Fatigue Analysis and Life Assessment of General Automobile Suspension Systems

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Abstract. The automotive suspension system is crucial for vehicle comfort, handling, and safety across diverse road conditions. Its design and performance directly influence the driving experience and vehicle durability. With the automotive industry's continuous evolution, assessing the fatigue life of suspension systems has become increasingly important, especially considering the variable loads and stresses encountered during daily operation. Furthermore, machining precision in the manufacturing of suspension components significantly affects their fatigue resistance and overall durability. Recent advancements, including high-strength materials and adaptive suspension control, have shown potential in extending component life and reducing fatigue-induced failures. Additionally, machine learning-based fatigue life prediction and AI-driven predictive maintenance approaches are emerging as effective tools for optimizing suspension performance and reliability. This paper delves into the fatigue characteristics of automotive suspension systems, exploring current fatigue analysis and life assessment methods, including finite element analysis (FEA), multi-body dynamics (MBD), and experimental testing. By evaluating existing technologies, this study proposes design optimization strategies, including advanced machining techniques, intelligent suspension control, and AI-enhanced maintenance solutions, to enhance the service life and safety of suspension systems.

Keywords: Lithium-Ion Batteries, State of Charge, Battery Management Systems, Kalman Filter, Neural Networks

1 Introduction

The automotive suspension system consists of springs, shock absorbers, control arms, ball joints, and stabilizer bars. These components work together to absorb road irregularities, ensuring vehicle stability and ride comfort. A well-designed suspension system not only enhances comfort but also plays a critical role in vehicle handling and safety. During operation, suspension components are subjected to complex and dynamic loads, which can lead to fatigue failure over time.

Fatigue refers to the progressive structural damage caused by cyclic loading. Given that suspension systems experience repeated stress during vehicle operation, assessing their fatigue behavior is essential to maintain long-term reliability. In addition to

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material properties and design, the precision of machining processes used to manufacture suspension components significantly influences their fatigue resistance. Poor machining precision can introduce residual stresses, surface roughness, and microcracks, all of which accelerate fatigue failure [1].

This paper aims to analyze the fatigue characteristics of automotive suspension systems while considering the effects of machining precision. It will explore fatigue analysis methods, including FEA, MBD simulations, and experimental fatigue testing, to evaluate component life and propose design optimizations for improved durability and safety.

2 Methodology

Fatigue analysis is essential for the design and maintenance of automobile suspension systems. By using different analysis methods, the fatigue damage that may occur to the suspension system during long-term use can be effectively evaluated [2]. These analysis methods can not only help engineers optimize the design but also predict the remaining service life of the suspension system and reduce the risk of failure [3]. The following will introduce several common fatigue analysis methods in detail, including finite element analysis (FEA), multi-body dynamics (MBD) analysis, and experimental methods.

2.1 Finite Element Analysis (FEA)

Finite element analysis (FEA) is one of the most commonly used structural analysis methods. It divides the complex suspension system model into multiple small units to solve the stress, strain, and displacement of the structure [4]. In the fatigue analysis of the suspension system, FEA not only helps predict the component response under static loads but also simulates the fatigue behavior under dynamic conditions.

2.1.1 Application of FEA.

The application of FEA in suspension systems involves many aspects, the most typical of which is fatigue analysis of components such as control arms, shock absorber brackets and springs. For example, suspension control arms often need to withstand repeated vibration loads from wheels, especially on bumpy roads and in sharp turns. FEA can identify potential fatigue weaknesses, such as stress concentration areas, by accurately calculating the stress distribution of these components under cyclic loads.

2.1.2 Material Models in FEA.

During the FEA process, material selection and model settings have an important impact on fatigue prediction. Usually, engineers define fatigue characteristic curves for different materials, such as the S-N curve of steel, or the fatigue limit of aluminum alloys. To improve the accuracy of the analysis, FEA can be combined with fatigue damage models to consider the nonlinear behavior of materials, including plastic deformation and multi-axial stress states.

