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Types and application of advance suspension system

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Abstract
This paper presents a comprehensive overview of vehicle suspension systems, discussing various types ranging from passive to semi-active and fully active systems. The importance of suspension systems in ensuring both safety and comfort during travel is highlighted, emphasizing their role in controlling vehicle dynamics and mitigating the effects of road irregularities. Each suspension type is examined in detail, outlining its components, working principles, and applications in production vehicles. Passive suspension systems are characterized by simplicity and cost-effectiveness but lack adaptability. Semi-active systems offer improved ride quality through real-time damping adjustments, while fully active systems utilize advanced control algorithms and actuators to dynamically manage chassis height and damping forces. Case studies of innovative suspension technologies from leading automotive manufacturers, such as Mercedes-Benz and Audi, are presented to illustrate the latest advancements in suspension design. The abstract concludes by discussing the challenges and future prospects of suspension technology, highlighting the ongoing research and innovation in the field.

Keywords: Active suspension system, semi-active suspension system, passive suspension system, vehicle dynamic, comfort control, ride control

Introduction
The suspension system comprises tires, springs, shock absorbers, and connectors that link the vehicle to its wheels, enabling smooth travel. Suspension systems are essential for both handling and consistency of travel [1]. The suspension system manages and regulates the static and dynamic forces and reactions between the vehicle and the ground. [2]. The suspension system is comprised of springs, safeguards, and connections between the vehicle and its wheels. It functions to physically isolate the car body from the wheels. Typically, the suspension system comprises three primary components: a structure that supports the vehicle's weight and defines the suspension geometry, a spring that converts kinematic energy into potential energy and vice versa, and a shock absorber, a mechanical device designed to dissipate kinetic energy. [3]. The main function of the shock absorber is to keep the vehicle tire continuously in contact with the road surface, ensuring optimal control and braking response for the vehicle. Figure 1 shows an example of a shock absorber used in the vehicle suspension system.

Fig 1: Automobile Suspension System [4]

The purposes of the suspension system are: to prevent road shocks from being transmitted to the vehicle's components, to protect the occupants from road shocks, and to maintain the vehicle's stability during pitching or rolling while in motion [4]. The increasing demands on overall vehicle dynamics and stability, coupled with the rapid development of hybrid and electric passenger cars, could drive the implementation of various controlled suspension systems and their integration into the overall control of passenger vehicles [1]. To date, numerous models for vehicle suspensions have been proposed. Modifying the suspension necessitates a profound comprehension of car suspension networks and vehicle dynamics. Maintaining contact between the wheel and the road is crucial for ensuring the safety of vehicle movement, as the entire weight of the car is supported through the contact surfaces of the tires [5, 6, 7].

Different Automotive Systems

Three types of vehicle suspension systems exist: active, semi-active, and passive suspension systems, which various experts have developed using different methodologies and algorithms. Compared to semi-active and active suspension systems, the passive suspension system lacks vehicle stability [8]. The dynamic behavior of passive automotive suspension systems relies on selecting the suitable spring stiffness (determined by the type of spring and its characteristics) and the damping coefficient representing the shock absorbers' characteristics [9, 10].

Passive Suspension System

The passive suspension system, illustrated in Figure 2, consists of setups with viscous linear springs and dampers that have constant stiffness and damping coefficients, respectively [11]. The passive suspension of a vehicle is reliable, simple, and economical. In this system, the shock absorber and spring are positioned between the body frame and the wheel bracket. A rod is used to push the piston from the outside. The piston moves through holes that allow liquid to flow between different sections of the cylinder. This liquid flow generates reaction forces relative to the flow speed, which is proportional to the displacement between the un-sprung and sprung masses.

Damping in a passive suspension system is achieved by converting the oscillatory energy into heat, which is then dissipated into the surrounding air. However, this system is inadequate for solving suspension problems as it lacks external control and does not accommodate significant variations in materials, valves, or shapes [12]. The fixed damper and spring components of the passive system are insufficient for absorbing the energy needed to handle the loads or road disturbances encountered by the vehicle. The mathematical equation of motion for the passive suspension system is shown in Figure 2.

