Hindawi
Shock and Vibration
Volume 2023, Article ID 1716615, 23 pages
https://doi.org/10.1155/2023/1716615

Review Article

The Evolution of Vehicle Pneumatic Vibration Isolation: A Systematic Review

Vincent Akolbire Atindana,[1] **Xing Xu**,[2] **Andrews Nanzie Nyedeb**,[1] **James Kwasi Quaisie**,[3] **Jacob Kwaku Nkrumah**,[1] **and Samuel Passim Assam**[1]

[1]*Faculty of Engineering (Automobile Engineering Department), Tamale Technical University, Tamale 00233, Ghana*
[2]*Automotive Engineering Research Institute, Jiangsu University, No. 301 Xuefu Road, Zhenjiang 212013, Jiangsu, China*
[3]*Faculty of Engineering (Welding and Fabrication Department), Tamale Technical University, Tamale 00233, Ghana*

Correspondence should be addressed to Xing Xu; xuxig@ujs.edu.cn

Received 14 December 2022; Revised 29 April 2023; Accepted 17 July 2023; Published 29 September 2023

Academic Editor: Stefano Manzoni

Whole-body vibration (WBV) is a significant concern for vehicle users as it can negatively impact their health and comfort. As such, effective vibration isolation is critical in vehicle suspension design. The ability of a vehicle suspension to isolate vibrations depends primarily on the suspension design and the type of springs used. One type of spring that has proven advantageous for vibration isolation is the air spring. Air springs can vary frequencies and adjust their stiffness in response to different loading conditions, making them ideal for meeting both suspension load-carrying and occupants' comfort requirements. Pneumatic (air) suspension has been in use in the automotive industry for several decades and has undergone significant advancements during this period. This paper presents a systematic review of pneumatic suspension since its inception. The review highlights different air spring modeling techniques, types of pneumatic suspension, and control methods. The study also discusses the functional flexibility of pneumatic suspension, its ability to offer a wide range of control options to drivers, and its broad application in almost all ranges of vehicles, including chassis, cabin, and seat suspension systems. In addition, this paper presents a summary of the pros and cons of pneumatic suspension and suggests future research directions. The advantages of pneumatic suspension include effective vibration isolation, improved ride comfort, and the ability to adjust suspension stiffness and ride height. On the other hand, the disadvantages include higher cost and complexity compared to other types of suspension. Overall, the findings of this review demonstrate that pneumatic suspension is a viable solution for vehicle suspension design, particularly in situations where vibration isolation and ride comfort are critical.

1. Introduction

Whole-body vibration (WBV) has been a subject of considerable interest for researchers due to its numerous adverse effects on human health, particularly on the spine. Low back pain caused by WBV has been reported in professional drivers [1] with clinical studies indicating that WBV exposure can increase spinal burdens [2] and raise the risk of spinal and sciatic pain [3], muscle fatigue [4], and disc injuries [5]. Long-distance commuters, particularly professional drivers, rank second in occupational-related ill health due to severe musculoskeletal disorders from continuous WBV exposure [6]. Heavy truck and off-road vehicle drivers, in particular, have a higher risk of back injuries due to constant WBV exposure.

Ride comfort for drivers and passengers can be influenced by various factors, such as road roughness, vehicle suspension system, seat suspension system, and cabin suspension system (in heavy commercial trucks) [7]. Although minor, the noise and vibration generated by internal combustion engines can also impact ride comfort [8]. Tiemessen et al. reported that acceptable suspension accelerations for working vehicles in European countries should be between 0.5 and 1.5 m/s^2 for 8 hours of continuous operation, with limit values, due to the high social cost of musculoskeletal diseases associated with working in low-frequency vibration environments [9]. The International Organization for Standardization (ISO) discovered that as vertical acceleration increases, ride comfort decreases, and the level of WBV increases (ISO 2631-1 1997). Therefore, it is crucial to design vehicle suspension systems that effectively isolate vibrations, provide comfort, and reduce the risk of adverse health effects due to WBV exposure.Given the significant impact of vibration on human health, the automotive industry places great importance on designing and manufacturing vehicles that reduce vibration to the barest minimum. This has led many (ISO) discovered that as vertical acceleration increases, ride comfort decreases, and the level of WBV increases (ISO 2631-1 1997). Therefore, it is crucial to design vehicle suspension systems that effectively isolate vibrations, provide comfort, and reduce the risk of adverse health effects due to WBV exposure.

Given the significant impact of vibration on human health, the automotive industry places great importance on designing and manufacturing vehicles that reduce vibration to the barest minimum. This has led many researchers to explore various approaches to achieving optimal vibration isolation. Some researchers focus on improving the vehicle's primary suspension system to reduce input vibration from the road through the chassis into the human body [10–12], while others aim to enhance the vehicle seat suspension design [13]. Some studies integrate chassis suspension and seat suspension systems to isolate the vibration transmitted to the human body [14, 15]. Additionally, researchers have investigated reducing the vibration transmitted through the vehicle cabin suspension system [16]. The primary means of isolating vibration in automotive vehicles is through some form of spring action, with metallic springs, hydraulic springs, and pneumatic springs being the most common types used. Air springs are considered the most versatile among these springs, and air suspension is expected to be the fastest-growing market compared to other suspension systems. This is partly due to the increased use of air suspension in buses in the Asia Pacific region, where governments in countries such as China and India focus on fuel efficiency and comfortable public transport, driving the demand for air suspension in buses [17].

The primary contribution of this study is to provide a comprehensive review of the evolution of pneumatic spring suspension as a medium for vibration isolation. The study identifies the various types of suspension, air spring modeling techniques, control methods, and applications of pneumatic suspension in different areas of the vehicle suspension. The study also identifies research gaps, analyzes the prospects and challenges of pneumatic suspension, and provides future research directions to optimize vibration isolation and improve the ride comfort of vehicle users. Overall, this study contributes to the field of vehicle suspension by providing a detailed and up-to-date overview of the pneumatic suspension system, its advantages and disadvantages, and potential future developments. It serves as a valuable resource for researchers, engineers, and industry professionals working in the field of vehicle suspension and vibration isolation.

This paper is organized as follows. Section 2 defines the functions of the vehicle suspension system and provides an overview of air suspension, as well as the differences between passive, semiactive, and active suspension. Section 3 outlines the air suspension control systems, while Sections 4 and 5 review the cabin air suspension of heavy and off-road vehicles and the application of air suspension in off-road vehicle seat suspension, respectively. Section 6 presents a general summary of the key findings. Finally, Section 7 presents the main conclusions, research gaps, and future projections.

2. The Functions of the Vehicle Suspension System

The suspension system is a critical component of any vehicle, and it primarily consists of three key elements: springs, dampers, and linkages, that connect the chassis to the axle and the road wheels. The primary purpose of the suspension system is to support the vehicle's weight and provide a smooth ride for its occupants by isolating them from the vibrations caused by road irregularities. In addition to providing a comfortable ride, the suspension system also plays a vital role in maintaining the stability of the vehicle. By keeping the tires in contact with the road surface, the suspension system offers resistance to lateral movement, pitching, and rollover. This ensures that the vehicle remains stable and easy to handle under all driving conditions, including during sudden maneuvers or in adverse weather conditions. The springs in the suspension system absorb the shocks caused by road irregularities, such as bumps or potholes, and provide the necessary support to the vehicle's weight. Meanwhile, the dampers (also known as shock absorbers) control the movement of the springs and prevent the vehicle from bouncing excessively. The linkages connect the various components of the suspension system and help to distribute the weight of the vehicle evenly, ensuring that the suspension system works effectively [18, 19].

2.1. Pneumatic Chassis Suspension System. A pneumatic suspension system is basically a type of suspension where air bellows (air springs), made mostly from textile-reinforced rubber, are used as the primary or sole vibration isolation medium. The air springs are filled with air from an engine-driven or electrically powered air compressor, raising the chassis from the axle. Due to their low natural frequency, air springs provide a more comfortable ride and a constant ride height irrespective of the vehicle load [20, 21]. The pneumatic suspension was predominantly used in trucks and buses but has evolved tremendously to a microprocessor-controlled precision system capable of much more than a conventional spring. Unlike metallic springs, the deflection of an air spring (suspension travel) is not proportional to its load, enabling it to function as a spring and at the same time to be used to raise and lower the vehicle ride height. Air suspension can be used with any damping system, including magnetorheological adaptive dampers and variable stiffness antiroll bars. Alternatively, air springs can be used independently of the dampers, particularly at the rear, and are arguably considered the most comfortable suspension ride [22].

2.2. Main Components of Pneumatic Suspension

2.2.1. Air Springs. An air spring can be described as an elastomeric bellow which can expand and contract to absorb externally excited vibrations according to the amount of compressed air charged into it or discharged out of it. As shown in Figure 1, air springs come in different sizes and shapes, such as the convoluted bag (single, double, and triple convoluted) [23]. The structure of the convoluted air spring includes a bead plate permanently attached to the bellows, making it more laterally flexible than other designs. The tapered sleeve offers a little more adjustability to ride height and is designed to fit well in tighter areas. The rolling sleeve air spring consists mainly of a bellow, a piston, and an upper plate, which in some cases can be varied according to the deformation of the diaphragm (guided rolling sleeve) to influence the spring's lateral stiffness [24]. Hence, the rolling sleeve air spring provides lateral flexibility and ride height adjustability for specific applications. The difference between the tapered and rolling sleeves is their variation in ride height, and they are designed to fit different vehicle applications [25]. Air springs are rated based on their load-carrying capacity, which is directly linked to the effective surface area (A_w) [26]. The air spring's internal pressure (P_i) is the main determining factor of its natural frequency and stiffness, defining the overall air suspension stiffness (supporting force, F) where $F = P_i \times A_w$ [27]. The effective surface area A_w is determined by the effective diameter (dw). Although air spring modeling is analogous to a large extent, their application difference requires that they come in varied designs. Also, the design difference can influence the spring performance. A case in point is the effective area, which is a critical parameter that defines the correlation between the air spring's internal pressure and the spring plate's force. This can be varied with displacement in some designs such as air springs with U-bellows where the lowest point of the fold determines the effective area, consequently influencing the spring stiffness (positively or negatively) even at constant internal pressures [28].

