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Review of Structural Design and Control Methods for Active Suspension Systems in Automobiles

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Abstract: To gain a thorough understanding of the current research status and main control methods of mainstream active suspension systems in automobiles, this paper introduces three types of active suspension systems: electro-hydraulic active suspension, electro-pneumatic active suspension, and electromagnetic active suspension. It also analyzes eight control methods for active suspension systems, including PID control, state feedback H_∞ control, fuzzy control, neural network control, sliding mode control, adaptive control, robust control, and predictive control. By comparing the advantages and disadvantages of different control methods, it is proposed that the current active suspension and its control technology are facing challenges such as high energy consumption, low energy recovery rate, idealized conditions set in simulation studies, the gap between the working conditions provided by test equipment and the actual operation of active suspension, and the difficulty in multi-system integrated control.

Keywords: Active suspension system; control method; Fusion control ;system performance

1. Introduction

The automotive active suspension system is a core component that determines vehicle quality and is crucial for enhancing ride smoothness and comfort. To meet the comprehensive demands of vehicles in terms of safety, comfort, and passability, suspension structures have continuously evolved. Compared to passive and semi-active suspensions, active suspension systems can dynamically and adaptively adjust suspension stiffness and damping characteristics based on driving conditions. Consequently, they exhibit significant advantages and design potential in terms of actuation force range, handling stability, and ride comfort [1].

In recent years, scholars and institutions worldwide have conducted extensive research on the structural design and control strategies of active suspension systems. Current research on active suspension systems demonstrates characteristics of intellectualization, refinement, and coordination. Studies not only pursue improved comfort but also increasingly focus on balancing safety and energy consumption. Li Zhongxing et al.[2]constructed an electronically controlled air suspension system by coupling and coordinating the interconnection state control and vehicle height control. Their research results indicated that this system improves steering stability during straight-line driving but somewhat sacrifices comfort during cornering. Sun et al.[4] proposed a quasi-zero stiffness suspension structure with air springs and magnetic springs in parallel, effectively reducing the system's natural frequency. Mathematical modeling and simulation verification showed that this design significantly reduces vehicle body acceleration and improves ride comfort and handling stability. Wenbo et al.[5] incorporated a hydraulic actuator into the controller design, proposing a control strategy without approximation or backstepping. Simulation results confirmed the performance enhancement of this method for electro-hydraulic active suspension.

In summary, developing high-performance, energy-efficient, and practical active suspension systems remains a critical challenge to be solved in the field of vehicle dynamics and control. To gain a deeper understanding of the current research status of mainstream active suspension systems and their control methods, this paper reviews the system composition of active suspensions, classical and modern control methods, analyzes the advantages and disadvantages of different methods, and prospects the future research directions and development trends in this field.

2. Active Suspension Systems

With the development of automotive electronic control technology and vibration damping technology, modern active suspensions mostly adopt electronic control units (ECU) for control, also known as electronically controlled active suspension systems. This system typically consists of three main parts: sensors and control switches, ECU, and actuators. It can adjust parameters such as suspension stiffness, damping force, and vehicle height in real-time. Currently, mainstream new active suspensions mainly include electro-hydraulic active suspension, electronically controlled air suspension, and electromagnetic active suspension systems

2.1 Electro-Hydraulic Active Suspension System

The electro-hydraulic active suspension system primarily consists of components such as the suspension ECU, hydraulic pump, fluid reservoir, hydraulic control valve, suspension hydraulic cylinder, vehicle height sensor, and acceleration sensor.

