OPTIMIZATION SIMULATION OF LOCOMOTIVE SEMI-ACTIVE SUSPENSION CONTROL BASED ON FUZZY CONTROL AND DETECTION OF ELECTROMECHANICAL EQUIPMENT

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Abstract - The key technology for accelerating locomotives and enhancing their stability is vibration control for vehicles. This paper analyzes the characteristics of passive suspension, active suspension, and semi-active suspension, and comes to the conclusion that semi-active suspension should be the preferred control mode for high-speed train suspension system in China due to its advantages of low energy consumption, simple control, and good failure-oriented safety. The goal of this paper is to improve the ride comfort and running stability of rolling stock, as well as the performance of suspension system. Meanwhile, this paper applies fuzzy control theory to semi-active suspension control based on the characteristics of rolling stock suspension systems, designs a fuzzy control system in accordance with the fuzzy control principle, creates a semi-active suspension model to implement this control system, and implements the control simulation of semi-active suspension system in MATLAB environment. This paper also analyzes the condition monitoring data gathered by mechanical and electrical equipment while it is operating, with the goal of researching the detection of locomotive equipment health conditions. It then extracts characteristic parameters based on the condition monitoring data gathered by sensors at a specific time. The condition monitoring data and the health state of electromechanical equipment are mapped using the adaptive neuro-fuzzy inference system to monitor the health status of electromechanical equipment. According to the simulation results, the semi-active suspension fuzzy control may moderate the suspension’s dynamic deformation fluctuation, lessen the wheels’ dynamic load, and lower the acceleration of the car’s body. The goal of this paper is to improve the performance of the semi-active suspension system by optimizing the membership function and fuzzy control rules of fuzzy controller.

Keywords: Fuzzy control; Semi-active suspension; Control system; Locomotive equipment detection; Simulation experiment.

1. Introduction

Road and air travel have displaced railroads' long-held monopoly on transportation due to the quick growth of the automotive and aircraft industries. In certain nations, aviation threatens long-distance passenger travel, highways have displaced short-distance travel, and big container trucks have taken the place of cargo vehicles for long distance travel. In terms of passenger transportation, especially, the accelerated pace of social life has further heightened people's perceptions of the worth of their time, making it important to reduce journey times. To improve the competitiveness of railway transportation, the operating speed of trains must be increased because the speed of conventional railway trains cannot keep up with market demand [1].

The development, analysis, and resolution of a train dynamics model is always a challenging problem since trains are intricate mechanical systems, and external loads are equally intricate and variable. It is obvious that track irregularity will impact the running performance of rolling stock, and as train running speeds increase, this preexisting influence will become more pronounced. Ride comfort is significantly impacted by the vibration of rolling stock brought on by track irregularity, thus it is crucial to increase vehicle stability, reduce vibration transmission between bogies and car bodies, and improve bogy running stability [2]. The running stability of rolling stock can be improved with a semi-active suspension system. As a result, one of the primary research areas in the design of rolling stock in this paper is suspension system design.
The amount of data generated by state monitoring of mechanical and electrical equipment has increased over time, outpacing the capabilities of conventional data processing and data storage due to the continuous improvement of requirements for health monitoring of mechanical and electrical equipment in the field of industrial manufacturing [3]. Therefore, it is extremely important theoretically and practically to do research on mechanical and electrical equipment health monitoring methods at this time.

Based on the aforementioned issues, this paper first examines the traits of passive suspension, active suspension, and semi-active suspension. It then elaborates on the semi-active suspension control strategy used by Chinese locomotives and rolling stock as well as the suspension system’s ceiling control principle. The second part of this paper applies fuzzy control theory to semi-active suspension control, designs a fuzzy control system in accordance with the fuzzy control principle, creates a model of a semi-active suspension to realize the control system, and performs control simulation of the semi-active suspension system in a MATLAB environment. The adaptive neuro-fuzzy inference system used in this paper creates a mapping link between condition monitoring data and the health state of electromechanical equipment, which is then used to monitor that equipment’s health.

