Fatigue Simulation of Railway Car Bogie Frame Based on Multi-body Dynamics and Finite Element Analysis

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Abstract: This paper proposes to combine multi-body dynamics and finite element method to study the fatigue strength and fatigue life of the bogie frame from the perspective of taking the vehicle as a whole. The analysis model established by the multi-body dynamics simulation software SIMPACK, the dangerous positions are determined from FEA software ANSYS, Based on the load-time history and Miner cumulative damage theory, the fatigue strength prediction is carried out using n-software, the study shows that the time-load history of each key position obtained by simulating working conditions can predict the life of components more accurately, this method can be applied to the initial stage of product design.

1. Introduction
With the continuous increase in the speed and load capacity of freight trains in China, in order to improve the performance of locomotives and reduce the cost of track maintenance, lightweight design is adopted in the load-bearing structure of locomotives and rolling stocks. At the same time, the structural reliability problems are becoming more and more prominent. Currently, the static strength and fatigue strength analysis of the products are mainly based on related design standards and vehicle service environment. The fatigue of mechanical parts is caused by cyclic strain in the local stress concentration area. In addition, the load-time history is random, therefore using the static strength analysis results to check the fatigue strength of the structure may cause serious problems. At present, there are few researches on fatigue simulation of locomotives and vehicles under dynamic load relatively. However, in the aerospace and automotive industries, multi-body dynamics has been introduced into the product design stage, and significant results have been achieved. Based on the literature[1]-[2], this paper proposes to combine multi-body dynamics and finite element method to study the fatigue strength and fatigue life of the bogie frame from the perspective of taking the vehicle as a whole.

2. Principle
The main research content of this paper is multi-body dynamics simulation of vehicle system, finite element analysis of side frame, fatigue strength check and fatigue life prediction. The brief process includes the establishment of the vehicle's multi-body dynamics model (using the multi-body dynamics software SIMPACK). At present, the entire structure is considered as rigid, and the time-load histories of the key parts required are extracted, and then predicting their fatigue life. The method proposed in this paper is expected to accurately predict structural fatigue characteristics in the early stage of product development, optimize product structural design, and provide a simple and
feasible path for actual production and research. The analysis flowchart is shown in Figure 1.

![Analysis flow chart](image)

**Figure 1. Analysis flow chart**

### 3. Modeling and simulation of multi-body dynamics

Vehicle systems, similar with other complex mechanical systems, can be effectively described by a model system composed of many rigid bodies and non-rigid bodies (also called flexible bodies or elastic bodies). According to related studies, it is feasible in engineering to consider all the main structural components in the vehicle system as rigid bodies because the rigidity of the main structural components is much greater than that of the suspension system. Therefore, a certain type of gondola car body used in this study can be determined by rigid body, force element, restraint, wheel-rail contact relationship, etc. The analysis model established by the multi-body dynamics simulation software SIMPACK is shown in Figure 2.

![Overall model of vehicle system dynamics](image)

**Figure 2. Overall model of vehicle system dynamics**

How to design the dynamic simulation analysis working conditions accurately and compare and verify with the standards is directly related to the validity of the results of the method proposed in this paper. Therefore, in addition to establishing a reliable vehicle system dynamics model, selecting a reasonable running speed and track spectrum is also very important, and then the load-time history of the vehicle body structure can be obtained through dynamic simulation calculations. So as to prepare for the final fatigue strength verification and comparison with the existing iron standard.

Research has shown [1] that the main railway track spectrum in China is between the 5th and 6th grades of railway track spectrum of the United States, so the U.S. grade 5 spectrum and grade 6 spectrum are used in this paper as orbital excitation. In the simulation analysis, consider the vehicle running on a straight track at 50-120km/h. Among them, orbital excitation of the vehicle at the speed of 50km/h and 60km/h is based on grade 3 spectrum and grade 4 spectrum separately, the orbital excitation of the vehicle at the speed of 70,80,and 90km/h is based on grade 5 spectrum , the speed of 100～120km/h are based on grade 6 spectrum. Six types of curve running conditions are also designed for curve passing performance analysis, as shown in Table 1.
Table 1. Dynamic simulation analysis of curve track conditions

| Under-elevation/mm | Curve radius/m | Easing curve length/m | Circular curve length/m | Super high/mm | Excitation spectrum |
|--------------------|----------------|-----------------------|-------------------------|---------------|---------------------|
| 110                | 250            | 100                   | 200                     | 120           | Grade 5             |
| 110                | 350            | 100                   | 200                     | 120           | Grade 5             |
| 108                | 600            | 100                   | 200                     | 125           | Grade 6             |
| 87                 | 800            | 100                   | 200                     | 125           | Grade 6             |
| 109                | 1000           | 100                   | 200                     | 125           | Grade 6             |
| 105                | 1200           | 100                   | 200                     | 125           | Grade 6             |

4. Establishment of load spectrum block
After completing the dynamic simulation analysis, the time-load history of the relevant position of the bogie frame under different working conditions can be obtained. The process of analyzing and categorizing the random response time-load history and processing it into a series of full cycles or half cycles is called counting method. In this paper, the rain flow counting method [3] is used to process the extracted data to obtain the load spectrum block at the required position [4]. Figure 3 shows the load spectrum block of the vertical load at the spring cap of side frame. The fluctuation center of the load spectrum block is 210kN, and the amplitudes of each level are 3kN, 8.8kN, 14.5kN, 20.3kN, 26.1kN, 31.8kN, 37.6kN and 43.4kN. The running distance of the vehicle is 1000m, a total of 308 vibrations were recorded. According to the current minimum standard of truck bogie operating mileage not less than 5 million kilometers[5], the total frequency of load spectrum block should be $1.54 \times 10^9$.