2.2.2. Air Supply. The air supply of a vehicle's pneumatic suspension system comprises mainly a compressor, mostly engine-driven or electrically powered, which generates air under pressure, and the air is stored in cylinders. Most vehicles that use pneumatic suspension also use other air-dependent systems such as braking, transmission, and auxiliary purposes. For this reason, the choice of a compressor depends on the needs of the vehicle's air operating system. In vehicles such as heavy trucks and buses, where the air-dependent systems are very high, the air compressor is also required to be of a higher capacity, so they usually employ engine-driven mechanical pumps, except for electric-powered vehicles. However, in smaller vehicles where the air is only used for suspension purposes, portable electrically operated air pumps/compressors are often used.

The main parameters of any air compressor are capacity, pressure, horsepower, and duty cycle. The performance parameters of air compressors are determined through various modeling techniques, such as statistical correlation-based models where the compressor output is calculated following polynomial equations and using geometric, isentropic, and volumetric efficiency variables. Other categories of models are phenomena-oriented models, where the compressor compression chamber is divided into control volumes (precompression, compression, and postcompression) based on the compressor's general internal occurrence [29]. Meanwhile, in construction-oriented models, differential-algebraic equations (DAB's) are used to calculate the performance control characteristics of each related individual component in the compressor and then summed together relative to the mass flow and energy (entropy/energy) to define the output [30]. Since this review focuses mainly on the evolution of pneumatic suspension, the study did not include a deeper analysis of air compressor performance.

2.2.3. Control Valves. Most pneumatic suspension systems employ solenoid-operated valves to regulate airflow from the high-pressure tank to the air spring and pneumatic actuators in the active suspension system [31]. This is because solenoid valves have been proven to be very effective in the precise metering of air pressure for optimal flow control. Solenoids offer fast and safe switching, high reliability, long service life, good medium compatibility of the materials used, low control power, and compact design [32]. Figure 2 shows a schematic diagram of multiple air suspension solenoid valves placed together on a manifold block.

All solenoid valves are modeled to comprehend their functional characteristics, which are used to grade their specifications for relevant applications. There exists a lot of literature relative to solenoid valve functionality and performance. Wong et al. proposed a fault-tolerant control methodology for solenoid valve degradation in electronic control air suspension (ECAS) based on finite-time stability constraints [33]. Gao et al. proposed a compounding approach for the determination of mass flow rate characteristics of high-pressure pneumatic components (HPPCs) through instantaneous polytropic exponents in the discharge process [34]. Also, Righettini et al. evaluated the sonic conductance of a pneumatic actuator valve using the piston position transducer [35]. In the study of Zhang et al., the flow field of a three-way solenoid valve is modeled taking into account the aerodynamics, magnetic circuit, and mechanical motion using computational fluid dynamics for response characteristics analysis. The experimental validation findings revealed that at a suitable working frequency, the action frequency has no significant influence on the valve's response characteristics [36].

2.3. Types of Pneumatic Suspension System

2.3.1. Passive. A passive pneumatic suspension system consists of an energy-storing element (air spring) and an energy-dissipating element (damper), placed between the chassis and the vehicle's axles. In pneumatic suspension, air springs and dampers are the main components used for vibration isolation. It relies solely on these elements to control the vehicle's dynamics, such as vertical motion, pitch, and roll. It is passive because the suspension elements cannot generate or add energy to the suspension system. As a result, passive

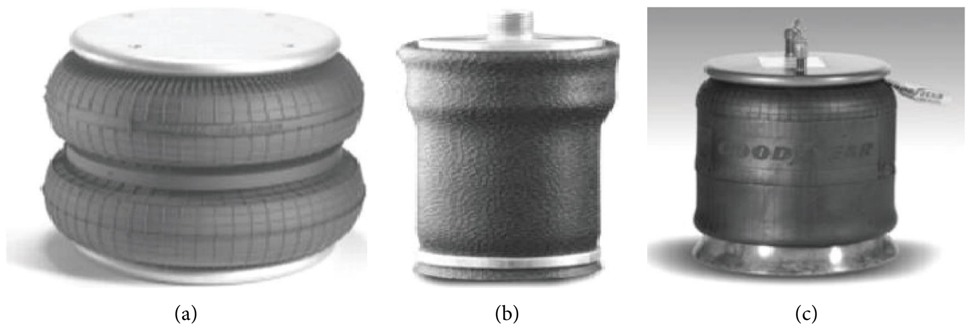

Figure 1: Types of air springs: (a) double convoluted, (b) tapered sleeve, and (c) rolling sleeve.

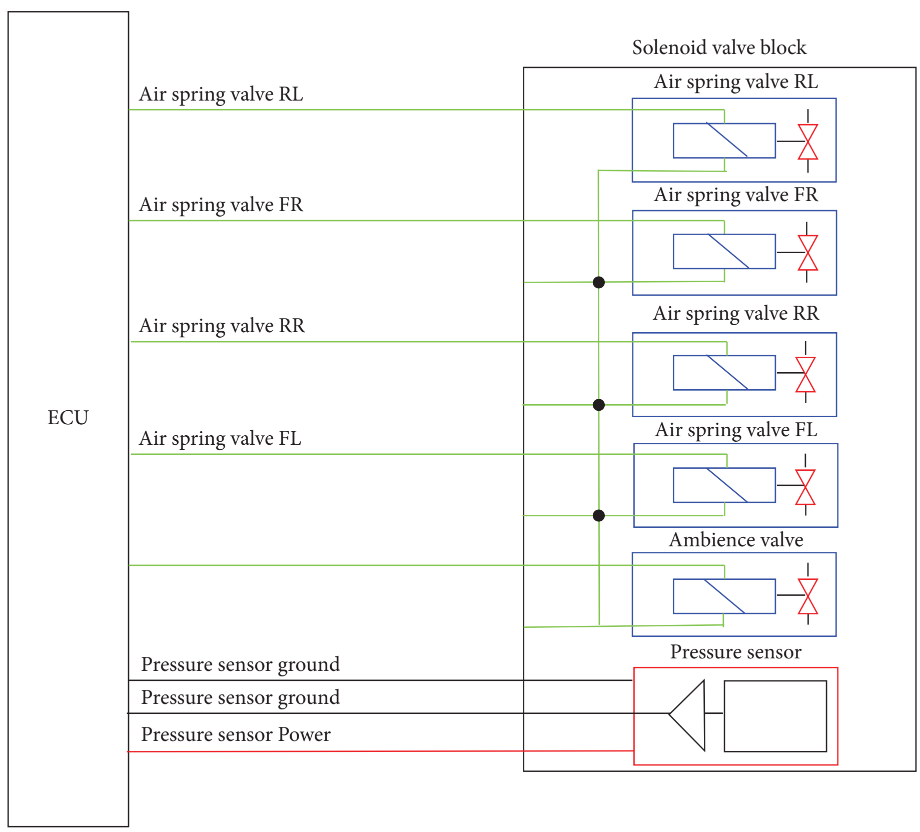

Figure 2: Air suspension solenoid valve block.

vibration control involves an inherent compromise between low-frequency and high-frequency vibration isolation [37]. Passive suspension is a conventional vibration isolator that depends only on the air spring's natural frequency to control the vehicle's body and wheel displacement by limiting their relative velocities at a pace that gives an acceptable ride comfort. Vibration attenuation is only effective in a high-frequency range but suffers from the low-frequency domain, such as 1 to 10 Hz [38]. However, vibration isolation can be significantly optimized in passive air suspension systems through careful and proper modeling of the air spring. Currently, there are four main categories of air spring modeling techniques. One such model is the thermodynamic model, which relies on mechanical and thermodynamic laws to describe the physical occurrences in the suspension system. The air spring volume variations are determined using energy conservation law and mass. Also, the variations of an air spring's stiffness are directly proportional to its varying effective area, just as its volume is proportional to the height [39]. Meanwhile, the model's input parameters are often collected experimentally. This model category usually ignores the air spring's lateral characteristics and concentrates mainly on its vertical characteristics.

Thermodynamic models can be categorized into various classes based on the types of elements used for vibration isolation, such as the auxiliary chamber, leveling valves, bellow, orifice, and pipelines. Additionally, these models can also be grouped based on physical phenomena like heat transfer, friction loss, and inertia, among others [28, 40, 41]. In the literature [24, 42], the heat exchange in air springs is evaluated isothermally and adiabatically to define their physical behavior. Similarly, Spiroiu reported that when the frequencies are above 0.3 Hz, the process can be termed adiabatic, and frequencies ranging from 0.1 to 0.3 Hz are deemed polytropic, while frequencies below 0.1 Hz are isothermal processes [43]. This claim was however challenged by Pintado et al. whose experimental research findings revealed otherwise. The study's results demonstrated that as the frequency increases, the polytropic indexes in both the air spring and reservoir decrease and eventually reach an isothermal state for frequencies above 0.3 Hz (0.1 Hz for the reservoir) [44]. This suggests that at higher frequencies, the compression and expansion of the air occur more rapidly, resulting in a more isothermal process.