2.1.3 FEA and Multi-Condition Analysis.

FEA can also be combined with multi-condition analysis to simulate the working conditions of vehicles under different conditions. For example, dynamic simulation tools are used to simulate load conditions under different road surfaces and driving behaviors, and stress concentration conditions under various working conditions are combined with fatigue damage models to evaluate the fatigue life of each component. This makes the fatigue assessment of the suspension system more comprehensive and accurate.

2.1.4 Dynamic response analysis.

FEA can perform dynamic response analysis to simulate the behavior of the vehicle suspension system under various dynamic loads. For example, time domain analysis or frequency domain analysis methods are used to simulate the response of shock absorbers and springs. Through this type of analysis, engineers can predict the fatigue response of the suspension system under different driving conditions and make appropriate adjustments in the design stage.

2.2 Multi body dynamics (MBD) analysis

Multi body dynamics (MBD) analysis is a computational method that simulates the interaction between various components of a mechanical system [5]. Unlike FEA, MBD focuses on simulating the dynamic process of motion, mechanical interaction, and interaction between various objects in the system. In the automotive suspension system, MBD analysis can provide richer kinematic data for fatigue assessment and help engineers understand the dynamic behavior of the suspension system in actual driving.

2.2.1 Application of MBD in suspension system.

MBD can accurately simulate the relative motion of various components in the suspension system (such as control arms, shock absorbers, springs, etc.). By analyzing these motions, MBD can reveal the load changes of the suspension system during driving, such as how the loads of various components of the suspension system change when the vehicle passes through uneven roads, and how these changes affect fatigue accumulation. For example, when a vehicle passes through a pothole, the control arms and springs of the suspension system will be subjected to instantaneous huge impact loads, which will cause local fatigue damage.

2.2.2 Coupling analysis of the body and suspension system.

MBD analysis can not only study the fatigue of the suspension system itself but also consider the coupling effect between the body and the suspension system. In dynamic analysis, the weight, stiffness and interaction between the body and the suspension system will affect the fatigue life of the suspension system. For example, the vibration of the body when turning or braking will generate additional fatigue loads on the suspension system, and MBD analysis can reveal the impact of these interactions on fatigue life.

2.2.3 Joint application of MBD and FEA.

MBD analysis can be used in conjunction with finite element analysis to provide a more comprehensive fatigue analysis. In this joint application, MBD can simulate the dynamic response of the suspension system under different working conditions, while FEA performs stress analysis on these responses and ultimately obtains fatigue damage prediction results. This method combines the dynamic modeling capabilities of MBD with the precise stress analysis capabilities of FEA to provide more accurate fatigue life predictions.

2.3 Experimental methods

Although computational simulation methods (such as FEA and MBD) are widely used in fatigue analysis, experimental methods are still an important means to verify fatigue analysis results and ensure design reliability. By conducting fatigue tests in actual environments, more intuitive and accurate data can be obtained.

2.3.1 Fatigue testing machine testing.

Using a fatigue testing machine to perform actual cyclic load tests on suspension system components is a common method for verifying fatigue theories and models. By simulating the loads that the suspension system is subjected to under different driving conditions, the fatigue testing machine can provide a direct assessment of the fatigue life of suspension system components. Common test methods include full-cycle loading, variable amplitude loading, and load simulation at different frequencies.

2.3.2 Continuous loading and failure analysis.

Long-term continuous loading tests in the laboratory can simulate the fatigue process of suspension system components in long-term use. By regularly inspecting the test components, the generation and expansion of fatigue cracks can be monitored, helping researchers evaluate the fatigue life of different components. For example, fatigue tests on shock absorbers can reveal the fatigue state of their internal structures under continuous operation, thus providing a basis for design improvements.

2.3.3 Field testing and data collection.

In addition to laboratory tests, field tests can also provide important fatigue data. By monitoring the suspension system for a long time under actual road conditions, real data on the performance and fatigue behavior of the suspension system can be collected. For example, installing sensors such as strain gauges and accelerometers can obtain the stress state and vibration of the suspension system in real time, thereby providing support for fatigue life assessment. This method can help engineers better understand the actual performance of the suspension system under different driving environments.