2. Literature Review

In China, research on semi-active suspension control of railway rolling stock got off to a late start since research institutions focused more on control theory. As a result, certain theoretical research findings were made: Aiming to address the drawback that the ceiling damping control cannot effectively reduce the vibration acceleration of the car body, Wang et al. developed a self-tuning semi-active suspension system based on acceleration feedback. The controller has a parameter estimation link that uses the body mass to compute the ideal target value and the best acceleration feedback coefficient based on changes in the body mass [4]. The semi-active suspension system can increase the vehicle’s ride comfort index by 10%–18%, according to the test results of Sharma and Lee on the locomotive vibration test bench [5]. In order to create an electronic control system, Bhardawaj et al. examined the semi-active suspension system of rolling stock with ceiling damping control. The entire system includes of sampling and filtering, arithmetic processing, power amplification, an adjustable throttle damper, and other components. The system’s processor is a single chip microcomputer. The test results demonstrate the system’s strong reliability and improvement of the rolling stock stability index [6].

Researchers are currently studying the health monitoring and life prediction of mechanical and electrical equipment in China and other nations. Fuzzy neural networks can be used to forecast power loads as well as to keep track of the condition of electromechanical equipment, as noted by Zhou et al. [7]. Large mechanical and electrical equipment was chosen by Cheng et al. as the research subject. Using fuzzy theory and neural networks, they examined the fault model, identified the equipment problems, and kept track of the equipment’s health state [8]. In order to monitor the status of electromechanical equipment and its state of health, Hedayati et al. developed a new data fusion approach employing numerous sensor data and an adaptive neuro-fuzzy inference system [9].

In conclusion, several academics have studied electromechanical equipment detection and locomotive semi-active suspension control, but there are still some issues that need to be resolved. This paper proposes an optimization strategy for semi-active suspension control of locomotives and electromechanical equipment detection based on fuzzy control, applies fuzzy control theory to semi-active suspension control, designs a fuzzy control system in accordance with fuzzy control principle, and constructs a semi-active suspension model to realize the control system. In order to implement the health status monitoring of electromechanical equipment, the mapping relationship between the condition monitoring data and the health state of the equipment is established using the adaptive neurofuzzy inference system.

3. Methods and Materials

3.1 Locomotive Suspension System

The traditional suspension system of railway rolling stock consists of elastic elements and damping elements, which do not consume external energy when working, so it is called passive suspension. This kind of suspension system is simple, reliable and easy to realize, but its adaptability is poor, so it cannot meet the higher requirements of dynamic performance when trains are running at high speed. The device with force generator actuator in suspension system is called active suspension. Excessive energy consumption is the inherent defect of active suspension. At present, active suspension is mainly used for high-speed trains. In the suspension system, the device with adjustable damping, which needs to input a small amount of energy, is called semi-active suspension. Semi-active suspension has a simple structure, low cost, and its performance is close to that of active suspension, and it does not need special high-power energy devices. This is a prominent advantage for all kinds of vehicles, so it is valued and has a good development prospect [10]. The suspension system models of these three types of locomotives and rolling stock are shown in Figure 1 below:
For the semi-active suspension control system, a controllable force $F_c$ is added on the basis of passive suspension, and its dynamic equation is expressed as:

$$m_1\ddot{z}_1 = k_1(z_s - z_t) + k_2(z_s - z_t) + F_c$$  \hspace{1cm} (3)$$

The active suspension system can provide damping force proportional to the absolute motion speed of the object to be damped, so the adjustment principle of the damper in the semi-active suspension system is to make the damping force provided by the semi-active suspension system close to that provided by the active suspension system [11]. The damping force provided by the active suspension system (ideal damping force) is expressed as:

$$F_i = -C_1 V_s$$  \hspace{1cm} (5)$$

In the above equation, $C_1$ represents damping coefficient. $V_s$ represents the absolute speed of the damping object.

The actual damping force provided by the semi-active suspension system is:

$$F_a = -C(V_s - V_u)$$  \hspace{1cm} (6)$$

In the above equation, $C$ represents damping coefficient. $V_u$ represents the absolute speed of basic motion.

The adjustment principle is: if $F_i$ and $F_a$ have the same sign, adjust the damping coefficient of semi-active suspension system to make $F_a \approx F_i$. Otherwise, make $F_a = 0$, which is expressed as:

$$F_a \approx F_i, \quad V_s \times (V_s - V_u) \geq 0$$  \hspace{1cm} (7)$$

$$F_a = 0, \quad V_s \times (V_s - V_u) < 0$$  \hspace{1cm} (8)$$

Through the regulation law of the above equation, the control effect of semi-active suspension system can be close to that of active suspension. Although the semi-active suspension was put forward later than the active suspension, it has simpler structure, lower cost and performance close to that of the active suspension. In addition, because it does not need special energy devices, it is a prominent advantage for all kinds of vehicles, so it is valued and has a good development prospect. However, it is still necessary to further study the damping control law and improve the performance. However, the characteristics of semi-active suspension system and the present situation of...
China's railway development determine that adopting semi-active suspension system based on fuzzy control strategy is the best form of suspension system development for high-speed trains in China at present [12].