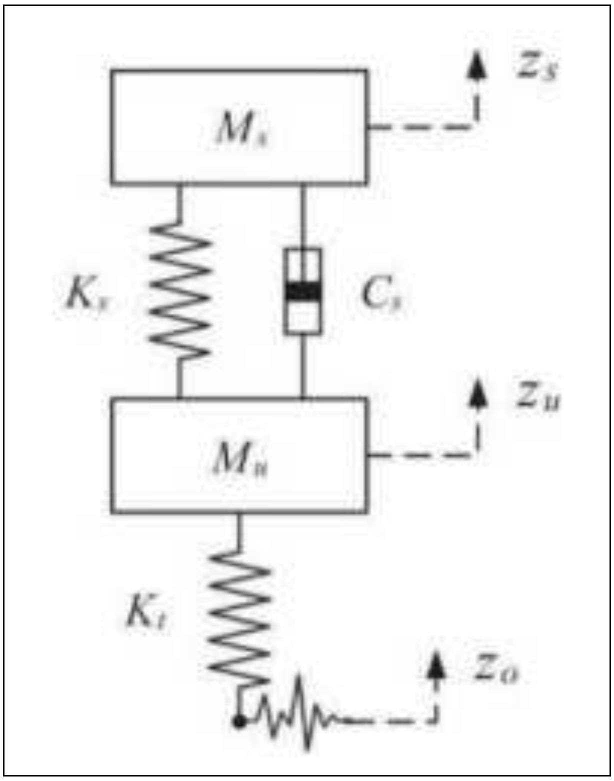

Fig 2: Passive Suspension System [13]

Semi-Active Suspension System

The semi-active suspension system employs a variable damper or other adjustable dissipative components. An example of a variable dissipater is a viscous twin-tube damper, where the damping coefficient can be modified by changing the piston hole diameter. Another example is a magnetorheological (MR) damper, which uses magnetorheological fluids. MR fluids change their rheological properties when exposed to a magnetic field, typically manifesting as an increase in yield stress. This enhances the damper's dissipative power by controlling the electromagnetic field applied to the fluid.

Semi-active suspension systems have been extensively studied to reduce actuation energy consumption. These systems are similar to passive suspensions, but with the key difference of having a variable damping coefficient while maintaining a fixed spring constant and lacking active power sources. This configuration enables seamless switching between passive dampers and semi-active dampers with adjustable coefficients, as illustrated in Figure 3.

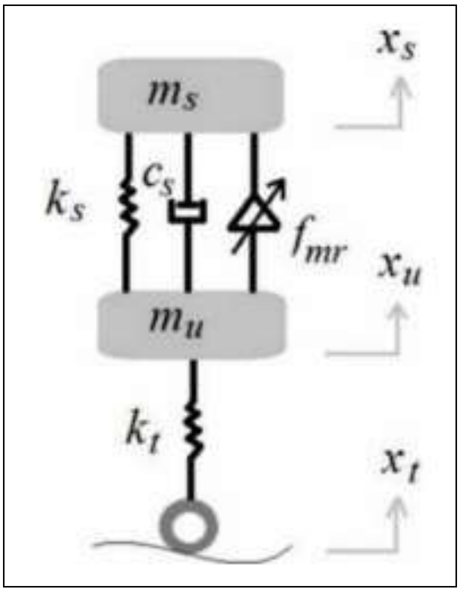

Fig 3: Semi-Active Suspension System [14]

While maintaining the use of a fixed spring, the continuously variable damper adjusts its functionality in real-time through a closed-loop feedback control system. This design ensures adequate energy dissipation, thereby enhancing the overall efficiency of the suspension compared to passive systems [15]. Semi-active suspensions can be electrically controlled remotely, allowing the mechanism to harden or soften as needed. Consequently, the damping coefficient can vary continuously or discontinuously, adapting to different driving conditions.

Semi-Active Suspension System

Active suspensions are equipped with electronic control systems that manage the operation of the suspension components. An example of an active suspension, as depicted in Figure 4, includes an actuator, a mechanical spring, and a shock absorber. The actuator in active suspension systems enables the suspension to absorb the energy from the wheel's acceleration, thereby minimizing the acceleration of the vehicle body.

