Research Article

Fatigue Analysis of a Light Truck Rear Axle Based on Virtual Iteration Method

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Firstly, the MBD (multi-body dynamics) model of the whole vehicle is built according to the measured vehicle parameters. Then, the road spectra acquisition test is carried out. Under the test road conditions, the acceleration, displacement, and force signals of multiple positions of the whole vehicle are collected. Taking the road test signals as the iterative target and the vehicle MBD model as the iterative carrier, the vehicle equivalent excitation is obtained by using the VIM (virtual iteration method). By applying the equivalent excitation obtained by VIM to the vehicle MBD model, the load spectra of key points of the driving rear axle are obtained. The accuracy of the model is verified by comparing the measured signals with the iterative signals, and the reliability of the key points load spectra is enhanced. Secondly, the FEA (finite element analysis) model of the rear axle is built, and the static analysis results of each key point under unit load are obtained with the help of FEA software. Thirdly, the FEA results, key points load spectra, and material fatigue characteristic curve of the rear axle are input into the fatigue software to conduct the fatigue simulation of the rear axle. According to the fatigue analysis results, the position where the fatigue life does not meet the set goal is accurately located. Finally, the structure is optimized based on the above results. The fatigue life evaluation of the optimized rear axle shows that its durability has been significantly improved.

1. Introduction

With the development of the automobile industry, automobile reliability has received more and more attention. Automobile reliability is a complex comprehensive performance, which refers to the ability of the automobile to complete the specified functions within the specified time and under the specified service conditions. Broadly speaking, it includes fatigue reliability, maintainability, and preservation. Among the indexes of automobile reliability, fatigue reliability is the top priority \cite{1-4}. Automotive structures are usually subjected to cyclic dynamic random loads, which will cause fatigue damage to the structure. When the fatigue damage accumulates to a certain extent, fatigue failure will occur. However, before that, there will be no obvious signs. Therefore, enough attention should be paid to fatigue analysis in the design stage of mechanical structure.

The traditional fatigue durability analysis method is a process of repeated iteration of design and test, which is characterized by large investments, long cycles, and slow effects. With the development of computer simulation technology, the fatigue life of automobiles can be predicted by using appropriate algorithms and necessary tests. Compared with the traditional method, there are the advantages of small investments, short cycles, fast effects, and high accuracies.

In this paper, a fatigue life evaluation method combining fatigue simulation and VIM (virtual iteration method) is introduced. And the method is applied to a driving rear axle. Meanwhile, FEA (finite element analysis), MBD (multi-body dynamics), and VIM are used in the process.
In recent years, many fatigue studies have used FEA and the MBD method. MBD and FEA method was used by Jin et al. to analyze the fatigue life of a vehicle body. The analysis results showed that, compared with traditional fatigue methods, more reasonable prediction results could be obtained by the method combining MBD and multiaxial fatigue [5]. Zhou et al. used the method of virtual bench test based on real road spectra to study the fatigue life of automobile parts, so as to quickly and accurately predict the fatigue life of automobile structure and guide the improvement of fatigue performance of structure [6]. Shen et al. extracted the load spectra with a sextant and MBD model. The life of the passenger car body was analyzed and optimized by them. Low-cost acquisition of the input load spectra was achieved by this method [7]. Edara et al. studied the fatigue durability of heavy truck suspension systems with the help of a virtual road test field and FEA. The feasibility of using digital prototypes and virtual test field simulation to evaluate the durability of suspension systems before the construction of a physical prototype is verified [8]. Sistla et al. studied the influence of different tires on vehicle fatigue with the help of MBD [9]. Sathish et al. completed the fatigue study of bus cabs with the help of load spectra collected from real road tests and MBD, which showed that the fatigue life of the vehicle can be effectively predicted by combining MBD and FEA method in the early design stage of the vehicle [10]. Cruz et al. used the method of combining ADAMS software and test to generate the load spectra. The application of this method greatly shortened the time spent in determining the load spectra and had good reliability [11]. Roy and Villaire established the whole vehicle model through ADAMS software and simulated it on the virtual road [12]. The high accuracy of this method could be verified by comparing the load spectra collected from the standard test site. To examine the effect of the wheel polygonization on the fatigue of the wheelset-mounted gearbox housing of a high-speed train, a three-dimensional multibody system railway vehicle model is established by Wu et al. to perform the FEA and MBD analysis simultaneously. The result shows that the stress distribution on the gearbox housing is significantly affected by the deformation of the wheelset [13]. Korba et al. obtained geometric models of brake discs by reverse engineering and performed the lifetime analysis using FEA method, which achieved the aim of assessing which variant reduces the risk of brake overheating better [14].

