Analysis and Research on Rubber Joint of the Axle Box Rotary Arm of CRH3 EMU

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Abstract: In order to study the stiffness performance of rubber joint of axle box rotary arm for EMU, the rubber joint of axle box rotary arm for CRH3 EMU was studied by combining finite element analysis with experiment. The structural composition of rubber joint of axle box rotating arm and several strain energy functions of rubber hyperelastic materials are described. The material constants of Mooney-Rivlin and Ogden models are obtained by curve fitting of rubber material test data. The radial stiffness and the axial stiffness of the rubber joint of the axle box rotating arm are calculated by using the finite element simulation software, and the experimental verification is carried out at the same time. It is found that the results of Mooney-Rivlin and Ogden models are similar in the case of small deformation, and Ogden model is more accurate in the case of large deformation.

1. Introduction
The rubber joint of the axle box rotating arm is an important component of the running part of railway vehicles. It is usually used in conjunction with the axle box coil spring, vertical shock absorber and rubber pad to form a suspension system of the running part of vehicles [1]. The rubber joint of the axle box rotating arm transmits the longitudinal force produced by traction motor and braking system, and bears the vertical force of the body and running part [2]. When the vehicle passes through the curve, the rubber joint of the axle box rotating arm transmits the longitudinal force produced by the traction motor. The rubber joint of the axle box rotating arm bears the transverse force between wheel and rail [3-4]. Because the stiffness of rubber joint of axle box rotating arm is much greater than that of axle box coil spring, it directly affects the safety and stability of vehicle operation. At the same time, the stiffness of rubber joint of axle box rotating arm is also related to the wear ratio between wheel and rail, and has certain influence on the economy of vehicle operation. Therefore, it is necessary to study the stiffness performance of rubber joint of axle box rotating arm. This is the case. With the development of finite element simulation software, the simulation analysis of rubber materials has been partially solved. After 2000, the finite element analysis of rubber materials has made a great breakthrough [8-9]. WANG Jin[10] and YANG Mingming [11] have studied the constitutive relationship of rubber materials from the test aspect of rubber samples and analyzed the constitutive relationship of rubber materials. The stiffness of rubber joints was analyzed by finite element analysis software based on the Yeoh model of rubber material by LIAO Ying-ying; WANG Li-rong et al. [13] based on uniaxial tensile data of rubber materials, applied finite element analysis software to analyze the stress of rubber joints; DING Zhi-ping [14] based on fracture energy theory, applied finite element software to analyze the fatigue life of rubber materials. In the above study, the metal rubber joint was
studied by finite element calculation or test, but the selection of constitutive model for different rubber materials and the difference between finite element calculation and test data were not analyzed in detail.

In this paper, material model constants are fitted based on uniaxial tension, biaxial tension and plane shear test data of rubber material samples. Mooney-Rivlin and Ogden rubber material constitutive models are selected respectively, and the radial and axial stiffness of rubber joint of axle box rotating arm are analyzed by using finite element analysis software Abaqus. Meanwhile, the radial stiffness and axial stiffness of the rubber joint of the axle box rotating arm were measured by experiment, which verified the accuracy of the finite element analysis. Finally, the finite element analysis results based on different constitutive models are compared with the test results, which provide a reference for the application of rubber products in railway vehicles.

2. Rubber joint of axle box rotary arm and rubber material model

2.1. Structure of rubber joint of axle box rotary arm
The rubber joint of axle box rotating arm includes three parts: metal outer ring, mandrel and rubber, as shown in Figure 1. As the main bearing part, the metal outer ring and core axle are made of high strength steel Q345E and 42CrMo, which are combined by rubber vulcanization. Because the ratio of radial stiffness to transverse stiffness is 20:1 and 10:1, the radial stiffness and axial stiffness of rubber joint of axle box rotator arm have great influence on the safety of vehicle operation and the stability of snake motion, and are the two most important parameters of rubber joint of axle box rotator arm. The metal outer ring and core axle of the rubber joint of the axle box rotating arm adopt symmetrical structure, so its vertical stiffness and radial stiffness are identical, which can be considered equally in finite element analysis and test.

![Figure 1. Composition of CRH3 EMU Rubber Joint of Axle Box Rotary Arm](image)

2.2. Constitutive relation model of rubber material
At present, the descriptions of mechanical properties of rubber materials are mainly divided into two categories: one is based on phenomenological descriptions, that is, rubber is a continuous medium, assuming that rubber is isotropic in the undeformed state, that is, the direction of long molecular chains is randomly distributed in rubber; the other is based on thermodynamic statistical methods, that elastic resilience in rubber is due to rubber. Due to the decrease of entropy in rubber, the elongation of rubber makes the structure of rubber change from highly disordered to orderly [15]. The constitutive relationship of rubber can be obtained by counting the length, direction and structure of molecular chains in rubber.