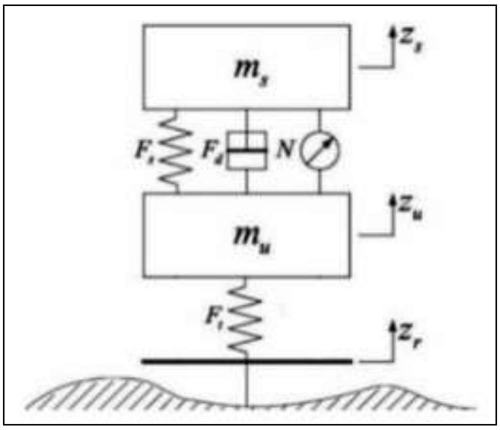

Fig 4: Active Suspension System [16]

Such systems are highly responsive to vertical forces induced by unpredictable road conditions, as the actuator force manages both shock absorbers. The actuator operates by distributing system power, which can be moderated by various types of controllers depending on the design specifications. Active suspension systems can achieve a better balance between vehicle handling comfort and driving stability, leading to an improved suspension design when appropriate control methods are applied.

Numerous researchers have recently concentrated on active suspension systems to improve vehicle stability and driving performance. Numerous control approaches have been employed in active suspension systems, including Quadratic Linear Control (LQR), Quadratic Gaussian Linear Control (LQG), Slider Mode Control, Control H, Adaptive Slider, Preview Control, Neural Network Methods, Fuzzy Logic, and Optimal Control. These control methods are crucial in improving the performance and effectiveness of active suspension systems.

Hydraulic or pneumatic active suspensions

The active suspension system, equipped with hydraulic or pneumatic actuators, operates through electrical drives with power supplied either from a battery source or a conventional internal combustion engine (ICE). Due to their simple design, high strength density, advanced technology, reliability, and the availability of various commercial components, hydraulic-based active suspension systems are widely used in body control systems.

For example, the Mercedes Active Body Control System utilizes high-pressure hydraulics to pre-stress the springs, generating anti-rolling forces without coupling the right and left wheels [17]. Nonetheless, hydraulic systems have drawbacks, including:

- Inefficient performance due to the continuous requirement of a pressurized system.
- Relatively high system time constant caused by flexible hoses and pressure loss.
- Environmental damage resulting from the presence of toxic hydraulic fluids in case of leaks or hose rupture.
- System volume and feasibility requirements, which can contribute significantly to the overall vehicle mass.

Suspension System used in different cars

The previous section covered various suspension systems, their components, and their functions. In production vehicles, these systems are implemented in different configurations and mechanisms, but the fundamental principles and operations remain consistent. Here are the different suspension systems used in production vehicles.

Cadillac MagneRide Suspension

MagneRide [18] is a notable semi-active suspension solution initially launched by Cadillac in 2002. Its enhanced version, MagneRide 4.0 [18, 19], as depicted in Figure 5, was introduced in Cadillac's latest models-the CT4-V, CT5-V, and CT5-in 2020 and 2021. In the MagneRide suspension system, the damping rate and tire contact with the road are regulated by magnetorheological fluid within the shock absorber.

Other representative semi-active suspensions include the Öhlins Semi-Active Suspension [20] and the Monroe intelligent suspension supplied by Tenneco [21, 22]. Like MagneRide, these systems adjust the damping coefficient of the shock absorber using an electronically controlled unit to adapt to various road conditions and improve ride performance. However, compared to fully active suspensions, semi-active suspensions cannot control the chassis attitude in terms of pitch and roll angles or chassis height.