In addition, VIM is gradually used to obtain external load spectra for fatigue analysis in recent studies. Wu et al. studied the fatigue of car bodies by VIM [15]. The simulation results were in good agreement with the measured strain gauge bench test results. It demonstrated that this method could quickly reflect the risk, greatly shorten the development cycle, and reduce the cost. Fatigue damage analysis and structural improvement of a commercial vehicle cab were carried out by Wang et al., in which a simulation technique and durability road tests were combined [16]. Liu et al. carried out fatigue analysis of medium truck cab based on VIM and verified the accuracy of simulation results combined with bench fatigue test results [17]. The combination of tests and virtual simulation not only shortens the fatigue analysis cycle but also ensures its accuracy. Dannbaue et al. investigated the fatigue durability of automobile front suspension with the help of FEA and MBD [18]. The results of the study proved that adding VIM in the analysis process could significantly improve the dynamic response of the complex mechanical system and improve the quality of fatigue life prediction. Ryu obtained the load spectra of the virtual test laboratory through VIM and proposed a strength specification, which provided guidance for early design [19]. Ge et al. proposed a compilation method that can completely retain the damage value, amplitude characteristics, and frequency characteristics of long-distance pavement load spectra. The proposed load spectra compilation method provides a solution for accelerating the virtual iteration of MBD model [20]. Taking the steering knuckle of an automobile as the research object, Dong et al. established the MBD simulation model of the whole vehicle and verified its accuracy. The virtual iteration method is used for simulation decomposition to obtain the load spectra of steering knuckle connection point. The feasibility and accuracy of the technical route of load spectra extraction are proved, which provides a reference basis for the development of automobile chassis parts and the analysis and verification of fatigue durability [21]. Meng et al. takes the cab of a heavy commercial vehicle as the research object, extracts the load spectra at the connection between the cab and the suspension system by using the virtual iterative method, analyzes the fatigue life of the cab according to the linear fatigue cumulative damage theory, and compares it with the indoor bench road simulation test results to verify the correctness of the simulation analysis results [22].

Generally speaking, the combination of the actual road test, VIM, MBD, and FEA is widely used in fatigue simulation. This method not only ensures the accuracy of fatigue analysis but also greatly improves the efficiency compared with traditional methods. However, there are few studies on the combination of the above method with the driving rear axle.

In this paper, a method combining simulation technology with road test is proposed and applied to the fatigue analysis of the driving rear axle of a light truck. To obtain the load spectra required for fatigue simulation, some response signals are collected through the road test. The load spectra are extracted with the help of VIM and the vehicle MBD model. The FEA model of the rear axle is established and its static analysis results are obtained. Combined with the load spectra, static results, and material characteristics, the fatigue life of the rear axle is simulated by using the nominal stress method. Finally, the structure of the rear axle is optimized. The optimized fatigue life of the rear axle shows that its durability has been improved.

2. Establishment of Load Spectra

It is a new method by using VIM to extract load spectra that combines tests with computer simulation. Through the easily observed response signals, the load spectra which are not easy to observe can be obtained by this method. The
reason why the actual test is combined with computer simulation is that in the test process, we often encounter some data that are difficult to collect or parts that are difficult to measure.

The process of VIM is an inverse solution process, a process of calculating input with output. The MBD model is taken as the carrier in this process [23], and on the premise of the system response, the equivalent excitation is solved. Finally, the equivalent excitation is input to the whole vehicle MBD model to obtain the load spectra of key points of the rear axle.

2.1. Establishment of the MBD Model. The MBD model is the carrier of the VIM process, so there is a direct impact for the construction of the MBD model on the effect of VIM [24, 25]. In this paper, the parameters used in model construction are measured by tests.

2.1.1. Cab Centroid and Moment of Inertia Test. In this paper, the centroid position and moment of inertia of the whole (cab and mounting seat) and individual mounting seat are measured by the KC test bench. The test equipment for the overall test of the cab and the mounting seat and for the separate test of the mounting seat are shown in Figures 1 and 2. According to the lever principle, the centroid position and moment of inertia of the cab are obtained.

2.1.2. Assignment of Material Properties of Elastic Elements. The driving rear axle is connected with the frame through leaf spring and the shock absorber. The stiffness curve of the leaf spring and the damping curve of shock absorber were measured on the test bench and shown in Figures 3 and 4.