Another category of models is the analytical model, which can also be classified into membrane-based and geometrical-based models. These models are promulgated by extensively studying and analyzing the behavior of the air spring under different conditions so that when certain characteristics are repeatedly exhibited over time under some specific conditions, a generalization could be made. The membrane class of models primarily defines the air spring stiffness and other relevant features such as the variations of the air bellow shape and the related spring fatigue using the material characteristics to determine the diaphragm contortion [45]. Studies [46, 47] show that the dynamic inflation of nonlinear rubber-like membranes is modeled using hyperelastic and viscoelastic models in a three-dimensional finite formulation. Eitzen et al. modeled an air spring to define its fatigue by relying on the cord-rubber microscopic loadings [48]. Equally, Verron and Marckmann computed the membrane coordinates of a cylindrical rubber bellow in a cubic B-spline model to determine the shape when inflated [49]. On the other hand, the modeling uncertainties are mostly geometrical-based, relying on the air spring's effective area and some assumptions and simplifications as a function of height. To this extent, different air spring stiffness models have been researched. For example, the vertical stiffness of a rolling lobe air spring and the rate at which the spring's effective area changes were investigated [50], and the quasi-static vertical stiffness of a belted air spring was also studied [51]. Similar reports analyzed the stiffness of a convoluted air spring with one lobe and a double-convoluted air spring [52–54].

Mechanical or phenomenological models are considered yet another famous category of air spring models, such as the Nishimura linear model, Berg's model, Simpack FE83, and vampire model (vertical and lateral) [55, 56]. In mechanical or phenomenological models, the suspension is modeled based on physical-mechanical circuits such as dashpots, springs, and mass, deriving the parameter values experimentally. These models are widely used in multibody simulations due to their fast and easy implementation. An air spring's vertical and lateral behavior can be described by connecting it parallel to a linear viscous dashpot. The nonlinearity of the suspension air spring is not factored in this simple mechanical model. Therefore, it has limitations on quasi-static simulation applications. However, it is applied in many vehicle suspension simulations. For instance, the effects of an auxiliary chamber and air pipeline parameters on a pneumatic suspension system performance are modeled using the vampire model [55], and the influence of parameter estimation of the airbag, rubber spring, and auxiliary reservoir on the suspension stiffness was also investigated [43]. Among the various models under this category, the Nishimura linear model and Simpack FE83 model are deemed to be more accurate in depicting the actual behavior of an air spring, and this is because both models factor in the viscous damping, including modeling the effect of air spring orifice and connecting pipelines.

Furthermore, finite element models (FEMs) are considered to be one of the sophisticated and efficient categories of suspension system models, which allow room for creating a very precise and customized parameterized model. However, due to their sophistication and the difficulty involved in linking them to the multibody simulation, FEMs are not commonly applied compared to other related models. FEM simulations are primarily centered on the influence of the construction parameter of the stiffness of the bellows, and they conform to 2D and 3D axisymmetric models. The impact of the bellow construction parameter on its static vertical stiffness is evaluated using fiber-implemented shell models developed in Abaqus, which is the most employed software [26, 56, 57]. Meanwhile, some studies employed ANSYS, which is a multiphysics modeling tool suitable for many engineering disciplines. Even though the effectiveness of a passive suspension system varies per road profile [58], the advantages of this type of suspension system are fewer parts and cheap production costs. It is also very reliable, making it the preferred choice for many heavy commercial vehicles and the production of low to average-cost vehicles over the years.

2.3.2. Semiactive. Min et al. first presented the semiactive suspension in the 1970s. It has attracted so much attention for its remarkable vibration isolation ability [59–62]. In a typical semiactive pneumatic suspension, vibration isolation optimization is achieved through active dampers or by simply regulating the air flow to and from the air springs to vary their stiffness without using actuators. The dampers function as actuators with variable force-speed characteristics and always act in opposition to the motion of the force generated. They require very low power consumption hardware to implement. This is because semiactive suspension systems only need a power input to actuate their modulating devices, but not directly for the generation of the actuation force. So, the semiactive suspension has a very minimal impact on the vehicle's overall energy consumption.

Commonly used semiactive actuators are hydraulic or pneumatic shock absorbers with controllable orifice areas, operated by controllable quick-operating valves, mostly solenoid valves or servo-valves [63, 64]. These dampers include magnetorheological (MR), electrorheological (ER), and electromagnetic dampers. One common category of pneumatic dampers includes those with double chambers whose characteristics are primarily governed by airflow control between connections. In this category of shock absorbers, valves are relied upon to create pressure differences between cavities/chambers. The vibrational energy dissipation is achieved through the process of air transfer from one cavity/chamber to the other. The degree of pneumatic shock absorbers' elastic damping characteristics is determined by their control valve design and calibration. According to Khamitov et al., pneumatic dampers' vibration absorption ability can be optimized by carefully modeling and defining their principles of operation relative to thermodynamic parameters through differential equations and the system's dynamic equation [65]. The idea of a semiactive pneumatic damper was patented in 1977 by Somm et al. and subsequently by Hiramoto et al. [66]. An active damping pneumatic damper design was also reported by Khamitov et al. In this design, the vertical vibration damping varies through intermittently reducing and restoring airflow to and from the two cavities of the primary vibration-absorbing element in proportionate to the external perturbation, which causes a reduction in the potential energy and consequently results in a decrease in the repulsion path [67]. Additionally, an adaptable pneumatic damper designed to achieve different damping characteristics through a high-precision piezoelectric valve regulating airflow between the inlet and outlet Hörbiger plates was investigated by Mikułowski et al. [68].

Similarly, various types of hydropneumatic suspension (HPS) systems have been developed for different vehicle suspension applications, including the single chamber HPS, double chamber HPS, and connected HPS [69]. Typically, HPS structures feature an external accumulator to achieve recovery characteristics, as well as a hydraulic damping system that uses a throttle valve to obtain ideal damping performance. Researchers have also proposed an HPS design with an integrated gas chamber in the cylinder, which separates the hydropneumatic medium using a floating piston or diaphragm [70]. While this structure is more compact, the floating piston presents a significant challenge for seal design. In recent years, more scholars have begun to explore the design of adjustable HPS systems to address the conflict between vehicle ride comfort and handling stability. For example, Theron and Els designed an HPS structure consisting of a hydraulic cylinder connecting the vehicle body to the unsprung mass, two nitrogen-filled accumulator springs, and two damper ports to achieve two-stage elastic force output [71]. The simulation results showed an improvement in HPS performance, although this structure could not actively adjust spring force.

Generally, pneumatic actuators are difficult to model mathematically due to their nonlinear characteristics and air thermodynamic properties occurring during compression and the fact that energy transfer and dissipation involve heat transfer which is influenced by the system's internal friction. Moreover, semiactive pneumatic shock absorbers' efficiency is theoretically very high. However, they cannot adapt and respond swiftly to system changes in real time due to the compressibility nature of air and the operational speed of the control valves. As a result, many pneumatic semiactive suspension systems feature MR and ER dampers with air springs instead [72].

For instance, Ahamed et al. designed an MR damper that combined energy generation and MR damping to achieve controllable damping force by controlling the voltage of the driving circuit to change the magnetic field strength of the excitation core [73]. While the performance of the MR damper was improved compared to traditional passive suspension, its output force range was limited due to material properties. Sun et al. changed the damping modes of the vehicle air suspension system by adjusting the states of high-speed on-off valves based on a single-cylinder shock absorber, establishing a mixed logic dynamic model with continuous and discrete system inputs and solving a constrained optimal control problem to manage the switching series of damping modes [32]. Karimi et al. achieved collaborative control of the stiffness and height of the vehicle HPS system by controlling the gas pressure in two additional air chambers of the air spring [20].

When magnetorheological (MR) dampers are used in combination with pneumatic suspension, the overall suspension performance can be significantly improved in several ways.

Firstly, the real-time adjustability of the MR dampers can enhance ride comfort by adapting to varying road conditions and driving situations. The dampers can adjust their stiffness and damping force in response to changes in the road surface, providing a smoother and more comfortable ride for passengers.

Secondly, the combination of MR dampers and pneumatic suspension can improve handling and stability during cornering and other maneuvers. The MR dampers can adjust their stiffness to provide better body control, while the pneumatic suspension can keep the vehicle level and stable, resulting in a safer and more enjoyable driving experience.

Thirdly, the combination of MR dampers and pneumatic suspension can provide better road holding by keeping the vehicle level stable over varying road conditions. The dampers and suspension can work together to absorb and dissipate energy from bumps, potholes, and other road irregularities, ensuring a stable and comfortable ride.

Fourthly, pneumatic suspension can automatically adjust the ride height of the vehicle to compensate for changes in load, while the MR dampers can further improve ride comfort and handling during load changes.

Finally, the real-time adjustability of the MR dampers can also help to reduce energy consumption by adjusting their stiffness and damping force in response to the driving situation, reducing the amount of energy needed to maintain vehicle stability and control.

2.3.3. Active Pneumatic Chassis Suspension. The active pneumatic suspension uses an onboard computer management system to control the suspension dynamics for enhanced performance. It uses sensors for the relevant signal gathering, based on which actuators are triggered to respond to the suspension needs [74–76]. The active pneumatic suspension has three main control functions; vehicle height, ride comfort, and vehicle stability control, and the actuation force direction is independent of the actuator speed. This feature enables it to control the ride height and cater to the varying vehicle body motions such as roll, pitch, and heave resulting from the longitudinal and lateral accelerations. The pressure control range of active air suspension is also widened to maintain a uniform performance quality under all loading and driving conditions. However, the generation of positive mechanical force requires a significant power input, which heavily impacts the vehicle's overall energy consumption. Figure 3 shows a schematic diagram of an active air suspension system workflow [77].

