Summary of fatigue durability analysis of whole vehicle

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Abstract: Technical characteristics and development trend of the fatigue durability analysis of the whole vehicle were reviewed in the directions. These existing research results were systematically summarized from the research status, signal acquisition, finite element analysis, load spectrum extraction and fatigue life. Wherein, the strengths and weaknesses of the virtual iteration technology was explained in detail, in which the result evaluation standard was mainly composed of relative damage value; and also the characteristics of fatigue damage theory and analysis method were summarized detailedly; additionally, the practical critical plane method possessed the advantages of the measurable component damage values, but this method still needed to be solved the problems of crack propagation direction. Moreover, according to the existing technology and achievements, reducing model errors and road conditions selection will become the development trends of vehicle fatigue durability technology in the future.

1. Introduction
Fatigue damage is one of the most important failure modes of automobile products [1]. As shown in Figure 1, there are currently many studies on vehicle fatigue durability, while the fatigue life analysis and prediction research based on CAE technology is relatively fewer, from the perspective of the entire R&D process, CAE technology has significantly reduced the R&D cycle and cost. Compared with the physical prototype test method, the CAE technology analysis method can complete the product design and optimization before the mechanical prototype stage [2].

There have been certain research results of vehicle fatigue analysis technology based on finite element software at home and abroad: the American MTS company has developed the first road simulation test bed for automobiles and proposed remote parameter control technology. Figure 2 (a) shows that this technology can accurately simulate the changes in the force and displacement of the vehicle, and can obtain more accurate excitation signals. Compared with the abroad research on automobile fatigue analysis, related technologies in China start relatively late, and mainly focusing on multi-component load decomposition and indoor multi-axis random shaking table simulation tests, the entire system that uses CAE technology for analysis is not yet mature[3]. However, with the continuous perfection and improvement of the vehicle fatigue durability test technology, the importance and practicability have been significantly improved. Various universities have also begun to conduct related research and have achieved some results, as shown in Figure 2(b).
2. Analysis method and process of vehicle fatigue durability

Fatigue damage is the main reason that affects the normal use of vehicles. In order to ensure the service life of the vehicle, fatigue analysis and life prediction of the entire vehicle structure are required to verify the feasibility. The main key technology of the fatigue durability analysis method of the whole vehicle has been studied at home and abroad. The main process is shown in Figure 3: firstly, collect and preprocess the road spectrum signal of the sample vehicle road test to provide input for the decomposition of the vehicle load; then, based on the established multi-body dynamics model and finite element model of the vehicle, the load spectrum is extracted based on virtual iteration; finally, combined with the fatigue life curve of the material and the finite element inertia release results of each component, the fatigue analysis and life prediction of the vehicle structure are carried out systematically.

Figure 3 The fatigue durability analysis process of the whole vehicle
2.1 Signal acquisition and preprocessing of vehicle road durability test

Due to the road surface, environment and testing equipment will affect the accuracy of the road spectrum signal of the vehicle road test, the error can cause the predicted fatigue life of the vehicle inconsistent with the actual situation. Therefore, it is necessary to preprocess the original signal of the road spectrum, and the signal acquisition process is shown in Figure 4[4-5]. On the basis of determining the road surface type, vehicle speed, and cycle times of the test vehicle, it is determined the measuring point position of the relevant sensor and its corresponding signal type [6-7].

In the road test of the prototype vehicle, the collected road spectrum signal can reveal the fracture, drift, burr and other phenomena [8], which will affect the accuracy of subsequent analysis results. Currently, nCode GlyphWorks and Femfit-Lab software are mainly used for data correction and damage value calculation. On the basis of obtaining the original signal of the road spectrum, three aspects are mainly analyzed as verifying the validity of the data: (1) signal integrity, (2) signal amplitude spectrum and accuracy of frequency spectrum, (3) errors in rain flow comparative analysis. Related research shows that the edited load spectrum is prone to distortion in the frequency domain and cannot be completely closed to the original road spectrum.

2.2 Establishment and verification of vehicle multi-body dynamics model

Multi-body system dynamics includes multi-rigid body system dynamics and multi-flexible body system dynamics. The main research methods include Newton-Euler method, Lagrangian equation method, Graph theory method, Kane method and modal integration method. American Chace uses the Gill's rigid integral algorithm and matrix technology to program the multi-body dynamics theory, and prompting the ADAMS software development. The modeling process of the vehicle dynamics model in the ADAMS/Car module is shown in Figure 5 [9]. The vehicle dynamics model mainly includes suspension frame system, steering subsystem, tire subsystem, braking subsystem and car frame system, etc [10]. In addition, MacPherson suspension is used more in actual engineering design, including BMW, Ford, Hafei and other car companies (all of them adopt this suspension design).