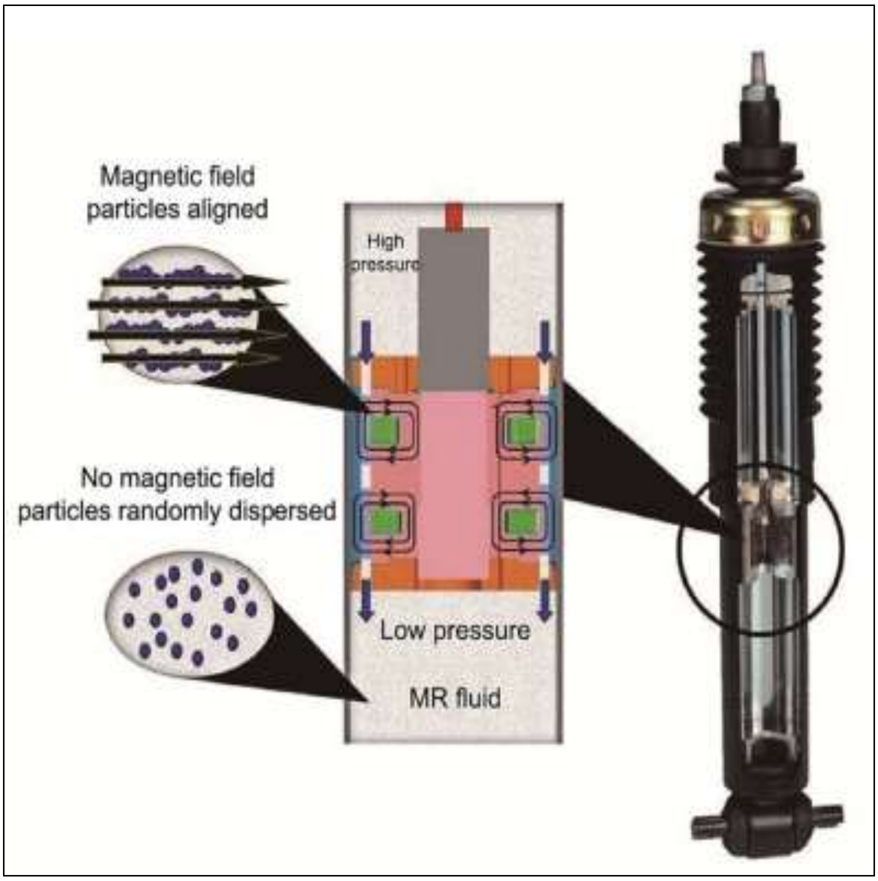

Fig 5: Cadillac MagneRide semi-active Suspension System [18, 19]

Michelin in-wheel active suspension

Michelin first proposed the active wheel concept in 1996 [23]. The Michelin in-wheel active suspension, as shown in Figure 6, integrates two motors inside a wheel. This system was developed specifically for electric vehicles (EVs), eliminating the need for a gearbox, clutch, transmission shaft, or anti-roll bar. All the braking, drive, and suspension components are contained within a single wheel.

In addition, without the need for a conventional engine at the front of the vehicle, the space can be dedicated exclusively to impact absorption. However, the effects of shocks, water, and snow on such an "in-wheel" design have not been thoroughly investigated. This project was interrupted in 2014 due to unacceptable weight increments, the space required inside the wheel, and economic costs [24].