3. Air Suspension Control

Suspension controllers play a pivotal role in the successful management of both semiactive and active suspension systems. They are electromechanical units responsible for gathering all suspension system input data, based on which implementation decisions are taken to respond to the vehicle suspension needs.

3.1. Semiactive Suspension Control. Semiactive control not only requires very minimal external energy acting as a controlled force but also has been proven to be more reliable and performs more stable than active control suspension. It also operates effectively over a broader frequency range and performs more flexibly than passive control. Hence, semiactive control systems are widely employed in many vehicle suspensions [64, 78]. There are three categories of semiactive control strategies: classical control, modern control, and intelligent control. Meanwhile, semiactive controllers are only capable of varying the viscous damping coefficient of the damper but cannot generate any external actuation force [79]. Semiactive controllers are comparatively cheap to employ because the algorithms required to vary their damping coefficient are simple and stable [78]. Classical control algorithms mainly include skyhook, groundhook, and hybrid control. Also, these algorithms do not depend much on the suspension model [80–84]. Similarly, modern control methods comprise mainly of model predictive control, optimal, and robust control algorithms. Under intelligent control, neural network control, fuzzy control, and genetic algorithm are the most featured algorithms. These control algorithms are capable of eliminating or reducing the nonlinearity, time-varying, and uncertainty characteristic effects.

Industry players and academia have researched deeply into various effective ways of realizing semiactive air suspension systems. Vehicle comfort and handling were improved by connecting the air springs to auxiliary air tanks through pipelines with different parameters. Choosing a short but large diameter pipe improved the ride comfort, whereas airflow through a long but small diameter pipe stiffened the suspension and enhanced vehicle handling. Switching between configurations is achieved by simply regulating airflow through the corresponding solenoid control valves, which operate according to the prevailing road condition information acquired through a GPS [85]. In a similar development, the characteristics of a semiactive pneumatic suspension system are achieved using a magnetorheological damper. The system uses a skyhook controller that relies on GPS-obtained road condition information and vehicle velocity to arrive at a decision map to control the gas flow and the current supply to the magnetorheological dampers to realize two feasible stiffnesses, four feasible damping configurations for improved vehicle ride and handling qualities [86].

3.2. Active Pneumatic Chassis Suspension Control. Although much research has been done to improve semiactive controllers, as elaborated in the previous section, semiactive controllers still operate within a very limited scope because the damping coefficient regulation depends on a predetermined logic (optimal or heuristic), which affects its efficiency for practical application. Therefore, it necessitates the development of active controllers capable of estimating the suspension system's demands and responding promptly to satisfy the predefined control objective through an externally produced actuation force. Vehicle active suspension is a complex electromechanical system with several complex varying factors that sometimes require learnable and adaptable controllers to overcome. Researchers and engineers have explored different control theories to satisfy different control objectives for optimal and robust vehicle suspension control [87]. Most researchers working in using air springs for active vibration control have often used the air spring as a force actuator. Some researchers worked on time delay control and used air mass flow as the control input [88, 89].

A robust active suspension system capable of handling suspension nonlinearities, uncertainty in the vehicle model parameters, and preload-dependent variation was designed by Xiao et al. for transit buses [90]. Zhao et al. employed the backstepping technique to control an active air suspension ride height to converge on a neighborhood of the desired height, achieving global uniform ultimate boundedness (GUUB); the control technique required designing parameter estimators and introducing some conservativeness in the control law to dominate the unmodeled dynamics [91]. However, most control theories show very feasible results during simulation but still suffer functional problems when implemented as hardware-in-the-loop controllers. This is partly because they lack proper data processing modules to digest and accurately interpret the data to trigger actuation effectively. An active pneumatic suspension control system mainly has three control options, namely, pressure-based, ride height-based, and combo control systems.

3.2.1. Pressure-Based Control. The pressure-based electronic control system is a control system that uses the air pressure in the air spring to predict the suspension position, which then translates to the vehicle ride height. This control method relies solely on the air pressure and does not use any sensors to measure the actual suspension position. The

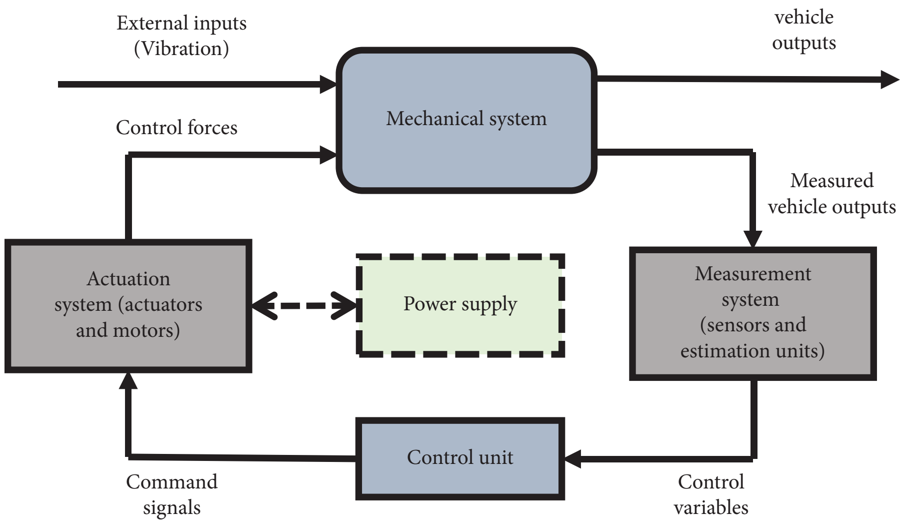

Figure 3: Active air suspension workflow.

system assumes a linear relationship between the air pressure and the ride height, and the spring rate is assumed to be constant. When the air pressure in the air spring changes, the ride height of the vehicle also changes accordingly. This control method is simple and easy to implement, but it only functions properly in reasonably well-balanced vehicles which do not experience significant load changes during operation. Meanwhile, the weight of passengers and luggage can cause fluctuations in the sprung mass of a vehicle, making it challenging to maintain a constant value. Moreover, various factors, such as road conditions and terrain, can affect the amount of air pressure needed to maintain a consistent ride height. As a result, it may no longer be reasonable to assume that a specific air pressure will always correspond to a particular ride height [92]. The equation for this control method is as follows:

$$h = \frac{p}{k}, \tag{1}$$

where h is the ride height, P is the air pressure in the air spring, and k is the spring rate. This equation assumes a linear relationship between the air pressure and the ride height, and the spring rate is assumed to be constant.

3.2.2. Ride Height-Based Control. The ride height-based system is a control system that controls the suspension based on signals gathered from individual vehicle body height sensors mounted at vantage points to directly measure the suspension's actual position. This control method uses feedback control to adjust the force applied to the suspension based on the difference between the desired ride height and the actual ride height. The damping coefficient is used to control the rate of change in the suspension position. The equation for this control method is

$$F = k\left(\frac{h\,\text{desired}}{h\,\text{actual}}\right) + c\left(\frac{\mathrm{d}h\,\text{actual}}{\mathrm{d}t}\right), \tag{2}$$

where F is the force applied to the suspension, k is the spring rate, h desired is the desired ride height, h actual is the measured ride height, c is the damping coefficient, and dh actual/dt is the velocity of the suspension.

As a result, a much better control response is achieved, and the performance is not hampered when the sprung mass varies. However, a ride height-based control system is prone to suffering cross-loading. This is a condition where the ride height is achieved radically by overinflating the horizontal corner air springs far more than the other springs, thus exceeding the acceptable side-side air pressure variation range of 20% maximum. When this happens, even though the correct ride height is achieved, the vehicle handling will be badly compromised [93, 94].

3.2.3. Combo. This control method combines the feedback control of the ride height-based system and the feedforward control of the pressure-based system. The spring rate for the suspension is based on both the ride height and the air pressure in the air spring, and the damping coefficient is used to control the rate of change of the suspension position. By combining both control methods, the combo system achieves a better control response and is less prone to cross-loading than the ride height-based system. It also has a broader system control range, resulting in optimum active pneumatic suspension performance and empowering vehicle users to choose their preferred configuration to meet all driving demands [95, 96].