In the further analysis of the vehicle dynamics model, the steady-state constant radius working condition and the transient frequency sweep working condition are mainly used to calibrate the handling stability of the vehicle; the vehicle ride comfort is measured by the vibration acceleration response of vehicle components under different road conditions [11].

2.3 Establishment and analysis of finite element vehicle model

The content of finite element analysis mainly includes modal analysis, stiffness analysis, strength analysis, vibration and noise (NVH), etc. [12-13]. This technology can adapt to various environments...
and has high calculation accuracy; however, there are still some shortcomings, the model needs to be geometrically cleaned, and the gaps are often generated between grid cells during mesh division, so a trade-off between model accuracy and calculation time is required to be taken into account. Due to the fact that the load of some parts in the whole vehicle structure (such as the knuckle connection, suspension push rod) is not directly obtained through experiments, it is incapable of comparing with the simulation data, and it needs to be obtained indirectly through finite element and strain gauge measurement[14-15]. Through the analysis, it can be seen that there is an error between the finite element simulation results and the actual situation, and it can also reduce the rate of deviation between the simulation value and the test value, which is one of the key issues of the finite element fatigue durability analysis.

Modal analysis technology is widely used in the fields of automotive new product development, old product improvement design and fault diagnosis [16]. Modal testing is principally divided into three methods: pulse excitation, step excitation and sine sweep. Also, the interpolation method and inertia release method are mainly used to obtain the specific values of stiffness, strength and stress cloud diagram, and the corresponding deformation curve is analyzed. [17-19]; generally, it can be classified into free vibration mode and forced vibration mode. Compared with the forced vibration mode, free vibration mode has the advantages of fast test speed, simple test equipment, low signal-to-noise ratio, and less vibration energy leakage [20-22].

2.4 Load spectrum extraction based on virtual iteration

After completing the vehicle structure modal analysis as well as the stiffness and strength analysis, the load spectrum needs to be extracted to provide load input for the vehicle fatigue life analysis. At present, the methods of obtaining component load spectrum, based on multi-body dynamics mainly, include semi-analytical method on account of six-component force, full-analysis method based on virtual pavement technology, and virtual iterative technology [23]. Among them, the virtual iterative technology is often used in occasions where the absolute displacement of components cannot be measured and vertical loads, wherein, the principle of virtual iteration is shown in Figure 6 [24]. On the strength of the virtual iteration to extract the load spectrum, the relative damage value of the iterative response signal and the original signal can be calculated at the same time, and the time domain comparison between the both can be performed. Helmut Dannbauer proposed in the research that the relative damage value in the virtual iteration process is stable within the range of 0.2~2, which is acceptable [25].

The virtual iterative method of extracting the load spectrum does not require the use of sensors to measure the solid prototype vehicle, and only needs to create the correct multi-body dynamics model to obtain an accurate vehicle structural stress and load spectrum. In addition, the instability of the whole vehicle can be effectively avoided during simulation, and no additional constraints can introduce the whole vehicle system [26]. However, the vehicle has many response signals, and insufficient iterative convergence may still occur in the actual analysis process. The convergence of the iteration results can be optimized by reasonably setting the number of channels of the response signal and the noise drive.

![Figure 6 Schematic diagram of virtual iteration](image)
2.5 Fatigue analysis and life prediction of vehicle structure

2.5.1 Overview of fatigue analysis
According to the classification of the complex state of the load, fatigue can be divided into uniaxial fatigue and multiaxial fatigue. At present, fatigue analysis technology is limited to single or simple assembly parts. For some complex vehicle structures, fatigue analysis and life prediction technologies are rarely used in vehicle fatigue durability analysis [27-28]. As shown in Figure 7, the fatigue durability analysis of the whole vehicle is a process of the continuous optimization based on the material characteristic curves, finite element models and random loads [29-30]. Due to the uncertainty of the load on the entire vehicle, it is necessary to use probability statistics for correlation analysis. Analysis methods are mainly divided into power spectral density method and cycle counting method, in which the rain flow counting method in the cycle counting method is widely used in fatigue analysis [31-32]. This method has the least impact on the original load waveform, and cuts the highest peak or lowest trough into two sections during processing to form a convergent-divergent wave, so that the rain flow counting method can be used repeatedly in the fatigue durability analysis process until the analysis is completed. In addition, the accuracy of the calculation results is relatively high because the rain flow counting method considers the mechanical factors of the components in the counting principle.