After a long period of theoretical research, the widely used constitutive models of rubber materials are polynomial model and Ogden model based on continuum mechanics theory, and model based on thermodynamic statistical theory. For isotropic materials, strain energy can be decomposed into two parts: strain deviation energy and volume strain energy.
In the formula, $C_{ij}$ is Taylor expansion coefficient; $N$ is polynomial order; $I_1$ and $I_2$ are the first and second strain invariant deviation of Cauchy-Green tensor respectively; $J$ is volume compression ratio; $D_i$ is the compression ratio of material, which depends on whether the material is compressible or not. At the time of $D_i = 0$, it shows that the material is completely incompressible. When the first two items are retained after the expansion of equation (1), $i = 1$, $j = 0$ and $i = 0$, $j = 1$, only the strain energy of the linear part is left, and the Mooney-Rivlin model is obtained.

$$U = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \frac{1}{D_i} (J - 1)^2$$

As a hyperelastic model, the mechanical properties of materials can be accurately described by Mooney-Rivlin model when the strain range of materials reaches 0-100%. When the strain range of materials exceeds 100%, the Mooney-Rivlin model will lead to large errors in calculation, and other constitutive models need to be selected.

Ogden model considers that the elongation of material can be directly used as an independent variable instead of the invariant to describe the strain energy function. The expression of Ogden model is as follows:

$$U = \sum_{\alpha=1}^{N} \frac{2 \mu_\alpha}{\alpha_\alpha} \left( \lambda_1^{\alpha_1} + \lambda_2^{\alpha_2} + \lambda_3^{\alpha_3} - 3 \right) + \sum_{i=0}^{N} \frac{1}{D_i} (J - 1)^{2i}$$

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In the formula, $\alpha_i$ and $\mu_i$ are material constant, which can be measured by experiment, $\lambda_1$, $\lambda_2$, and $\lambda_3$ are three main elongation ratios. Ogden model covers a wider range of material strain. This model is not only suitable for materials with small strain compression and shear models, but also suitable for materials with 700% strain in simple tensile tests. At the same time, the strain energy function expressed by elongation is more intuitive than the strain invariant.

3. Simulation analysis of rubber joint stiffness of axle box rotary arm

3.1. Stiffness calculation method of rubber joint of axle box rotating arm

After loading the radial or axial direction of the rubber joint of the axle box rotating arm, the load-displacement curve is obtained, as shown in Figure 2. In the figure, $F$ is the load on rubber joints. $s$ is the deformation under the load $F$, the radial and axial stiffness of the joints $K_J$ and $K_Z$ are obtained by taking the point to point in the curve as the interval of stiffness calculation for the loads $F_1$ and $F_2$ on the joints and the deformation caused by the loads.

$$K_J = K_Z = \frac{F_2 - F_1}{s_2 - s_1}$$

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3.2. Finite element analysis of rubber joint of axle box rotary arm

According to the vehicle dynamics calculation and test, the stress and ideal stiffness range of rubber joint of axle box rotating arm can be obtained. The loading range of finite element calculation and test can be obtained through TB/T 2843-2015 “General Technical Conditions for Rubber Elastic Components for Locomotives and Vehicles” [16]. See Table 1.

| Direction | Load area/kN | Stiffness calculation area /kN | Stiffness required/(kN/mm) |
|-----------|--------------|-------------------------------|---------------------------|
| Radial    | 0~90         | 0~90                          | 120×（1±15%）              |
| Axial     | 0~22         | 0~22                          | 12.5×（1±15%）             |

In the finite element analysis, in order to minimize the calculation time and improve the efficiency on the premise of ensuring the accuracy of the calculation results, it is necessary to simplify the calculation model according to the actual situation. The simulation model of rubber joint of axle box rotating arm mainly considers the deformation of rubber under load. Therefore, metal outer ring and core shaft are not the key points of calculation. It is necessary to simplify the sharp angle and transition area position of core shaft, and refine the rubber part. The metal outer ring material of rubber joint of axle box turning arm is Q345E, and the core material is 42CrMo. Its elastic modulus is 2.06×10^5 Mpa, Poisson’s ratio is 0.3. The metal part is made of C3D8R unit, totaling 14277 units. C3D8H unit is selected as rubber part, which consists of 40767 units. Mooney-Rivlin model and Ogden model are used to calculate the constitutive relationship of materials. The finite element mesh model of rubber joint of axle box turning arm is shown in Figure 3.