Most modern vehicles are equipped with active pneumatic suspension systems that include self-leveling, raising, and lowering functions. These features prevent the vehicle from sagging when carrying heavy loads or towing, reducing air drag and enhancing safety during high-speed driving. Electronic control air suspension (ECAS) height adjustment function in trucks makes loading and unloading operations easier. Additionally, adjusting the height of the third axle according to momentary requirements can significantly improve the performance and driving properties of a truck as well as reduce tire wear [97–100]. Figure 4(a) illustrates

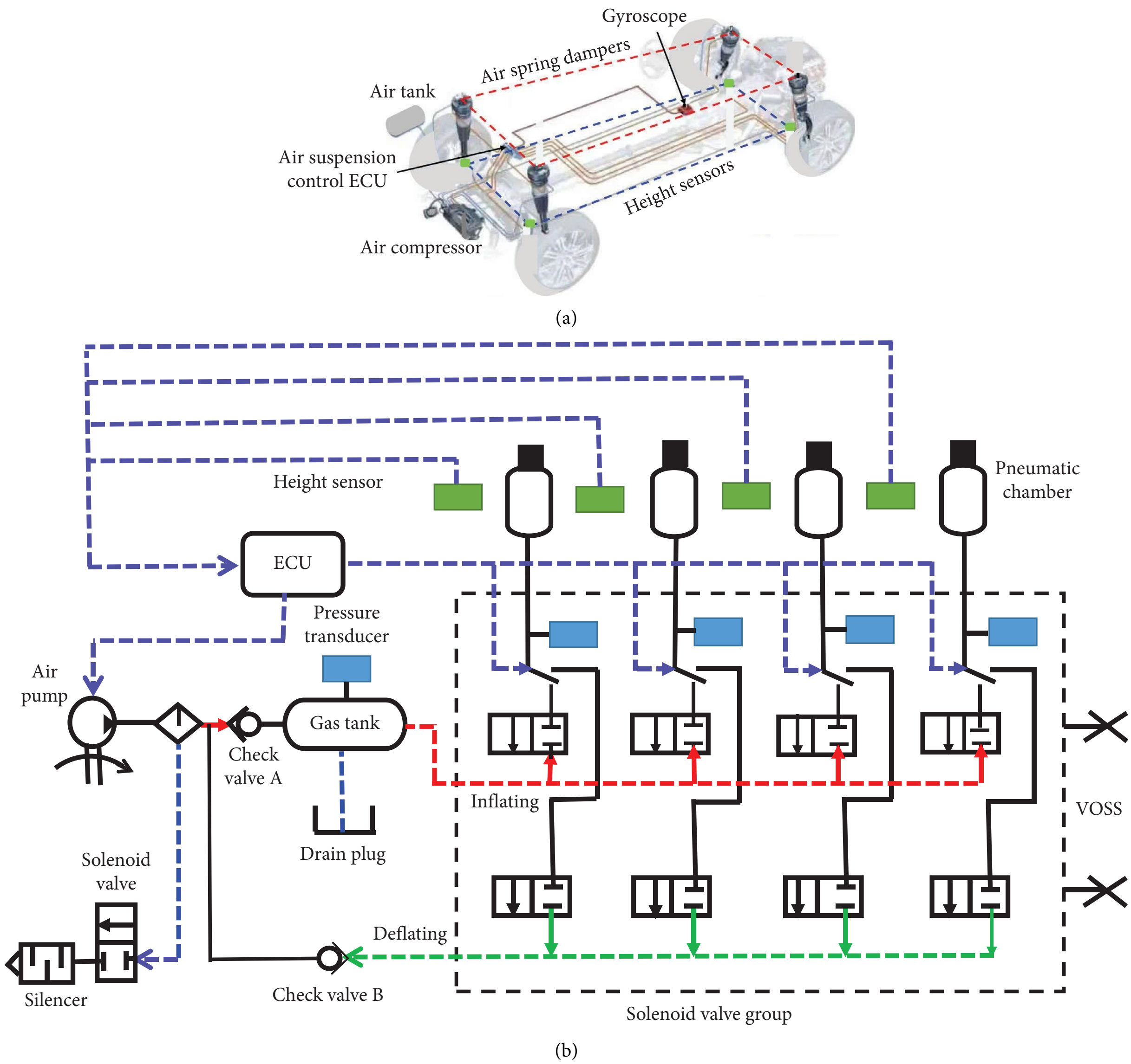

FIGURE 4: (a) Schematic diagram of the electronically controlled air suspension system. (b) Layout of the active air suspension system using air spring dampers.

a classical schematic diagram of ECAS vehicle height adjustment based on the static equilibrium position state observation algorithm [101]. Figure 4(b) also depicts the layout of the air suspension system using active air spring dampers [20].

Typically, ride height adjustment is achieved by charging and discharging compressed air into and from air springs. These air springs contain variable mass systems, which involve aero-thermodynamic and vehicle dynamic processes. When equipped with self-leveling functionality, the vehicle body can be suspended more softly, leading to improved driving comfort, while maintaining ground clearance under all loading conditions. Additionally, track or camber changes are avoided when the vehicle is laden, and the ball joints experience less wear due to reduced working angles [91, 102]. This type of air suspension control provides vehicle users with the flexibility to adjust the vehicle's height as required to meet their loading and driving needs. At the cutting edge of active suspension systems lies the ABC (Active Body Control) system, which is currently in series production in the Mercedes CL and S Class. This system compensates for pitch and roll forces and effectively controls body vibrations caused by road roughness [103].

Extensive research has been conducted on advanced pneumatic suspension systems. For example, an ADAM software-created basic air suspension model was explored, relying on air spring performance curves measured at various air pressures and corresponding displacements to define suspension positions at all wheels. Leveling valves were used to regulate suspension stiffness and maintain vehicle ride height [104]. Yin et al. developed a novel way to control suspension stiffness and vehicle ride height to suit different driving and loading conditions [92]. They achieved this through a tuning submanagement system that regulates accumulators and a double-acting air cylinder. Eskandary et al. studied and experimentally validated an optimized air suspension design capable of tuning suspension stiffness and ride height [20]. They based the design optimization on a careful analysis of the suspension system, arriving at mathematical equations that determine the optimum accumulator volume and equilibrium air chamber pressures necessary to maintain the desired vehicle height regardless of the load. Bouvin et al. studied a two-degree quarter car pneumatic self-leveling suspension model using the Commande Robuste d'Ordre Entier (CRONE) approach to improve system robustness and stability while minimizing parameter requirements and offering a high degree of design specification freedom [105].

Previous studies developed and tested a full car nonlinear model for an electronic air suspension (EAS) on a city bus [106, 107]. They used a charging/discharging gas mass variation system to define the air spring thermodynamic behavior and fuzzy sliding mode control (FSMC) to establish the optimal control law to manage the vehicle height and minimize pitching and rolling effects on vehicle stability. Xu et al. used a variable structure technique and fuzzy control theory to design a hierarchical controller that manages an electronic air suspension [102]. They first mathematically modeled the system to ascertain ride height decentralized control and the vehicle's body dynamics centralized control parameters, relying on three-point sensor signals to describe the degree and rate at which the vehicle pitching and rolling angles deviate to assign the corresponding control laws. In parallel development, Sun et al. designed a novel vehicle height management system of an electronic air suspension (EAS) using mixed logical dynamical modeling (MLD) and hybrid theory [108]. They took into account the solenoid valves' on-off and charging/discharging gas mass variations and related vehicle body dynamics.

Further studies explored the hybrid approach in the electronic air suspension to control vehicle height and reduce rolling and pitching angles during height adjustment operations [32, 109, 110]. They obtained a mixed logical dynamical model (MLD) using the hybrid system description language (HYSDEL) to define suspension characteristics. The electronic air suspension functions can easily destabilize the vehicle body position due to the possibility of the air springs being overly charged/discharged, especially when reaching the set height. To control this phenomenon, Yin et al. designed a robust control system using the finite-time approach to convert the system's nonlinear behavior to a linear model through a third-order integral chain that can better describe the real dynamics of the air suspension for optimal control and stability [111]. Another robust control design for electronic air suspension is reported in the literature [112], where the authors aimed to improve the conventional proportional integral derivative (PID) controller by exploiting the seeker optimization algorithm (SOA) and the crowd search algorithm for optimal control parameters. They achieved robust and quick controller response time with a minimal overshoot in a novel transverse interconnected electronic control air suspension (TIECAS) system.

Traditional control systems for ECAS (electronic-controlled air suspension) have been found to have some limitations, such as control overshoot and delayed control response time. Control overshoot happens when the control system causes the suspension system to overshoot the desired ride height, resulting in uncomfortable or unsafe driving conditions. Delayed control response time means that there is a lag between the time when a command is given to the suspension system and when the suspension system actually responds to the command. To overcome these limitations, researchers have explored various approaches, including hybrid and integrated adaptive control systems. These systems combine different control strategies and algorithms to achieve better performance and stability. However, despite extensive research, achieving a perfect electronic-operated air suspension system remains a challenge. Table 1 provides a summary of some chassis pneumatic suspension systems. It can be a useful reference for understanding the characteristics and performance of different types of suspension systems, which can be helpful for engineers and researchers working on designing and improving suspension systems.

4. Pneumatic Cabin Suspension of Heavy Vehicles

Ride comfort in heavy commercial vehicles, off-road vehicles, and agriculture tractors is considerably enhanced by cabin suspension and cabin damping separately from the chassis suspension. Also, air suspension is one of the most effective vibration isolation systems suitable for providing the needed comfort for drivers of such vehicles, thus reducing driver fatigue and improving driving safety [123]. In some applications, such as construction trucks, tractors, and other agriculture vehicles where metallic springs are used for road-chassis vibration isolation, the cabin subsuspension system mostly relies on pneumatic springs for optimal vibration isolation [124–126]. Farm tractors' vibration isolation was improved by installing two hydropneumatic suspensions at the cabin's two rear mounting positions and a semiactive optimal control algorithm [123–125].

Since the inception of pneumatic springs in cabin suspension, various modules have been explored and developed. Longa et al. conducted a study to compare the performance of different suspension systems in heavy trucks, specifically the hydropneumatic suspension system with rubber and leaf spring suspension systems, in terms of cab ride comfort [124]. The study analyzed the root mean square (rms) acceleration of the vertical cabin, pitch angle, and roll angle of the cabin. The results showed that the hydropneumatic suspension system significantly reduced these parameters compared to the rubber and leaf spring suspension systems, indicating that the hydropneumatic suspension system provided better ride comfort. Other studies have also investigated the performance of suspension systems in heavy trucks. For example, some studies analyzed the impact of the hydropneumatic suspension system on the ride quality of a truck on different road surfaces, loads, and speeds [127, 128]. Another study proposed dynamic models

Table 1: Summary of chassis pneumatic suspension systems.

