           |
| 0.5mm-2Hz | 4.1          | 193            | 17           | 1.7          | 233            | 12           |
| 0.5mm-6Hz | 4.1          | 265            | 16           | 1.7          | 268            | 14           |
| 0.5mm-12Hz| 4.1          | 313            | 22           | 1.7          | 308            | 13           |
| 1mm-1Hz   | 3.8          | 79             | 11           | 1.5          | 127            | 12           |
4.3. The effects of temperature on dynamic damping

![Figure 6. Nonlinear characteristics of dynamic damping at -40°C](image)

(a) Amplitude dependent characteristics  (b) Frequency dependent characteristics

Table 2. High/low temperature characteristics of axial dynamic damping of laminated rubber springs

| load case | 23°C (kN.s/m) | -60°C rise (%) | 60°C drop (%) | 23°C (kN.s/m) | -60°C rise (%) | 60°C drop (%) |
|-----------|---------------|----------------|---------------|---------------|----------------|---------------|
| 0.5mm-1Hz | 96            | 542            | 71            | 25.3          | 750            | 33            |
| 0.5mm-2Hz | 50.1          | 637            | 71            | 13.6          | 810            | 32            |
| 0.5mm-6Hz | 17.2          | 841            | 67            | 5.5           | 862            | 31            |
| 0.5mm-12Hz| 9.3           | 905            | 66            | 3.5           | 820            | 37            |
| 1mm-1Hz   | 71.5          | 330            | 60            | 26.5          | 472            | 29            |
| 1mm-2Hz   | 37.6          | 402            | 59            | 14.4          | 513            | 29            |
| 1mm-6Hz   | 13.7          | 529            | 58            | 5.8           | 555            | 31            |
| 1mm-12Hz  | 7.6           | 607            | 57            | 3.4           | 591            | 29            |

The dynamic damping is highly dependent on the amplitude and frequency of load as shown in Fig. 6. Table 2 shows the high/low temperature characteristics of the axial and radial damping (-60°C ~ 60°C). The trends of the frequency- and amplitude- dependent characteristics of the dynamic damping are basically the same at different temperatures. Compared with high temperature cases, the effects of low temperature on the damping are more significant, which is due to the transition of rubber from rubber phase to glass phase. The axial damping increases by 5-9 times (0.5 mm) and 3-6 times (1 mm), while the radial damping increases by 7-9 times (0.5 mm) and 5-6 times (1 mm) at -60°C, which indicates that the damping increases significantly at extremely low temperatures by up to nine times.

5. Conclusions

The dynamic parameters of layer rubber spring of bogies have the nonlinearity frequency dependent, amplitude dependent and temperature dependent characteristics. The traditional parameter testing only reflects frequency- and amplitude-dependent characteristics of rubber, but the corresponding parameter change associated with each frequency and amplitude is highly dependent on the temperature. This paper finds that the trends of frequency dependent characteristics and amplitude dependent characteristics under low and high temperature conditions are still the same, but the variation of dynamic parameters
under corresponding frequency and amplitude conditions is strongly related to temperature, which varies the most in extremely low temperature cases. The transformation from rubber phase to glass phase under temperatures below 0℃ would cause the change of its elastic modulus and resilience. Therefore, it is necessary to carry out a complete parameter test, as well as theoretical study and simulation on all elastic rubber parts of the vehicle in order to accurately obtain the parameter variation region of the suspension system.

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