2.1.3. Construction of MBD Model. Adams software is used to build the MBD model of seven subsystems such as suspensions, leaf springs, tires, transmission shaft, powertrain, steering system, frame, and cab, and then the subsystems are assembled into the whole vehicle model.

The coupling between the different components is summarized as follows:

1. The connection mode between the front/rear wheel and the front/rear suspension is fixed connection;
2. The connection mode between the front/rear suspension and the front/rear leaf spring is fixed connection;
3. The connection mode between the front/rear leaf spring and the frame is bushing connection;
4. The front/rear suspension is connected with the frame in the form of bushing through shock absorber;
5. The connection mode between the power assembly and the frame is bushing connection;
6. The connection mode between the transmission shaft and the power assembly is Hooke hinge;
The connection mode between the transmission shaft and the rear axle is Hooke hinge; 

The connection mode between the transmission shaft and the frame is bushing connection; 

The connection mode between the frame and the cab is bushing connection; 

The steering system is connected with the frame through the steering rack in the way of fixed pair; 

The connection mode between the steering system and the front suspension is bush connection.

The key mass parameters of the vehicle MBD model are summarized in Table 1. 

The MBD model of the whole vehicle is shown in Figure 5.

2.2. The Load Spectra of Rear Axle Obtained by VIM. In this paper, VIM is used to calculate the key point load spectra of the rear axle. The premises of VIM are the vehicle MBD model and the measured road spectra. The equivalent excitation of the whole vehicle can be obtained by using VIM. Then, the load spectra of key points can be gained by applying the equivalent excitation to the MBD model.

2.2.1. Road Spectra Data Acquisition Test. The load spectra of monitoring points collected in the road test can be combined with the vehicle MBD model to obtain the load spectra of key points through VIM. The role of the load spectra collected in the road test is the objective function of virtual iteration [26].

In the road test, there are 31 monitoring points (including acceleration monitoring points, displacement monitoring points, and force monitoring points) and 101 corresponding test channels. The shock absorber displacement sensor and six-component force sensor are shown in Figure 6.

During the road test, the driver controls the test vehicle to drive on the specified road, and the whole process speed is controlled between 20km/h and 30km/h. The road conditions, duration, and cycles of the test road are summarized in Table 2.

After the acquisition, pretreatments such as zero drift, deburring, noise removal, and filtering are carried out based on the measured signals. Z-direction acceleration signals of steering knuckles on both sides of the front axle, Z-direction acceleration signals of the wheel hub on both sides of the rear axle, the displacement signals of four shock absorbers as the objective function of VIM, the Z-direction displacement spectra at the grounding point of four wheels as the result of VIM, the virtual iterative calculation is carried out, and then the equivalent excitation of the whole vehicle is obtained.

The quality judgment method of iterative results is to compare with the measured signal. The comparison diagrams under the twisted road condition are shown in Figure 8. From Figure 8, it can be seen that the peak value and trend of the iterative signals are consistent with the measured signals.

In addition to comparing the peak value and trend of the iterative signal and the road test signal, the coincidence degree of the two signals can usually be judged by the relative damage value in the process of virtual iteration. The relative damage value is a dimensionless value, which refers to the ratio of the damage value caused by two signals to the structure. The closer the relative damage value is to 1, the higher the coincidence degree is. The relative damage value of iteration signal and road test signal after each iteration is shown in Figure 9. It can be observed from the figure that the relative damage value after six iterations tends to be close to 1, indicating that the convergence effect of iterative signal can be accepted.

2.2.2. Vehicle Equivalent Excitation by Femfat Lab. Femfat lab is a data analysis and processing software, which can perform iterative calculations to obtain internal load by using the vehicle MBD model and external measured data.

<table>
<thead>
<tr>
<th>Table 1: Key mass parameters of the vehicle MBD model.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front suspension</td>
</tr>
<tr>
<td>Rear suspension</td>
</tr>
<tr>
<td>Power assembly</td>
</tr>
<tr>
<td>Cab</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

The vehicle MBD model is taken as the carrier of VIM. Taking the Z-direction acceleration signals of the steering knuckle on both sides of the front axle, the Z-direction acceleration signals of the wheel hub on both sides of the rear axle, the displacement signals of four shock absorbers as the objective function of VIM, the Z-direction displacement spectra at the grounding point of four wheels as the result of VIM, the virtual iterative calculation is carried out, and then the equivalent excitation of the whole vehicle is obtained.