References	Type	Innovation	Summary
[113]	Patent	Vibration damper and pneumatic suspension system	A self-actuating pneumatic vibration damper with an air spring and a defined air chamber
[114]	Patent	Pneumatic self-leveling suspension damper	A damper with a pumping chamber that expands and contracts in response to normal road undulations to inflate the air chamber
[115, 116]	Article	Dynamic analysis of the hydropneumatic front axle suspension of agriculture tractor	A tractor front axle hydropneumatic suspension with single-acting cylinders and automatic level control
[117]	Patent	Combination of the chassis frame and pneumatic suspension for vehicles	The invention is a simplified chassis frame incorporating essential parts of the pneumatic suspension in the forming process
[118]	Patent	Pneumatic suspension	The design involves an articulated component located on the air-spring cover near the air-spring bellows, which allows pivotal displacement when under pressure and forms a second air-spring loop that extends substantially in a radial direction
[119]	Article	Adaptive sliding mode control-based nonlinear disturbance observer for active suspension with pneumatic spring	An adaptive sliding mode controller based on nonlinear disturbance observer (NDOB) for improved passenger comfort and safety
[120]	Patent	Suspension control valve arrangement for a pneumatic suspension system of a commercial vehicle	The design includes supply and delivery ports, an exhaust port, a service valve arrangement, and an operation control mechanism for switching the service valve arrangement modes
[121]	Article	Design and performance analysis of the hydropneumatic suspension system for a novel road-rail vehicle	A multicylinder hydropneumatic suspension system, modeled based on in-plane multibody dynamic and road models, to adapt to rough terrains and enhance the vehicle ride performance
[122]	Article	Modeling and characteristics of hybrid coupling hydropneumatic suspension for a seven-axle vehicle	The system includes a hybrid coupling scheme of parallel connection and contralateral cross-linking based on the characteristics of high centroid position and low rollover threshold on hydropneumatic suspension (HPS) for a seven-axle elevated platform vehicle

of traditional and new air suspension systems to compare their performance in reducing negative impacts on the road surface [128]. Additionally, some studies developed models to evaluate the effects of suspension systems on road surface friendliness and to analyze and evaluate the performance of air suspension systems with semiactive fuzzy control [129, 130].

Furthermore, some studies have developed models to control the cab's isolation system of heavy trucks using a fuzzy logic controller. For instance, one study established a 3D dynamic model with 13 degrees of freedom to control the cab's isolation system of heavy trucks using a fuzzy logic controller [131]. Moreover, the ride comfort of an agriculture tractor was improved using a linear quadratic Gaussian semiactive hydropneumatic suspension model, which was found to be a better vibration isolator compared to a passive cab suspension based on the ISO 2631 ride comfort index [124]. These studies highlight the importance of pneumatic suspension systems in heavy trucks and the need to optimize their performance for better ride comfort and road surface friendliness. A summary of some pneumatic cabin suspension system studies and patents is shown in Table 2.

Summarily, several studies have investigated the performance of suspension systems in heavy trucks and their impact on ride comfort and road surface friendliness. These studies have proposed dynamic models of different suspension systems, evaluated their effects on the road surface, and developed models to control the cab isolation system of heavy trucks. The findings of these studies provide valuable insights into the design and optimization of suspension systems for heavy trucks, which can lead to better ride comfort and reduced negative impacts on road surfaces.

Notwithstanding these achievements, the research gaps identified in the current literature including the need for more advanced control strategies and the need for more field studies are directly related to improving pneumatic suspension. The development of more advanced control strategies for pneumatic suspension can improve its precision and efficiency, leading to better ride comfort and reduced negative impacts on road surfaces. Similarly, more field studies can help to validate the findings of laboratory tests and provide a more accurate assessment of the performance of pneumatic suspension in actual operating conditions. This can lead to better optimization of pneumatic suspension for heavy trucks and further improvements in ride comfort and road surface friendliness. Additionally, evaluating the impact of pneumatic suspension on other aspects of heavy truck performance, such as fuel efficiency and maintenance costs, can help to ensure that the overall performance of the vehicle is optimized. Therefore, addressing these research gaps can help to improve the design and optimization of pneumatic suspension for heavy trucks, leading to better performance and increased safety.

5. Pneumatic Seat Suspension

Due to the harsh conditions in which off-road vehicles, especially construction trucks and agriculture vehicles, are designed to work, their chassis suspension systems are usually very tough and stiff and unable to isolate vibration effectively [138]. Therefore, exposing the drivers/operators to unending whole-body vibration, most often emanating from road surface unevenness, leads to severe health problems and lost productive hours [139]. According to ISO 2000, the vibration felt in a typical earth-moving machine vehicle usually occurs at frequencies from 0 to 20 Hz. Many vehicles in this category are now fitted with an air seat suspension to reduce these vibrations and their related consequences to the barest minimum [140].

Vehicle seat suspensions are mainly categorized as passive, semiactive, and active accordingly. Considerable research work has been carried out in these respective categories. Passive suspension systems are generally very simple and cheap, comprising mainly a spring and an ordinary damper [141]. In [142], a passive seat suspension for rigid frame dump trucks was proposed, where the vibration isolation was improved using an air spring with auxiliary volume. The feasibility of enhancing the vibroisolation properties of a passive seat suspension with an air spring and shock absorber was explored in [143]. The main limitation of conventional passive seat suspension, comprising a spring with positive stiffness and damper element arranged parallelly, is that it cannot effectively isolate low-frequency vibrations. Also, the vibration isolation effect of linear isolators is usually felt when the excitation frequency is more than $\sqrt{2}$ times its natural frequency [144]. To further enhance driver comfort, many researchers in the recent past studied semiactive seat suspension, which uses dampers (magnetorheological MR and electrorheological ER) with variable force-speed characteristics, functioning as partial actuators [145]. Driver comfort was enhanced using a magnetorheological (MR) elastomer-based isolator [108]. Deng et al. [146] designed a semicontrolled variable stiffness and variable damping (VSVD) rotary MR damper seat suspension. Also, in [147], the impact protection of a seat suspension with an MR damper was studied. Although semiactive dampers require very low power consumption hardware to implement, they still need a power input to actuate their modulating devices.

Similarly, some researchers have given attention to exploring active seat suspension, which largely depends on one form of a mechanical actuator or the other, such as hydraulic, electromagnetic, or pneumatic actuators. According to [148], a primary controller for horizontal vibration isolation was proposed for a seat suspension relying on pneumatic muscles. Using a scissor-like design and an optimally controlled rotary electric motor actuator, the literature [138, 149–151] reports studies on commercial vehicles' active seating vibration reduction systems. Also, employing an electromagnetic linear actuator and a filtered-x least-mean-square (FXLMS) adaptive control algorithm, Gan et al. [152] developed a seat with active actuation force for enhanced occupant comfort. Ali et al. [153] simulated a 13-degree-of-freedom (DOF) seat system with a biodynamic model of a pregnant woman; the seat was controlled using a genetic algorithm-optimized PID controller. Although the active seat suspension systems offer maximum comfort, they are very sophisticated and comparatively

Table 2: Summary of pneumatic cabin suspension systems.

References	Type	Innovation	Summary
[132]	Patent	Pneumatic suspension system for a truck tractor	A longitudinal movable suspension support member with an underneath air spring mounted between the parallel frame members of the truck-tractor support plate
[93]	Article	Vibration isolation analysis and optimization of commercial vehicle cab suspension system	Genetic algorithm optimization design method for enhanced vibration isolation
[133]	Patent	Truck cab suspension system	The design comprises air springs, a hydraulic shock absorber, and a height control valve. Also, the system can be fine-tuned to isolate vibrations and still provide adequate stiffness.
[134]	Patent	Vehicle cab suspension system design	The design balances out the twisting force impact on the cab frame by positioning two air springs on either side of the vehicle centerline under the sill and two shock absorbers aligned along the vehicle centerline between the air springs
[135]	Patent	Controlled truck cab suspension system	The invention comprises an air strut and a control module for sensing the distance between the cab and truck frame and selectively pressurizing the air spring in response to changes in that distance
[136]	Article	Simulation analysis of cab mounting system of flat-head truck	Performance evaluation of pneumatic cab mount using ADAMS software
[137]	Patent	Cab suspension systems and associated methods of manufacture and use	An integrated control system using a single vehicle controller (ECU) to control all cabin suspension components

Table 3: Summary of pneumatic seat suspension systems.