Both the active suspension system and the semi-active suspension system can use the ceiling control to calculate the control force.

Both of them achieve the vibration reduction requirements by generating the control force required to reduce the absolute speed of the car body, so the vibration reduction effect is similar. Ceiling damping control is the most commonly used method for semi-active vibration control of suspension system. This method is simple, effective and easy to implement [13]. Its principle is shown in Figure 2 below:

![Figure 2: Principle of ceiling damping suspension](image)

The dynamic equation of its suspension model is expressed as:

\[
m_{c}y_{c} = -k_{z}(y_{c} - y_{t}) - C_{rs}y_{t} \quad (9)
\]

\[
m_{t}y_{t} = k_{z}(y_{c} - y_{t}) - C_{rs}y_{t} + k_{t}(x_{t} - y_{t}) \quad (10)
\]

In the equation, \( y_{t} \) represents the displacement of the wheel axle. \( y_{c} \) represents the displacement of the car body. \( C_{rs} \) and \( C_{rt} \) both represent the damping coefficient of the shock absorber.

3.2 Fuzzy Control Optimization Simulation of Locomotive Semi-Active Suspension

Fuzzy control system is an automatic control system, which is based on fuzzy mathematics, the form of fuzzy language and the rule reasoning of fuzzy logic, and is a digital control system composed of computer control technology. Its core is an intelligent fuzzy controller [14]. The composition structure of the fuzzy controller is shown in Figure 3 below:

![Figure 3: Composition of fuzzy controller (a. Components of fuzzy controller; b. Structure diagram of fuzzy controller)](image)
Fuzzy controller is a kind of language controller which simulates the control characteristics of human beings, and it reflects the way of thinking of human beings to some extent. However, there are no ready-made control rules in the objective world. It needs to be extracted from a large number of observation and experimental data according to the structure of fuzzy controller, and a series of language control rules described by fuzzy conditional statements are formed through the process of removing the false and preserving the true, and removing the coarse and preserving the fine [15].

The analytic expression of fuzzy controller with adjustable factors can be summarized as follows:

$$U = -[\beta E + (1-\beta)E_c], \quad \beta \in (0,1) \quad (11)$$

In the above equation, $E$ represents a fuzzy input variable. $E_c$ represents the rate of change of fuzzy variables; $U$ represents fuzzy output control quantity. $\beta$ is an adjustable factor, and its value range is $(0,1)$.

A typical semi-active control system is generally a closed-loop control system composed of an actuator, vehicle system, measuring sensor and controller. The sensor measures the absolute speed of the car body or the relative speed of the car body to the bogie, and the acceleration of the car body, and inputs the signals into the microprocessor as the input variables of fuzzy control. After fuzzy processing, fuzzy reasoning and decision-making, and non-fuzzy processing, it sends out instructions to control the damper with adjustable damping in real time and adjust the damping force. The adjustment of damping must be carried out according to the control rules, and once the fuzzy rules are determined, it is difficult to change them. Therefore, the adaptive change of fuzzy control rules is the key to semi-active control [16]. The fuzzy control structure of semi-active suspension of locomotive is shown in Figure 4 below:

![Figure 4: Fuzzy control structure of locomotive semi-active suspension](image)

In this paper, the fuzzy control technology is mainly used in locomotive semi-active suspension control strategy, and the establishment of locomotive virtual prototype simulation platform is mainly carried out by Automatic Dynamic Analysis of Mechanical System (ADAMS) and MATLAB software. ADAMS software is very suitable for simulating large complex multi-body systems, and it is widely used in the design and research of complex systems such as automobiles. One of the basic and key problems in analyzing and researching the system by using simulation technology is to model the system, and system modeling is the core of system simulation. For the purpose of modeling, establishing a correct, reliable and effective simulation model is the key and premise to ensure the high reliability of simulation results. The model of the mechanical system in MATLAB is read, and then the block diagram of the control module is generated, as shown in Figure 5 below:
The model has four input ports and seven output ports, and is a module formed by the mechanical dynamics algorithm, which is represented by the state space equation:

\[
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx + Du
\end{align*}
\]

(12)

In the above equation, \(x\) represents the vector of state variables, \(u\) represents the input signal vector and \(y\) represents the output signal vector.