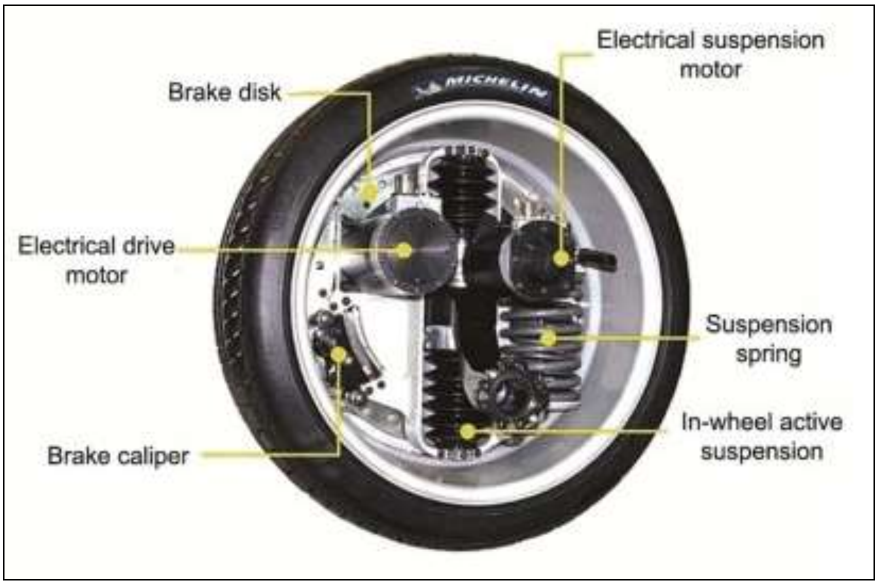

Fig 6: Michelin in-wheel Suspension System [23]

Electronic Air Suspension System

In contrast to a mechanical spring system that deflects proportionally to the load, air springs allow height adjustments independent of the load by altering the spring pressure. Electronically controlled air suspension (ECAS), developed by Dunlop Systems and Components Ltd. (Coventry, UK), was first installed in the Range Rover Classic in 1993 and later in the Range Rover P38A [25]. The chassis height is automatically controlled to adapt to driving conditions, with an optional manual ride-height switch. ECAS has been widely adopted in high-end grand tourer (GT) cars, including the Mercedes-Benz AIRMATIC (Fig. 7), Ford Expedition Models [27], Tesla Model S [28], and Audi A8 AI Suspension (Fig. 8) [29].

Fig 7: Air Suspension System [26]

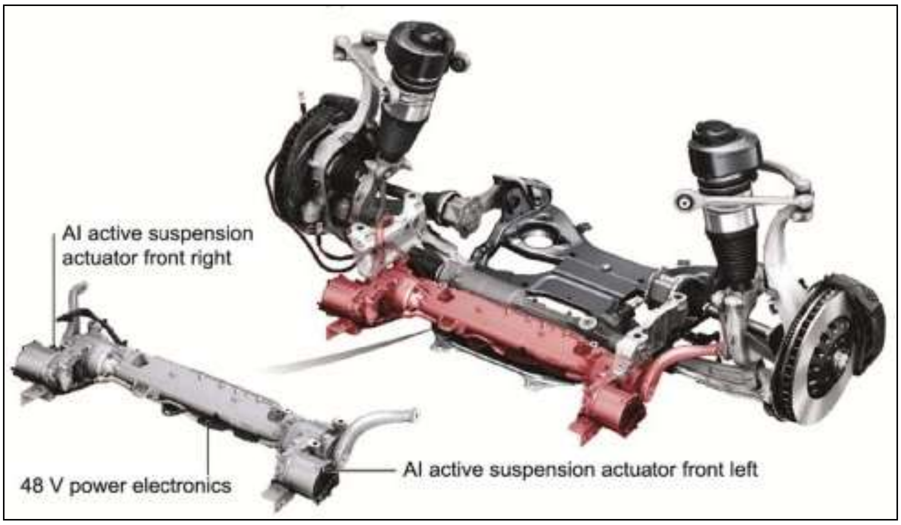

Fig 8: Audi A8 Predictive Active Suspension System [29]

Mercedes Active Body Control

Mercedes ABC, as illustrated in Figure 9, is a fully active hydraulic suspension system designed by Mercedes-Benz, which entered series production in 1999 [30]. The ABC system can independently control the spring and damping forces at each wheel, minimizing rolling, pitching, and vertical motions.

A road surface scan function was later added to the Mercedes-Benz S-Class (W222) in 2013, enabling predictive control that responds to the road surface 15 meters ahead of the vehicle at driving speeds of up to 130 km/h [32]. This feature, combined with air suspension technology, provides even better ride comfort and handling ability.