References	Type	Innovation	Summary
[158]	Patent	Vehicle seat with a device for controlling a pneumatic suspension system	The design comprises a directional-control valve that regulates airflow to and from the air spring
[159]	Patent	Seat suspension assembly	The pneumatic seat suspension, comprises upper and lower support members (connected with scissors linkages), a pneumatic spring, a height adjuster, a dump valve, and a safety rollover valve which ensures air is released from the pneumatic spring to lower the seat position when it approaches an angle of about 80 degrees from the horizontal
[160]	Patent	Seat suspension	The system comprises a hydraulic bag with a valve orifice, a partially filled reservoir with lower and upper orifices, and a baffle to impede flow
[161]	Article	Position control of seat suspension with minimum stiffness	Generated control criteria considering the position and velocity variability in operating an immanently unstable "negative" stiffness mechanism
[162]	Article	Analysis of vibro-protection characteristics of pneumatic relaxation seat suspension with the capability of vibration energy recuperation	The system comprised a pneumatic motor recuperator activated by using airflow from one additional volume to another installed in air piping between additional volumes
[163]	Article	Vibration control of an active horizontal seat suspension with a permanent magnet synchronous motor	The system describes the control design of an active horizontal seat suspension with an electromagnetic actuator
[164]	Article	A novel negative stiffness magnetic spring design for vehicle seat suspension system	The system employs a couple of columnar magnets to design a negative stiffness magnetic spring (NSMS)
[165]	Article	A systematic literature review of various control techniques for active seat suspension systems	The study proposed a predictive model controller for active vibration control of seating suspension systems
[166]	Article	A comparative study of transmissibility factors of traditional and pneumatic dumper seats using one-third octave band analysis	The study presented an analysis of seat vibrations of two different types of dumpers in opencast mines

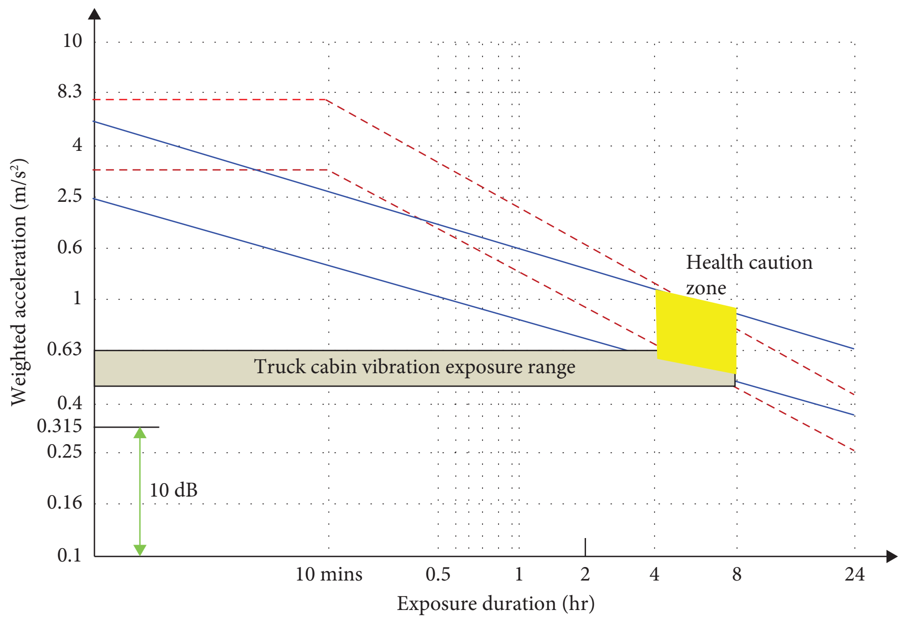

Figure 5: Health guidance caution zones for vehicle occupants.

expensive. Also, the generation of positive mechanical force requires a significant power input, which heavily impacts the vehicle's overall energy consumption. Furthermore, active seat suspension systems are challenging to model and are prone to failure.

Though conventional passive suspension systems with linear isolators are poor at isolating low-frequency vibration, another method of optimizing vibration isolation in the low-frequency band while avoiding the cost and complications associated with active seat suspension is the negative stiffness suspension (NSS) technology. NSS is a nonlinear vibration isolation system with high static and very low dynamic stiffness characteristics, giving it the advantage of achieving a wider displacement range around the equilibrium position. The force transmissibility of a quasi-zero vibration isolation system using the harmonic balance approach was analyzed and experimented with in [154]. Also, in the work of [155], a nonlinear low-frequency isolation model was realized, using a pneumatic cylinder through the mechanical structure of a wedge and cam-roller springs mechanism. Ahn et al. designed a vibration isolation system for a vehicle seat that conformed to QZS theory; they investigated an active system incorporating a pneumatic actuator in the same direction as the sprung mass displacement and parallel with the spring providing stiffness under static conditions [156]. Palomares et al. studied a negative stiffness mechanism using a pair of double-effect pneumatic actuators and a positive stiffness pneumatic spring [157]. A summary of some pneumatic seat suspension system studies and patents is shown in Table 3.

Despite these advancements, there are still research gaps that need to be addressed. For instance, further research is required to optimize the performance of pneumatic suspension systems by reducing energy consumption and increasing their reliability. More experiments are also needed to evaluate the performance of these suspension systems under different operating conditions and in different types of vehicles. Overall, pneumatic seat suspension systems show promise in improving driver comfort, and continued research and development could lead to more efficient and effective systems.

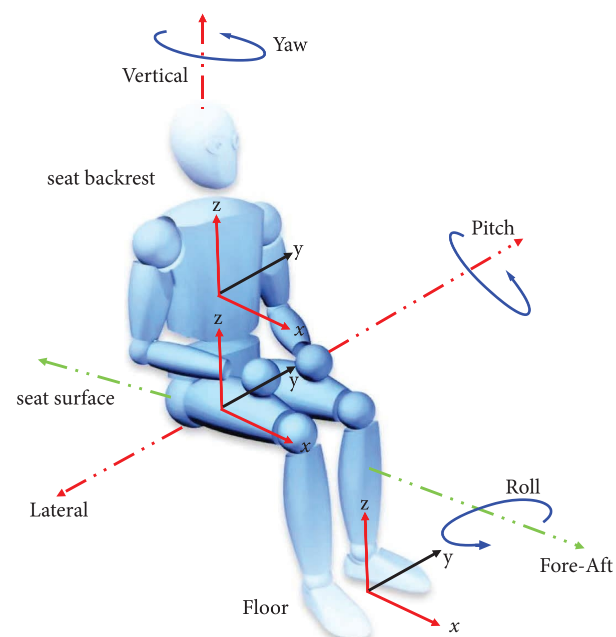

Figure 6: Vibration transmission paths in a seated person.

6. General Summary

In order to achieve effective vibration isolation, it is important to ensure that an isolator's natural frequency (fn) is less than 50% of the lowest disturbing frequency (fe). When fe is close to or coincides with the natural frequency of the

Table 4: A comparison of three pneumatic suspension systems.

	Advantages	Disadvantages
Passive	(i) Much simpler in design and configuration (ii) Comparatively cheaper (iii) Very reliable (iv) No actuator is required	(i) Relies solely on the air spring's natural frequency for vibration isolation (ii) Not effective at low-frequency band vibration isolation (iii) A compromise between ride comfort and vehicle handling
Semiactive	(i) Better vibration isolation over a broader frequency range than passive pneumatic suspension (ii) Cheaper and more reliable than active suspension (iii) Requires very little external energy (iv) Simple design configuration compared to active pneumatic suspension	(i) Vibration isolation is not effective in overall frequency ranges (ii) Cannot add energy to the suspension system (iii) Relatively complex and more expensive than passive pneumatic suspension
Active	(i) Optimal ride comfort and vehicle handling (ii) Adapts to all road conditions (iii) Better vehicle stability under all loading conditions (iv) Self-leveling functions (v) Offers different suspension stiffness to meet driver demands (vi) Adjustable ride height	(i) Comparatively expensive than both passive and semiactive suspension (ii) Increases the overall vehicle power consumption (iii) Complex design configuration (iv) Prone to failure due to several sensors and control demands

supporting structure, it can cause consequential effects. Metallic spring suspension systems can only effectively isolate vibrations above 5 Hz, as their lowest natural frequency is around 2.5 Hz. However, low-frequency vibrations below 5 Hz, especially in the vertical direction, can be particularly hazardous to seated humans. In contrast, pneumatic spring suspensions have a lower natural frequency of about 1.5 Hz, making them effective at isolating vibrations below 5 Hz. Vehicles equipped with pneumatic suspension (passive, semiactive, or active), whether as the main chassis vibration isolator, cabin floor, or driver seat subsystem vibration isolator, are more likely to offer better ride comfort that falls within the acceptable limits of the health guidance caution zone graph, as shown in Figure 5. To illustrate the importance of effective vibration isolation, Figure 6 depicts the vibration transmissibility paths of a seated person in a moving vehicle. Both figures demonstrate that vibration isolation plays a crucial role in protecting the health of vehicle users. Meanwhile, Table 4 presents a summary of the merits and demerits of passive, semiactive, and active pneumatic suspension systems.

7. Conclusion, Challenges, and Future Research Direction

Pneumatic vehicle suspension is a type of vibration isolation system that utilizes air springs instead of traditional metallic springs. This technology has been in use for several decades and has been applied to various areas of the vehicle where vibration isolation is needed, resulting in improved comfort and reduced unsprung weight. This study provides a comprehensive review of the evolution of air suspension's technological advancement and performance optimization since its introduction in the automotive industry. The review covers its application across a wide range of vehicle types, including small luxurious cars, buses, trucks, and off-road vehicles. Furthermore, the study investigates the installation of air suspension systems in different parts of the vehicle, such as the chassis, cabin, and seat suspension systems, respectively. The objective is to provide insights into the advancements and benefits of air suspension technology for the automotive industry.

7.1. Air Spring Modeling. Air spring modeling is an essential area of pneumatic suspension study that is categorized into four main types: thermodynamic, analytical, mechanical/phenomenological, and finite element models. While these models are widely used, there are still research gaps that need to be addressed to improve their accuracy. In thermodynamic models, one research gap is investigating the air spring's lateral characteristics and using alternative methods to collect input parameters. Meanwhile, analytical models require further research in investigating the effect of material characteristics on the air spring's behavior and developing more accurate geometrical-based models. For mechanical or phenomenological models, there is a need to investigate the nonlinearity of the suspension air spring and develop more accurate models that account for this nonlinearity. Finally, in finite element models, there is a need to develop more efficient and user-friendly software and investigate the linkage of these models to multibody simulations to improve their accuracy.

Overall, there is a need to synergize research efforts to develop a holistic understanding of air spring modeling. Integrating the research gaps identified in each of the modeling categories will result in a more comprehensive and accurate air spring model that can be used to develop better suspension systems.