Figure 3. Load spectrum block of vertical load program

Such a huge amount of loading condition will cause huge waste in test time and cost, which is impossible in engineering tests. Therefore, the specimens need to be subjected to accelerated fatigue tests under intensified conditions[6]. The accelerated fatigue test should meet two basic conditions: First, the test under the strengthened condition should be essentially the same as the test under the normal condition, it is within the range of elastic deformation in this paper, that is, it cannot exceed the yield limit of the material; second, the sum of the damage caused under the strengthened condition should be the same as the sum of the damage produced under the normal condition.

5. Fatigue strength check and comparison
This paper uses ANSYS software to establish the finite element analysis model of the bogie frame, as shown in Figure 4. The static strength check is carried out according to the requirements of TB/T1335-1996 "Code for Strength Design and Test Appraisal of Railway Vehicles". The simulation analysis result is shown in Figure 5. The side frame material is grade B steel, the maximum equivalent stress is 113.131MPa, which meets the requirement of 117MPa specified by the standard, and is consistent with the test results.
Figure 4. Finite element model of side frame

Figure 5. Stress distribution cloud of side frame finite element model

In the fatigue analysis software n-soft, the standard load spectrum block is established according to TB1959; instantaneously, the virtual load spectrum of the interest position can also be established according to the statistical processing results of the dynamic simulation analysis results, the lateral and vertical virtual load spectral blocks are shown in Figure 6a and 6b.

Figure 6a. Virtual vertical load spectrum block

Figure 6b. Virtual lateral load spectrum block

In order to speed up the calculation time, according to the principle of fatigue damage accumulation, the total cycle frequency of the enhanced load spectrum block after simulation analysis is $1.5 \times 10^3$, and the damage result counted is one hundredth of the full cycle. Figure 7 shows the fatigue damage cloud diagram obtained from the virtual load spectrum block, and Figure 8 shows the fatigue damage cloud diagram obtained from the standard load spectrum block.

Figure 7. Fatigue damage cloud diagram under virtual load spectrum

Figure 8. Fatigue damage cloud diagram under standard load spectrum

It can be seen from Figure 7 that the damage accumulation of the largest node of the side frame under the affect of the virtual load spectrum is $4.541 \times 10^{-3}$. Because the number of cycles is 1% of the total frequency, the total fatigue damage accumulation is about $4.541 \times 10^1$. It can be seen from Figure 8 that under the affect of the standard load spectrum, the damage accumulation of the largest node is $2.028 \times 10^{-3}$, that is, the total fatigue damage accumulation is about $2.028 \times 10^1$. Through comparison, it is known that the damage accumulation under the affect of the virtual load spectrum is much larger than the damage accumulation under the China railway standard condition. There are two
main reasons for the result: on one hand, the standard load spectrum is formed by TB1959, and its load characteristics are based on the previous railway freight cars in China, that is, the actual operating speed and load capacity are relatively low; while the virtual load spectrum takes more into consideration the operating speed of freight cars in the range of 90-120km/h. The lateral and vertical test load has been reduced a lot compared with the TB standard, and it is suitable for lower speeds. The speed and working conditions selected in this paper are relatively harsh. On the other hand, the TB standard does not consider the impact of amplitude changes on damage, so this paper uses level 8 amplitude. It can be seen that the use of virtual load spectrum can not only examine the vertical load, lateral load and torsional load in the standard load spectrum, but also obtain the load spectrum of the position between the side frame and the bolster at the diagonal wedge, so the results obtained from virtual load spectrum by simulation is more rigorous compared with using the standard load spectrum, which can more reflect actual conditions. For example, in the “Compilation of Typical Failures of Railway Freight Cars”, about a quarter of the fatigue accidents of similar bogies occurred at the corners of the inspection holes on the inner side of the wear plate, as shown in Figure 9 (the arrow indicates the part). Comparing Figures 7 to 10, it can be seen that the fatigue damage obtained by the virtual load spectrum analysis can predict the damage at this location, but the method using the TB1959 load spectrum cannot. Other dangerous locations are basically the same.

6. Conclusion
Based on the combination of multi-body dynamics and finite element analysis, this paper uses this method to calculate and check the fatigue strength of a certain domestic freight car bogie according the test conditions and related standards. The following conclusions are obtained:

1) Use the multi-body dynamics software SIMPACK to establish a vehicle model, extract the time-load history of key parts of the bogie, and use the rainflow counting method to compile it into a load spectrum block. The fatigue strength was checked and compared with the method specified in the TB standard. The results obtained prove that this method is more accurate and effective.

2) The time-load history of each key position obtained by simulating working conditions can predict the life of components more accurately.

3) This method can be applied to the initial stage of product design, starting from the dynamic performance of the vehicle, studying the fatigue characteristics of the structure, and providing an accurate and convenient way for product design and manufacturing. At the same time, it can also provide useful suggestions to formulate relevant fatigue strength calibration standards.

Reference
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