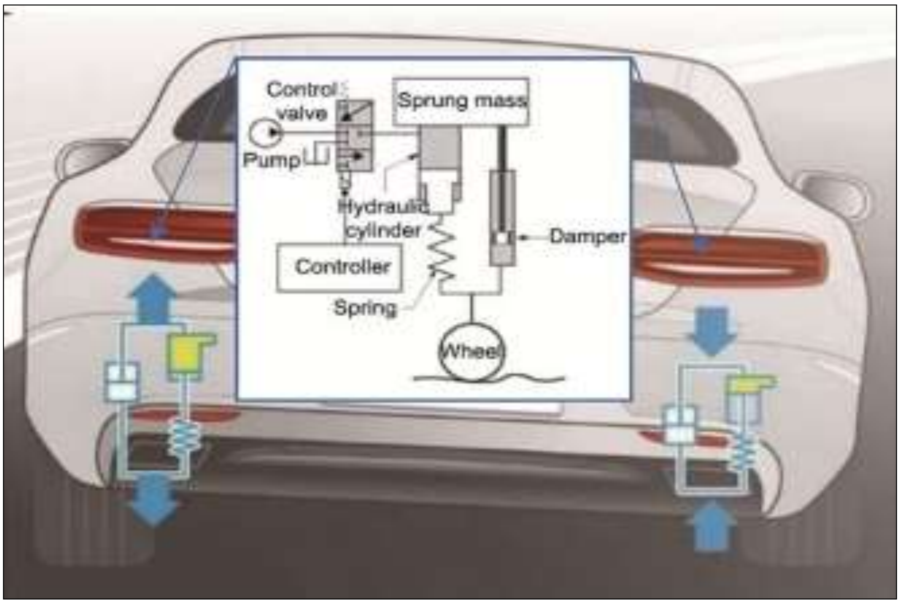

Fig 9: Electro-Hydraulic Suspension system of Mercedes ABC [30]

Audi Predictive Active Suspension System

In 2017, Audi introduced a high-tech innovation for its flagship model, the Audi A8 [28]: predictive active suspension. This fully active suspension system comprises a double wishbone, an air spring, a rotary electrical damper, and an electromechanical actuator. The electromechanical actuators independently raise or lower each wheel, actively controlling the chassis height by up to 85 mm, thereby reducing air drag force.

Additionally, the Audi A8 Predictive Active Suspension offers both "dynamic" and "comfort plus" driving modes. In the "dynamic" mode, the Audi A8 experiences only a two-degree change in chassis roll angles during hard cornering at 1 g lateral acceleration, compared to more than 5 degrees with a passive suspension. In contrast, the "comfort plus" mode minimizes chassis vibration accelerations. In both driving modes, the system optimally distributes the vehicle's rolling moment to reduce the "diving" sensation during acceleration or braking.

Bose Electromagnetic Active Suspension System

It has been decades since Bose first demonstrated an electromagnetic suspension system that maintained a perfectly level vehicle chassis, regardless of road bumps, at low driving speeds. Recently, Bose has designed a novel tubular permanent magnet electromagnetic actuator, as shown in Figure 10, to replace the conventional spring-damper unit at each corner of the chassis [31].

The actuator has following features:

- A direct drive with a small occupied volume.
- A higher frequency bandwidth compared to other fully active systems.
- Lower power consumption than an electro-hydraulic system, which requires continuous hydraulic pressurization.

Fig 10: Bose Electromagnetic Suspension System [33, 34]

Conclusion

In conclusion, vehicle suspension systems play a pivotal role in ensuring both safety and comfort during travel. Throughout this discussion, we've explored various types of suspension systems, ranging from passive to semi-active and fully active systems. Each system has its own set of advantages and limitations, influencing its suitability for different vehicle applications.

Passive suspension systems, characterized by fixed spring stiffness and damping coefficients, are simple and economical but lack the adaptability of their semi-active and active counterparts. Semi-active suspension systems offer improved ride quality by adjusting damping coefficients in real-time, but they cannot control chassis attitude as effectively as fully active systems. Fully active suspension systems, such as those pioneered by Mercedes-Benz and Audi, utilize advanced control algorithms and actuators to actively manage chassis height, damping forces, and even predict road conditions. These systems provide unparalleled ride comfort, handling, and safety by dynamically adjusting to changing road conditions and driving situations.

While fully active suspension systems represent the pinnacle of suspension technology, they also come with challenges such as increased complexity and cost. Nevertheless, ongoing research and innovation continue to push the boundaries of suspension design, promising even greater advancements in the future.

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