2.3.4 Combining experimental data with fatigue models.

Combining experimental data with theoretical fatigue models can provide more accurate predictions for fatigue life assessment. For example, the stress level and damage accumulation data measured by the test can be matched with the stress distribution in the FEA model, and finally a more reliable fatigue life prediction result can be obtained [6].

These methods complement and work together to make the fatigue analysis of the automobile suspension system more comprehensive and accurate. In modern engineering, FEA and MBD have become mainstream tools, which help engineers foresee potential fatigue problems and optimize designs. The experimental method provides real-world verification for the simulation results, ensuring the reliability and safety of the design.

2.4 Experimental Setup

A fatigue testing machine was used to simulate cyclic loading on a suspension control arm. The test aimed to evaluate the fatigue life of the component under realistic stress conditions and analyze the impact of machine tool processing precision on crack initiation and failure progression.

Test Equipment: Hydraulic fatigue testing machine with load cell and displacement sensor Material Tested: High-strength steel control arm (CNC machined vs. conventional machined) Test Load: Sinusoidal cyclic load, peak force: 8 kN, frequency: 10 Hz Environmental Conditions: Room temperature (25 ° C), dry condition. Measurement Tools: High-speed camera for crack propagation analysis, strain gauges for stress monitoring.

Test Procedure: 1. Preparation of Test Samples: Two control arm samples were prepared—one CNC-machined with high precision surface finish, and the other conventionally machined.

2. Mounting on Fatigue Testing Machine: The samples were secured, and strain gauges were attached to critical areas.

3. Cyclic Loading Application: A sinusoidal cyclic force (8 kN, 10 Hz) was applied to simulate road-induced fatigue stress.

4. Crack Initiation and Growth Monitoring:

CNC-machined sample: No significant cracks observed up to 500,000 cycles. Conventionally machined sample: Initial micro-cracks observed at 200,000 cycles, leading to failure at 350,000 cycles.

5. Data Collection: Real-time stress-strain data and crack propagation images were recorded.

3 Results

To evaluate the influence of machining precision on the fatigue performance of automotive suspension components, a comparative fatigue test was conducted on two suspension control arms: one manufactured using high-precision CNC machining and the other through conventional machining techniques. The following table summarizes the key experimental parameters and outcomes:

Table 1. Fatigue Test Results for CNC-Machined and Conventionally Machined Suspension Control Arms

Test Item	CNC-Machined Sample	Conventionally Machined Sample
Test Equipment	Hydraulic fatigue testing machine	Hydraulic fatigue testing machine
Material	High-strength steel	High-strength steel
Machining Method	CNC machining	Conventional machining
Test Load	Sinusoidal cyclic load, peak force: 8 kN	Sinusoidal cyclic load, peak force: 8 kN
Test Frequency	10 Hz	10 Hz
Environmental Conditions	Room temperature (25°C), dry condition	Room temperature (25°C), dry condition
Crack Initiation Cycle	No significant cracks observed up to 500,000 cycles	Initial micro-cracks observed at 200,000 cycles
Failure Cycle	No failure observed	Failure occurred at 350,000 cycles
Stress Monitoring Tool	Strain gauges	Strain gauges
Crack Monitoring Tool	High-speed camera	High-speed camera
Fatigue Life Improvement	40% longer fatigue life compared to conventional machining	–

This table clearly demonstrates the superior performance of CNC-machined components in terms of fatigue life under identical testing conditions. The CNC-machined control arm exhibited no visible cracks even after 500,000 cycles, whereas the conventionally machined sample developed initial micro-cracks at 200,000 cycles and failed structurally at 350,000 cycles.

The improved fatigue performance of the CNC-machined sample can be attributed to several key factors. First and foremost is the enhancement in surface quality. CNC machining results in a smoother surface finish with minimal tool marks, reducing the potential sites for crack initiation caused by surface roughness. Additionally, CNC machining offers higher dimensional accuracy, which eliminates geometric inconsistencies that could lead to localized stress concentrations.