3.2.1 Radial stiffness analysis

In the calculation of radial stiffness, constraints are applied to the support positions on both sides of the mandrel, and loads are applied to the outer ring of the rubber joint of the axle box rotating arm. The calculated displacement nephogram is shown in Figure 4. According to Mooney-Rivlin model,
when the radial load is 90 kN, the relative radial displacement between the outer jacket and the mandrel is 0.796 mm. According to formula (4), the radial stiffness $K_J$ is calculated to be 113 kN/mm. According to the Ogden model, when the radial load is 90 kN, the relative radial displacement between the outer jacket and the core shaft is 0.776 mm. According to formula (4), the radial stiffness $K_J$ is calculated to be 116 kN/mm.

The radial stiffness values calculated by Mooney-Rivlin model and Ogden model are within the stiffness index range of the rubber joint of the axle box rotating arm. The deviation of the radial stiffness calculated by the two models is small, and the deviation from the median is only 2.6%.

3.2.2 Analysis of Axial Stiffness

In the analysis of axial stiffness, the constraints are also applied to the mandrel position, and the load is applied to the outer ring of the rubber joint of the axle box rotating arm. The calculated displacement nephogram is shown in Figure 5. According to Mooney-Rivlin model, when the axial load is 22 kN, the relative radial displacement between the outer jacket and the mandrel is 2.04 mm. According to formula (4), the axial stiffness $K_Z$ is calculated to be 10.8 kN/mm. According to Ogden model, when the axial load is 22 kN, the relative radial displacement between the outer jacket and the mandrel is 1.91 mm. According to formula (4), the axial stiffness $K_Z$ is calculated to be 11.5 kN/mm.

4. Stiffness Test and Result Analysis

4.1. Radial stiffness test

Radial stiffness test method: the radial stiffness of rubber joint of axle box rotating arm is loaded from 0 to 100 N at the speed of 1 mm/min, and the displacement is cleared; then the same speed is loaded to 90 kN, and then unloaded to 100 N; the load-displacement data of the third cycle is recorded, and the radial stiffness of rubber joint of axle box rotating arm is calculated with the load-displacement data of interval (0-90 kN). The radial stiffness test photograph is shown in Figure 6, and the test curve is shown in Figure 7. The radial stiffness measured by the test is 108 kN/mm.
4.2. Axial stiffness test
Axial stiffness test method: load the rubber joint of axle box turning arm from 0 to 100N at the speed of 5mm/min, then load it to 22kN at the same speed, then unload it to 100N; record the load-displacement data of the third cycle for three cycles, and calculate the axle box turning arm rubber joint's axial stiffness with the load-displacement data of the interval (0-22kN). The axial stiffness test pictures are shown in Figure 8 and the test curves are shown in Figure 9. The measured axial stiffness is 11.3 kN/mm.
4.3. Error Analysis of Finite Element Computation and Test Results

Comparisons between finite element calculation and test results are shown in Table 3. By comparing the radial and axial stiffness calculated by Mooney-Rivlin model and Ogden model with the experimental values, it can be seen that:

1) The radial stiffness calculated based on the two rubber constitutive models is close to the axial stiffness. The deviation between the radial stiffness and the median is 2.6%, and the deviation between the axial stiffness and the median is 6.3%. Because the radial stiffness is close to the 10 times of the axial stiffness, it can be seen that the two material constitutive models are applicable to a wide range.

2) The calculated radial stiffness based on the two rubber constitutive models is close to the experimental value. The maximum error of radial stiffness and axial stiffness is 7.1% and 4.5% respectively, which verifies the accuracy of finite element calculation.

3) For the radial stiffness, the results based on Mooney-Rivlin model are closer to the test results, with a deviation of 4.5%. For the axial stiffness, the results based on Ogden model are closer to the test results, with a deviation of only 1.8%. This also proves that Mooney-Rivlin model has better applicability for small strain and Ogden model is more suitable for large strain range.

| Direction | Finite Element Analysis Based on Mooney-Rivlin Model / (kN/mm) | Finite Element Analysis Based on Ogden Model / (kN/mm) | Test results / (kN/mm) |
|-----------|---------------------------------------------------------------|----------------------------------------------------------|------------------------|
| Radial    | 113                                                           | 116                                                      | 108                    |
| Axial     | 10.8                                                          | 11.5                                                     | 11.3                   |

5. Conclusion

1) Based on Mooney-Rivlin model and Ogden model, the radial stiffness and axial stiffness of the rubber joint of the axle box rotating arm are analyzed. The results show that the difference between the two models is small, and they are suitable for the calculation of the rubber joint of the axle box rotating arm.

2) The radial stiffness and axial stiffness calculated by the two constitutive models are close to the experimental results, with the maximum deviation of 7.1%. It shows that the finite element analysis software, as an effective calculation method, can be widely used in the design and development of rubber products, which improves the efficiency and reduces the cost.

3) According to the comparison between the results of finite element calculation and experimental measurements, it can be seen that Mooney-Rivlin model has better applicability for small strain and
Ogden model is more suitable for large strain range.

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