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2.2.3. Load Spectra of Key Points of Rear Axle Calculated by MBD. The rear axle is connected to the outside at seven positions. The load spectra at these seven locations need to be used as an input for fatigue analysis. These seven positions are, respectively, at the centers of the left and right spring seats of the rear axle, the connection points between the left and right shock absorbers and the shock absorber mounting seats, the centers of the left and right axle sleeves of the rear
In the MBD software Adams, the Z-direction displacement spectra of wheel grounding points are applied to the vehicle MBD model to obtain the load spectra of seven key points of the rear axle. The units of y-axis for each graphs are N, N, N, N \( \times \) m, N \( \times \) m, and N \( \times \) m, respectively.

3. FEA Model Construction and Stress Analysis of Rear Axle

The establishment of the FEA model of the rear axle is one of the prerequisites for fatigue analysis, which has a direct impact on the accuracy of fatigue simulation. The FEA modeling of the rear axle is carried out by HyperMesh software, and the static strength analysis is performed by NASTRAN software. The FEA model of the rear axle is shown in Figure 12.

The element size is 10mm, and the number of elements is 79962. Among them, hexahedral element is used in the rear axle housing, axle shaft sleeve and rear cover of final drive, and tetrahedral element is adopted in the spring seat. The quadrilateral shell element is used to deal with the cladding, and then the mass point at the center of mass is used to simulate.

The rear axle FEA model is used for static strength analysis. The constraint is inertia release; the load is the unit load in X, Y, and Z directions, and the unit torque in X, Y, and Z directions. What is more, the action points are the above seven key points.

As shown in Figure 13, it is the stress contour of the rear axle when the unit load in the Y-direction acts on the center of the final drive. According to the stress contour, the maximum stress exists at the edge of final drive, and the maximum stress value is 0.008 MPa.

There are 42 working conditions in total. The load application and static analysis results of each working condition are summarized in Table 3.

4. Fatigue Analysis

In this paper, the fatigue analysis software nCode is used to simulate the fatigue life of the rear axle by using the nominal stress method, which is an empirical method to predict the fatigue damage and life of the structure. This method is based on the S-N characteristics of the material and is suitable for high cycle fatigue failure in the elastic range [27].

4.1. Fatigue Analysis Process of the Rear Axle. The fatigue simulation is carried out based on the previously obtained load spectra of key points, FEA results file, and the S-N curve of the material. The flow of the fatigue simulation is shown in Figure 14.

It is necessary to input the S-N curve of the material before fatigue simulation with the nominal stress method. The rear axle material is DL510, with a tensile limit of 510 MPa, a yield limit of 355 MPa, and an elastic modulus of 210000 MPa.

In this paper, the S-N curve is fitted by nCode. The fitted S-N curve is shown in Figure 15.
Figure 7: Measured road spectra. (a) Z-direction acceleration signals of the steering knuckle on both sides of the front axle. (b) Z-direction acceleration signals of wheel hubs on both sides of the rear axle. (c) Z-direction displacement signals of left and right front shock absorbers. (d) Z-direction displacement signals of left and right rear shock absorbers.
Figure 8: Comparison diagrams between the iterative signals and the measured signals (twisted road). (a) Left and right front shock absorbers displacement signals. (b) Left and right rear shock absorbers displacement signals. (c) Steering knuckle acceleration signals on both sides of the front axle. (d) Wheel hub acceleration signals on both sides of the rear axle.
**Figure 9:** Change trend of relative damage value.

**Figure 10:** The positions where the rear axle is connected to the outside.

**Figure 11:** Continued.
### Table 1: Load Spectra

<table>
<thead>
<tr>
<th>Component</th>
<th>FX (N)</th>
<th>FY (N)</th>
<th>FZ (N)</th>
<th>TX (N*m)</th>
<th>TY (N*m)</th>
<th>TZ (N*m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left axle sleeve</td>
<td>252</td>
<td>-174</td>
<td>151</td>
<td>21.1</td>
<td>5.62</td>
<td>7.27</td>
</tr>
<tr>
<td>Right axle sleeve</td>
<td>-200</td>
<td>-140</td>
<td>-2.94E4</td>
<td>-20.8</td>
<td>-6.12</td>
<td>-8.16</td>
</tr>
<tr>
<td>Final drive</td>
<td>310</td>
<td>157</td>
<td>-2.94E4</td>
<td>21.1</td>
<td>5.62</td>
<td>7.27</td>
</tr>
</tbody>
</table>

### Figure 11: Load Spectra of Key Points

(a) Positions at the centers of the left and right spring seats of the rear axle.
(b) Positions at the connection points between the left and right shock absorbers and the shock absorber mounting seats.
(c) Positions at the centers of the left and right axle sleeves of the rear axle.
(d) Position at the center of the final drive.