Before the simulation, make sure that all MATLAB files called in the simulation are in the same folder. In this way, you can directly open the set MATLAB/Simulink, then open the previously generated .m file on the main page of MATLAB, and read in the input and output module of simulation in MATLAB. At this point, the preparatory work for the simulation has been completed. Running Simulink file and calling the whole vehicle model in ADAMS/view through ADAMS/Control module, the simulation is realized. The overall design block diagram is shown in Figure 6 below:

**Figure 5: Block diagram of simulation control module**

**Figure 6: Design block diagram of simulation experiment**
(a. Communication block diagram between ADAMS and MATLAB; b. Block diagram of experimental design)
In this section, the source of vehicle vibration excitation is analyzed, and the optimization simulation model of locomotive semi-active suspension control based on fuzzy control is established. The simulation data input from road surface is imported into ADAMS/View, the input and output state variables of suspension model are defined by ADAMS/Controls module, and the data files of suspension model generated by ADAMS are imported into MATLAB, and the joint simulation platform based on ADAMS and MATLAB is established to realize the simulation experiment of locomotive model.

3.3 Condition Detection Technology of Locomotive Equipment

Locomotive condition detection and maintenance have become the most important task of railway equipment maintenance. After the birth of any kind of locomotive, the problems of overhaul and maintenance always follow. The locomotive condition detection and diagnosis system can detect and diagnose the locomotive running state in real time, record the whole equipment working state data and abnormal fault information, and automatically analyze, alarm and put forward treatment measures when faults or even fault precursors occur.

It can be convenient for flight attendants to work, free of interference and maintenance, and effectively guide flight attendants to improve locomotive emergency handling capacity to achieve the purpose of saving energy, reducing consumption and optimizing operation [17].

The locomotive condition detection and diagnosis system provides information about locomotive operation and equipment condition to the crew when the locomotive is in normal operation. When the locomotive equipment fails, the system displays the detected and diagnosed fault information, and displays relevant fault diagnosis analysis and emergency maintenance suggestions. Using the locomotive equipment status data recorded by the vehicle-mounted device can help the ground maintenance personnel to analyze and evaluate the locomotive equipment status, and make use of the ground management and technical process conditions to carry out the locomotive return section maintenance, thus reducing the maintenance cost. The locomotive operation management function of the system compares the actual locomotive operation data with the standard optimized operation parameters, thus reducing the locomotive energy consumption [18]. The locomotive condition detection process is shown in Figure 7 below:

![Figure 7: Condition detection process of locomotive equipment](image-url)
The status of the tested locomotive’s equipment is unknown, and unexpected situations may occur in the process of measurement and control, such as locomotive impulse, powering up the failed electrical equipment, etc., which requires careful design of the test program. The electronic and control components of the locomotive should be tested first, and then the power-on test of the power transmission part should be carried out after it is confirmed to be correct. However, careful redundancy design of the measurement and control system is still needed to improve its reliability in case of sudden accidents. Except for sudden faults, the states of locomotive components depend on the analysis of test data to infer their fault trends. Therefore, the microcomputer measurement and control system should not only record and print all test data, but also save all test data of the same locomotive. According to this, the fault trend and current state can be inferred. That is, it should have good man-machine interface and document processing ability [19]. The vehicle-mounted device, data box and ground microcomputer data processing system are shown in Figure 8 below:

![Locomotive equipment condition detection system](image.png)

Figure 8: Locomotive equipment condition detection system

Each vehicle-mounted device includes a host, two vehicle-mounted displays, sensors, connecting cables, etc. The main engine is installed in the locomotive electrical appliance room, and the isolated switching power supply obtains the driving power of the system from the locomotive control circuit, and is directly connected with the locomotive circuit and sensors through the high-voltage isolation circuit to obtain the signals to be detected. According to the condition monitoring data in the normal operation process of electromechanical equipment, the condition monitoring data are grouped, the characteristic parameters are extracted, and the mapping relationship between the condition monitoring data and the health status of electromechanical equipment is revealed, thus realizing the health status monitoring of electromechanical equipment [20].