Figure 7 Fatigue analysis process

2.5.2 Multiaxial fatigue life analysis
In the vehicle fatigue durability analysis test, the fatigue analysis methods mainly include the nominal stress method, strain fatigue analysis method, local stress-strain method, stress field strength method, etc., as shown in Table 1, the nominal stress method and strain fatigue analysis method are widely used in actual analysis [33-36]. In the traditional automobile fatigue analysis test, the stress and strain in the multiaxial stress state are usually equivalent using various strength yield criteria [37]. The drawbacks of this method: under the condition of non-proportional loading, cyclic strengthening and cross-hardening are prone to occur, resulting in a reduction in the fatigue life of parts. At the same time, the energy method and the critical plane method are chiefly used in the multi-axis fatigue life prediction analysis, which can largely overcome the shortcomings of the traditional methods that cannot analyze the critical plane tensile component damage value [38]. However, this kind of method still possesses its shortcomings with the crack formation state, and the direction of crack cannot be considered in the process of multi-axis fatigue analysis of the whole vehicle.

Table 1 Comparison of nominal stress method and strain fatigue analysis method

| Factors          | Nominal stress method | Strain fatigue analysis |
|------------------|-----------------------|-------------------------|
| Material curve   | S-N curve             | E-N curve               |
| Fatigue analysis | High cycle fatigue    | Low cycle fatigue       |
| Advantages       | To predict the total life of the structure. | To give full play to the potential of materials. |
2.5.3 Fatigue cumulative damage criterion
The key point of predicting fatigue life is to solve the problem of accumulated fatigue damage. When the vehicle parts are loaded with a single cyclic stress, the fatigue life of the parts can be directly predicted based on the S-N curve. As the multiple cyclic stresses are loaded at the same time, the life of the vehicle parts needs to be predicted based on the relevant cumulative damage theory; at present, there are mainly linear, bilinear, and nonlinear fatigue accumulation theories [39]. Additionally, with the predicting of the life for the vehicle components based on the theory of cumulative fatigue damage, the combination of rain flow counting method and material characteristic S-N curve can improve the accuracy of vehicle fatigue life prediction. As shown in Table 2, Miner's law is most used in the fatigue durability analysis of the whole vehicle [40].

| Theoretical                           | The research methods                          | Laws                        | Advantages and disadvantages          |
|---------------------------------------|-----------------------------------------------|-----------------------------|---------------------------------------|
| Linear fatigue cumulative damage theory| The damage caused by different stresses is independent. | Miner rule | The criterion is intuitive, simple and practical. |
| Bilinear fatigue cumulative damage theory | Fatigue is divided into early stages and late stages. | Mason's bilinear cumulative damage superposition law | The time boundary between prophase and anaphase is difficult to demarcate. |
| Nonlinear cumulative loss product theory | There is an interaction between the loading process and the damage. | Damage curve method and Corten-Dolan theory | The stress constant is difficult to assign. |

2.5.4 Analysis and optimization of fatigue life of solder joints
With the development of lightweight vehicles, the use of thin plates in the design and production has gradually increased, increasing the use of welding processes, thereby reducing the reliability of the entire vehicle structure, and improving the fatigue analysis standards of solder joints with the reduction of the solder joint fatigue damage [41]. Spot welding is the most commonly used welding method in the automobile production process. When the welded joint is carried out in a high-temperature environment, its structure and performance are not uniform, and all the stress concentration, cracks, slag inclusion, pores and poor size are also easy to appear, the fatigue life of solder joints needs to be further optimized [42]. At present, topological optimization, topography optimization, size optimization, and shape optimization are mainly used at domestic and overseas to obtain the optimal distribution scheme of solder joints under certain boundary conditions. Furthermore, for the optimization research of the solder joint fatigue life in future, seeking a relatively small solder joint volume will become one of the optimization directions.

3. Summary
This work mainly summarizes and illustrates the vehicle road endurance test signal acquisition and preprocessing. Wherein the vehicle multi-body dynamics model is established and verified; and the establishment of finite element model for vehicle analysis, load spectrum extraction based on virtual
iteration and the vehicle structure fatigue analysis and life prediction of vehicle fatigue durability analysis methods were systematically summarized, and the research results were separately stated. Among them, this work mainly discusses the development overview, application methods, advantages and disadvantages and development direction of vehicle fatigue durability analysis, and also this paper puts forward the prospect of vehicle fatigue analysis: (1) to reduce the error between model data and prototype data during CAE modeling; (2) to accurate and timely verification of finite element simulation results based on prototype vehicle data in actual fatigue analysis; (3) to adequately meet the actual requirements of users and experiencing road conditions.

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