Strain gauges installed at critical stress regions captured real-time data during cyclic loading. The data indicated that the conventionally machined sample experienced significantly higher local stress amplitudes under the same external load. These high-stress zones corresponded to areas where cracks were later observed via high-speed camera footage, confirming a direct correlation between machining-induced imperfections and fatigue failure mechanisms.

In contrast, the CNC-machined sample displayed a more evenly distributed stress profile, effectively reducing peak loads and mitigating the accumulation of fatigue damage. This result aligns with prior studies which suggest that eliminating geometric irregularities and controlling residual stress distributions significantly improves fatigue life [7].

Moreover, the results suggest that not only does CNC machining delay the initiation of cracks, but it also appears to decelerate the propagation phase. The traditionally machined part transitioned from micro-crack formation to complete failure in approximately 150,000 cycles. The CNC sample, by contrast, maintained its structural integrity for the full test duration, offering a potential for even longer life beyond 500,000 cycles if extended testing were conducted.

This 40% improvement in fatigue life has far-reaching implications for automotive engineering. For vehicle manufacturers, increasing the fatigue resistance of suspension components means longer service intervals, reduced risk of component failure, and improved customer safety and satisfaction. From a cost-efficiency standpoint, the use of CNC machining—though initially more expensive than conventional methods—can result in lower lifecycle costs by minimizing warranty claims and maintenance needs.

Additionally, the study's findings provide valuable input for predictive maintenance systems and digital twin models. By integrating fatigue data from high-precision components into simulation environments, engineers can build more accurate digital representations of system behavior over time. These models can be used to predict failure windows and schedule maintenance proactively, ultimately extending vehicle longevity and reliability.

The results also reinforce the necessity of combining simulation techniques (like FEA and MBD) with real-world experimental data. While simulations can predict stress hotspots and expected life cycles under variable conditions, physical testing provides empirical validation and reveals practical deviations due to material inconsistencies or manufacturing variances.

In conclusion, the experimental findings validate the hypothesis that machining precision significantly influences fatigue life in suspension components. CNC-machined samples exhibited delayed crack initiation, extended operational cycles, and more favorable stress distributions. These observations advocate for broader adoption of high-precision manufacturing techniques in the automotive sector, especially for safety-critical parts exposed to cyclic mechanical loads.

4 Conclusion

The fatigue analysis of automobile suspension systems is critical for ensuring vehicle durability and safety. The experimental fatigue test demonstrated that CNC-machined suspension components have a significantly longer fatigue life due to improved machining precision and surface quality. Finite element analysis (FEA), multi-body dynamics (MBD), and experimental fatigue testing provide a comprehensive framework for fatigue assessment. By integrating advanced fatigue analysis methods with high-precision machining, the automotive industry can enhance suspension system reliability and longevity [8].

4.1 Discussion

The integration of advanced simulation tools with experimental testing offers a powerful framework for fatigue life assessment. While simulations using FEA and MBD enable accurate modeling of stress distributions and dynamic interactions, experimental validation ensures that these models reflect real-world behavior. The significant difference observed between CNC-machined and traditionally machined components under fatigue testing highlights the importance of precision engineering. These findings advocate for broader industry adoption of high-accuracy machining techniques and further development of predictive maintenance systems using AI and real-time sensing [9].

5 Discussion and Optimization Strategies

5.1 Material and Structural Optimization

Using high-strength materials and optimized component geometry enhances fatigue resistance.

Composite materials and surface treatments can improve durability.

5.2 Machining Precision Enhancement

Advanced machining techniques (e.g., laser cutting, precision milling) minimize surface defects and residual stresses.

Post-machining treatments (e.g., shot peening) further improve fatigue resistance.

5.3 Adaptive Suspension Systems

Intelligent suspension systems adjust damping characteristics based on road conditions, reducing fatigue-inducing stress variations [10].

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