### Figure 12: FEA Model of Rear Axle

![FEA model of rear axle](image)

### Figure 13: Stress Contour

Stress contour of the rear axle when the unit load in the Y-direction acts on the center of the final drive.

Max = 7.791E-03
Min = 6.470E-18
Node 1538276
Node 616889

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**Note:** The values in the table and figures are illustrative and subject to actual experimental or simulation results.
4.2. Fatigue Simulation Results of the Rear Axle. The FEA analysis results file, load spectra, and material S-N curve are input into nCode software to analyze the fatigue life of the rear axle. The analysis results are shown in Figure 16. The set goal is that the fatigue life of the rear axle is higher than one million kilometers. The total length of the road test section is 12.5 kilometers, which is converted into 80000 cycles. Therefore, 80000 cycles are taken as the fatigue life standard in this paper.
It can be seen from Figure 16 that the node with the weakest fatigue life is 68610 cycles, which does not reach the set goal. The fatigue life of unqualified nodes is summarized in Table 4.

Table 4: The fatigue life of unqualified nodes.

<table>
<thead>
<tr>
<th>No.</th>
<th>Damage</th>
<th>Life (cycles)</th>
<th>Kilometers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.46E−05</td>
<td>6.86E+04</td>
<td>8.58E+05</td>
</tr>
<tr>
<td>2</td>
<td>1.08E−05</td>
<td>9.22E+04</td>
<td>1.15E+06</td>
</tr>
<tr>
<td>3</td>
<td>5.23E−06</td>
<td>1.91E+05</td>
<td>2.39E+06</td>
</tr>
<tr>
<td>4</td>
<td>4.60E−06</td>
<td>2.17E+05</td>
<td>2.72E+06</td>
</tr>
<tr>
<td>5</td>
<td>2.80E−06</td>
<td>3.58E+05</td>
<td>4.47E+06</td>
</tr>
<tr>
<td>6</td>
<td>2.20E−06</td>
<td>4.55E+05</td>
<td>5.69E+06</td>
</tr>
<tr>
<td>7</td>
<td>2.16E−06</td>
<td>4.63E+05</td>
<td>5.78E+06</td>
</tr>
<tr>
<td>8</td>
<td>1.52E−06</td>
<td>6.59E+05</td>
<td>8.23E+06</td>
</tr>
<tr>
<td>9</td>
<td>1.26E−06</td>
<td>7.94E+05</td>
<td>9.92E+06</td>
</tr>
</tbody>
</table>

4.3. Structural Optimization and Simulation Verification. Through the rear axle fatigue simulation result, the fatigue failure concentrated position of rear axle housing is found, which has guiding significance for structural optimization.

Two optimization schemes are proposed here: the first is to use materials with higher strength. The second is to increase the thickness of the axle housing locally according to the simulation results. In this paper, the method of increasing thickness is used for optimization and simulation verification.

Because the simulation life did not meet the set goal, the axle housing was locally thickened by 0.5mm according to the simulation result. The fatigue simulation of the optimized structure is carried out, and the contour and fatigue life table of the thickened rear axle are displayed in Figure 17 and Table 5.

After the optimization, the simulation life of the axle housing is increased from 68610 cycles to 88270 cycles, reaching the set goal and meeting the fatigue requirements.
5. Conclusion

In this paper, the MBD model of the whole vehicle is built, the load spectra of key points are obtained with the help of road test and VIM, the FEA analysis of the rear axle is carried out. Through the above results, the fatigue life of the rear axle is simulated.

The fatigue simulation results show that there are several nodes failing to reach the target of 80000 cycles, in which the life of the weakest node is 68610 cycles. Then, the structure is further optimized based on the fatigue analysis results. After optimization, the life of the weakest node is 88270 cycles, reaching the set goal. The results of this study indicate the idea that the durability of the optimized rear axle structure is verified from the perspective of simulation.

The fatigue simulation of a light truck rear axle is of guiding significance for the optimal design of the rear axle. Compared with the traditional fatigue test method, it greatly shortens the design cycle and reduces investment.

Data Availability

The data used to support the findings of this study are available from the corresponding author (changjian-long1989@126.com) upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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