This system transmits energy through hydraulic control to maintain vehicle body balance, counteract road excitations, and ensure good handling stability. When the vehicle corners and experiences roll, the pressure in the outer hydraulic cylinder increases while the pressure in the inner cylinder decreases. The pressure signals are collected and processed by the ECU, which then sends commands to adjust the output oil pressure of the hydraulic pump to compensate for the vehicle's attitude and minimize roll

2.2 Electronically Controlled Air Suspension System

The electronically controlled air suspension system mainly comprises an air spring, shock absorber, acceleration and height sensors, suspension control unit, air reservoir, air supply system, solenoid valves, and piping harness. During driving, the ECU assesses the vehicle's status based on height sensor signals and manages the inflation and deflation of the air spring by adjusting the duty cycle of the solenoid valves, thereby adjusting its stiffness and vehicle height. When the vehicle height is too low, the compressor inflates the air chamber to increase pressure and height; conversely, it deflates to lower the height, optimizing ride comfort. Furthermore, air suspension can adjust chassis stiffness and effectively isolate high-frequency vibrations, improving NVH performance.

2.3 Electromagnetic Active Suspension System

The electromagnetic active suspension (also known as magnetorheological fluid damper suspension) has garnered attention for its rapid response, high control precision, and high energy efficiency. This system mainly consists of a linkage, electromagnetic actuator, torsion bar spring, and wheel-side damping system. Based on actuator configuration, it can be divided into linear motor type and rotary motor type. By monitoring road excitations via sensors, the ECU precisely regulates the electromagnetic force and vehicle height by changing the current to the damper, thereby enhancing comfort.

3. Active Suspension System Control Methods

The performance of an active suspension system largely depends on its control strategy. Based on the development and application characteristics of control theory, its control methods can be divided into classical control methods and modern control methods. However, with technological advancements, this boundary has gradually blurred, and intelligent control and composite control strategies have become the new mainstream. This section will systematically review the characteristics, applications, and new developments of various methods.

3.1 Classical Control Methods and Their Advantages/Disadvantages

3.1.1 PID Control

PID control is one of the most widely used controllers in industry. Its advantages lie in its simple structure, ease of implementation, clear physical meaning of parameters, and the fact that it does not require an precise system model. It can provide fast response speeds in linear systems or small-range nonlinear systems near an operating point. However, its disadvantages are also prominent: for suspension systems with strong nonlinearity, significant time delay, and strong coupling characteristics, parameter tuning is difficult, control performance is limited, and it lacks robustness against system uncertainties and external disturbances.

3.1.2 State Feedback H∞ Control

H∞ control is an optimal control method aimed at minimizing the impact of disturbances on system output. Its advantage is the ability to precisely control multi-input multi-output (MIMO) systems. Through the design of weighting functions, it can balance multiple performance indicators such as ride comfort, handling stability, and safety across different frequency bands, offering strong robustness. Its main disadvantages are the complex design process, involving solving complex Riccati equations or Linear Matrix Inequality (LMI) optimization, which requires significant computational effort. It also heavily relies on an accurate system model and full state feedback; the introduction of a state observer in practical applications increases system complexity.

3.1.3 Fuzzy Control

Fuzzy control mimics human reasoning and decision-making processes. Its core advantage is that it does not rely on an precise mathematical model of the controlled object. It can handle complex nonlinear systems and uncertainties using expert knowledge and is insensitive to noise. However, its disadvantage is that control performance heavily depends on expert experience and the completeness of fuzzy rules. The formulation and adjustment of the rule base often rely on trial and error, making it difficult to guarantee global optimality. Furthermore, it theoretically lacks strict stability proof, so it often needs to be combined with other control methods to form composite controls like fuzzy-PID or fuzzy sliding mode control.

3.1.4 Neural Network Control

Neural networks possess powerful nonlinear mapping capabilities and self-learning characteristics. Their advantage is the ability to learn the complex dynamic characteristics of a system through training, handling highly nonlinear and uncertain systems with great adaptability. Whether used for system identification or directly as a controller, they show great potential. However, their disadvantages include a complex training process requiring substantial offline/online computational resources and high-quality, large-quantity training data. Training results may suffer from local optima, and the "black box" nature of the network makes its decision-making process difficult to interpret, hindering its application in safety-critical automotive systems.