### 4. Results

In this paper, the fuzzy control model is used to optimize the design of semi-active suspension controller for rolling stock. The membership function of the fuzzy subset is selected as triangular membership function, and the input language variables of the fuzzy controller are set to deviation and deviation change, and the output language variables are set to control the output change. Taking the population size as 50, iteration times as 100, and simulation time as 2 seconds, the results of vertical acceleration of car body, dynamic load of wheels and dynamic deformation of suspension before and after optimization are shown in Figure 9 below:
According to the analysis of simulation results, the peak value of the vertical acceleration response of the optimized car body reaches 2.21 m/s², and the mean square value is 0.673 m²/s². Compared with the simulation results of semi-active suspension fuzzy control, the response peak value decreases by 20% and the mean square value decreases by 19%. Through comparison, it can be seen that the vertical vibration of the car body is effectively attenuated, and the ride comfort is improved. After optimization, the dynamic load fluctuation of the wheels becomes smaller, the difference is only 7260 N, which is 7% lower, and the handling stability is improved. The dynamic deformation of the suspension after optimization has not changed much compared with that before optimization, and the dynamic deformation of the suspension fluctuates in the range of (-0.00112, 0.0127).

On the premise of ensuring the optimization of the first two important indexes, the dynamic deformation of the suspension is still in an acceptable range.

In a word, the vertical acceleration of the optimized car body is obviously reduced, and the ride comfort is improved. The dynamic load fluctuation of wheels becomes smaller, and the handling stability is improved. After the dynamic deformation of the suspension is optimized, the ride comfort of the suspension system is improved without destroying the handling stability of the rolling stock. The optimization results show that the fuzzy control system with optimized design can control the system better than the single control system designed manually.
5. Discussion

Han et al. focused on discussing the characteristics and constraints of three improved fuzzy control methods based on adjustable factors, variable universe, and evolutionary algorithm to optimize fuzzy rules in their research on fuzzy control of the locomotive semi-active suspension system. Han et al. introduced the structure and principle of the locomotive semi-active suspension fuzzy control system. The development path for fuzzy control for locomotive semi-active suspension is finally presented [21]. In their investigation of big data-oriented health monitoring techniques, Entezami et al. proposed an electromechanical equipment big data-oriented health monitoring system. The health status monitoring of electromechanical equipment in a big data environment is successfully solved by installing and configuring the Hadoop platform in a Linux environment, and using Hadoop's distributed file system and parallel computing mode MapReduce to realize distributed storage and distributed computing of massive data [22]. This paper explains the ceiling control principle and semi-active suspension control approach used by Chinese locomotives and rolling equipment. It does this by drawing on existing theories. Second, this paper applies fuzzy control theory to the control of semi-active suspensions, designs a fuzzy control system in accordance with the fuzzy control principle, builds a semi-active suspension model to realize the control system, and performs control simulation of the semi-active suspension system in the simulation environment. Meanwhile, to map the relationship between condition monitoring data and the health state of electromechanical equipment and to monitor that relationship, this paper employs an adaptive neuro-fuzzy inference system. The outcomes demonstrate that the optimized car body's vertical acceleration is clearly decreased, and ride comfort is increased. Wheels experience less dynamic load variation as a result, and handling stability increases. The ride comfort of the suspension system is increased once the dynamic deformation of the suspension is tuned, without compromising the rolling stock's handling stability.

6. Conclusions

The suspension system of rolling stock is examined in this paper, and the design of a semi-active suspension controller is optimized using a fuzzy control system with ceiling damping as a reference model. The developed model is turned into a simulation model in the environment, and a fuzzy control system is used to manage the semi-active suspension. The outcomes demonstrate that the evaluation index of the suspension system can achieve the desired result by using fuzzy control in conjunction with a reference model. Second, the research object for this article is the locomotive and rolling stock equipment. By analyzing and processing the condition monitoring data collected by the electromechanical equipment during normal operation, it can achieve detection and real-time diagnosis of the electromechanical equipment's health condition, assist the ground maintenance staff in analyzing and evaluating the condition of the locomotive equipment, and utilize the technical and management conditions on the ground to maintain and repair the locomotive return section, which can have an impact on the locomotive's performance.

Meanwhile, this paper still has some flaws. For example, the simulation process assumes that the frame and car body's elasticity is much lower than that of the suspension system and treats the two as rigid bodies, failing to take the rail's elastic deformation into account, producing unrealistic simulation results. This is due to the short research time and other objective conditions. As a result, further research needs to be done in the future on the semi-active suspension system's control method.

References