3.2 Modern Control Methods and Their Advantages/Disadvantages

3.2.1 Sliding Mode Control

Sliding mode control is renowned for its "invariance" property. Its core advantage is extremely strong robustness against system parameter variations and external disturbances. Once the system state reaches the sliding surface, its performance is entirely determined by the predefined surface, offering fast response and high control accuracy. However, its most critical drawback in practical applications is the inevitable high-frequency chattering phenomenon due to the switching nature of the control law, system inertia, and sampling delays. This not only can damage actuators but may also excite unmodeled high-frequency dynamics, degrading system performance. Effectively suppressing chattering is key to the engineering application of sliding mode control.

3.2.2 Adaptive Control

The core of adaptive control lies in "online adjustment." Its advantage is the ability to identify changes in system parameters or adjust controller parameters online through its own adjustment mechanism to adapt to slowly varying uncertainties, making it very suitable for suspension systems operating under complex and variable conditions. Its disadvantages include complex system structure, large computational load, generally slow parameter convergence speed, high requirements for real-time identification accuracy, and issues related to stability and convergence proofs.

3.2.3 Robust Control

Sharing the same lineage as H∞ control, robust control primarily addresses bounded uncertainties. Its advantage is the ability to guarantee system stability and performance metrics within pre-defined uncertainty bounds, offering strong robustness against disturbances and model errors. Its disadvantage is relatively strong design conservatism; to cover the worst-case scenario, optimal performance under the nominal model is often sacrificed. The design process is also complex and relies on high-precision models.

3.2.4 Predictive Control

Predictive control employs a "rolling optimization, feedback correction" strategy. Its greatest advantage is the ability to explicitly handle multivariable, constrained optimization problems and perform anticipatory control based on predictions of future system behavior. This is particularly suitable for control problems like suspension systems which have physical constraints such as actuator output force and suspension travel. However, its disadvantage is an extremely high dependence on the system model. Real-time online optimization requires powerful computing capabilities, posing severe challenges to the computational power of onboard ECUs and limiting its application in high-speed, real-time systems.

3.3 Control Method Integration and Development Trends

From the above analysis, it is evident that a single control method often struggles to achieve a perfect balance between control performance, real-time capability, robustness, and complexity. Therefore, integrating multiple control methods to combine their strengths and compensate for their weaknesses, forming composite control strategies, has become an inevitable trend in the development of active suspension control. For example:

Adaptive Fuzzy PID Control: Combines the adaptive capability of fuzzy logic with the simple structure of PID for online parameter self-tuning.

Neural Network Sliding Mode Control: Uses neural networks to approximate system uncertainties, thereby reducing the switching gain in sliding mode control and effectively suppressing chattering.

Robust Predictive Control: Integrates the ideas of robust control into the predictive control framework, enhancing the ability of MPC to handle model uncertainties.

These composite strategies aim to synthesize the advantages of multiple methods, thereby comprehensively improving the control precision, response speed, and robustness of active suspension systems.

4. Conclusion

This paper has systematically reviewed the structural classification, core control methods, and latest research progress of active suspension systems. Through the analysis of electro-hydraulic, electronically controlled air, and electromagnetic active suspension systems, the applicable scenarios and performance characteristics of various systems have been clarified. The inherent advantages and engineering application limitations of various strategies, from classical PID to modern predictive control, were compared and analyzed.

Analysis shows that a single control method is difficult to meet the multiple goals of high performance, high robustness and low energy consumption of active suspension. The integration and complementarity of multiple methods, learning from each other's strengths and weaknesses, is an inevitable trend in technological development. The integration and complementarity of multiple methods, combining their strengths, is an inevitable trend in technological development. Simultaneously, current research still faces core challenges such as high energy consumption, idealized verification conditions, and difficulty in multi-system coordination.

Looking forward, research on active suspension technology will transcend mere "control algorithm" design, moving towards a multidisciplinary systems engineering approach. Its development will closely revolve around four major directions: energy efficiency, connectivity, intelligence, and integration. With the maturation of by-wire chassis technology and the evolution of automotive electronic architectures, the active suspension, as a key component for enhancing vehicle ride quality, is destined to witness greater innovative breakthroughs and broader application prospects.

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