7.2. Chassis. The article provides an in-depth overview of the research conducted on advanced pneumatic suspension systems, with a particular emphasis on electronic air suspension (EAS) and electronic-controlled air suspension (ECAS). These studies have focused on developing innovative techniques to regulate suspension stiffness, enhance ride height, and reduce rolling and pitching angles during height adjustment operations, to improve vehicle stability and passenger comfort. To achieve these goals, researchers have employed various approaches, including mathematical modeling, fuzzy sliding mode control (FSMC), mixed logical dynamical modeling (MLD), and robust control systems. These techniques have been proven to be effective in enhancing the performance of electronic-operated air suspension systems and reducing unwanted oscillations and vibrations.

However, irrespective of the significant progress in this field, there are still some limitations that need to be addressed. For instance, control overshoot and delayed control response time can lead to unstable vehicle behavior, which may affect occupants' comfort and safety. Therefore, future research can focus on developing more advanced control systems that can overcome these limitations and achieve better performance and stability for electronic-operated air suspension systems. Overall, the research conducted on advanced pneumatic suspension systems, especially EAS and ECAS, has made remarkable progress in enhancing vehicle stability, passenger comfort, and safety. With continued research, we can expect to see further improvements in the performance and reliability of electronic-operated air suspension systems, leading to better driving experiences and increased safety on the roads.

7.3. Cabin. Summarily, several studies have investigated the performance of suspension systems in heavy trucks and their impact on ride comfort and road surface friendliness. These studies have proposed dynamic models of different suspension systems, evaluated their effects on the road surface, and developed models to control the cab's vibration isolation system of heavy trucks. The findings of these studies provide valuable insights into the design and optimization of suspension systems for heavy trucks, which can lead to better ride comfort and reduced negative impacts on road surfaces.

Notwithstanding these achievements, the research gaps identified in the current literature include the need for more advanced control strategies and the need for more field studies, which are directly related to improving pneumatic suspension. The development of more advanced control strategies for pneumatic suspension can improve its precision and efficiency, leading to better ride comfort and reduced negative impacts on road surfaces. Similarly, more field studies can help to validate the findings of laboratory tests and provide a more accurate assessment of the performance of pneumatic suspension in actual operating conditions. This can lead to better optimization of pneumatic suspension for heavy trucks and further improvements in ride comfort and road surface friendliness. Additionally, evaluating the impact of pneumatic suspension on other aspects of heavy truck performance, such as fuel efficiency and maintenance costs, can help to ensure that the overall performance of the vehicle is optimized. Therefore, addressing these research gaps can help to improve the design and optimization of pneumatic suspension for heavy trucks, leading to better performance and increased safety.

7.4. Seat. The article also provides an overview of pneumatic suspension systems used in vehicle seats. These suspension systems use pneumatic actuators to isolate vibrations and improve driver comfort. The review highlights various research works that have been conducted on the design and optimization of these suspension systems. For example, researchers have explored the use of pneumatic muscles and rotary electric motor actuators to control horizontal vibrations. Electromagnetic linear actuators and filtered-x least-mean-square adaptive control algorithms have also been used to develop active seat suspension systems. Additionally, researchers have investigated negative stiffness suspension technology using pneumatic cylinders and wedge and cam-roller springs mechanisms.

Despite these advancements, there are still research gaps that need to be addressed. For instance, further research is required to optimize the performance of pneumatic suspension systems by reducing energy consumption and increasing their reliability. More experiments are also needed to evaluate the performance of these suspension systems under different operating conditions and in different types of vehicles. Overall, pneumatic suspension systems show promise in improving driver comfort, and continued research and development could lead to more efficient and effective systems.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Vincent Akolbire Atindana was responsible for the write-up of the main manuscript. Xing Xu offered academic guidance and supervision in structuring the entire paper. Andrews Nanzie Nyedeb and James Kwasi Quaisie assisted in gathering the relevant literature. Jacob Kwaku Nkrumah and Samuel Passim Assam edited the manuscript.

References

[1] M. J. Griffin and J. Erdreich, *Handbook of Human Vibration*, Acoustical Society of America, New York, NY, USA, 1991.

[2] M. Fritz, "Estimation of spine forces under whole-body vibration by means of a biomechanical model and transfer functions," *Aviation Space and Environmental Medicine*, vol. 68, no. 6, pp. 512–519, 1997.

[3] L. Burström, T. Nilsson, and J. Wahlström, "Whole-body vibration and the risk of low back pain and sciatica: a systematic review and meta-analysis," *International Archives of Occupational and Environmental Health*, vol. 88, no. 4, pp. 403–418, 2015.

[4] D. G. Wilder, A. R. Aleksiev, M. L. Magnusson, M. H. Pope, K. F. Spratt, and V. K. Goel, "Muscular response to sudden load: a tool to evaluate fatigue and rehabilitation," *Spine*, vol. 21, no. 22, pp. 2628–2639, 1996.

[5] E. Thalheimer, "Practical approach to measurement and evaluation of exposure to whole-body vibration in the workplace," *Seminars in Perinatology*, vol. 20, no. 1, pp. 77–89, 1996.

[6] J. H. Kim, M. Zigman, L. S. Aulck, J. A. Ibbotson, J. T. Dennerlein, and P. W. Johnson, "Whole body vibration exposures and health status among professional truck drivers: a cross-sectional analysis," *Annals of Occupational Hygiene*, vol. 60, no. 8, pp. 936–948, 2016.

[7] S. Cinquemani, M. Cutini, G. Abbati, G. Meloro, and E. Sabbioni, "Experimental assessment of the effect of different tires on comfort of construction truck operators," *Special Topics in Structural Dynamics*, vol. 5, pp. 249–257, 2019.

[8] M. Demić, J. Lukić, and Ž. Milić, "Some aspects of the investigation of random vibration influence on ride comfort," *Journal of Sound and Vibration*, vol. 253, no. 1, pp. 109–128, 2002.

[9] I. J. Tiemessen, C. T. Hulshof, and M. H. Frings-Dresen, "An overview of strategies to reduce whole-body vibration exposure on drivers: a systematic review," *International Journal of Industrial Ergonomics*, vol. 37, no. 3, pp. 245–256, 2007.

[10] S. Wen, M. Z. Q. Chen, Z. Zeng, X. Yu, and T. Huang, "Fuzzy control for uncertain vehicle active suspension systems via dynamic sliding-mode approach," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 47, no. 1, pp. 24–32, 2017.

[11] Y. Huang, J. Na, X. Wu, X. Liu, and Y. Guo, "Adaptive control of nonlinear uncertain active suspension systems with prescribed performance," *ISA Transactions*, vol. 54, pp. 145–155, 2015.

[12] F. Zhao, S. S. Ge, F. Tu, Y. Qin, and M. Dong, "Adaptive neural network control for active suspension system with actuator saturation," *IET Control Theory and Applications*, vol. 10, no. 14, pp. 1696–1705, 2016.

[13] D. Ning, H. Du, S. Sun, W. Li, and W. Li, "An energy saving variable damping seat suspension system with regeneration capability," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 10, pp. 8080–8091, 2018.

[14] H. Du, W. Li, and N. Zhang, "Integrated seat and suspension control for a quarter car with driver model," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 9, pp. 3893–3908, 2012.

[15] M. Devdutt, "Active vibration control of passenger seat with HFPIDCR controlled suspension alternatives," *International Journal of Mechanical and Mechatronics Engineering*, vol. 10, no. 5, pp. 916–923, 2016.

[16] K. Wang and F. Gao, *Vibration Isolation Analysis and Optimization of Commercial Vehicle Cab Suspension System*, SAE International, Warrendale, PA, USA, 2018.

[17] A. S. Al-Ogaili, A. Q. Al-Shetwi, T. Sudhakar Babu et al., "Electric buses in Malaysia: policies, innovations, technologies and life cycle evaluations," *Sustainability*, vol. 13, no. 21, Article ID 11577, 2021.

[18] A. Goodarzi and A. Khajepour, "Vehicle suspension system technology and design," *Synthesis Lectures on Advances in Automotive Technology*, Morgan and Claypool Publishers, vol. 1, no. 1, pp i–77, California, CA, USA, 2017.

[19] R. S. Sharp and D. A. Crolla, "Road vehicle suspension system design- a review," *Vehicle System Dynamics*, vol. 16, no. 3, pp. 167–192, 1987.

[20] P. Karimi Eskandary, A. Khajepour, A. Wong, and M. Ansari, "Analysis and optimization of air suspension system with independent height and stiffness tuning," *International Journal of Automotive Technology*, vol. 17, no. 5, pp. 807–816, 2016.

[21] P. Pradhan and D. Singh, "Review on air suspension system," *Materials Today: Proceedings*, vol. 81, pp. 486–488, 2023.

[22] K. Wittmer, O. Sawodny, and K.-U. Henning, "Model-based estimation of vehicle center of gravity height and load," *Journal of Dynamic Systems, Measurement, and Control*, vol. 145, no. 5, Article ID 51001, 2023.

[23] J.-J. Chen, Z.-H. Yin, X.-J. Yuan, G.-Q. Qiu, K.-H. Guo, and X.-L. Wang, "A refined stiffness model of rolling lobe air spring with structural parameters and the stiffness characteristics of rubber bellows," *Measurement*, vol. 169, Article ID 108355, 2021.

[24] F. Löcken and M. Welsch, "The dynamic characteristic and hysteresis effect of an air spring," *International Journal of Applied Mechanics and Engineering*, vol. 20, no. 1, pp. 127–145, 2015.

[25] R. Zhou, B. Zhang, and Z. Li, "Dynamic modeling and computer simulation analysis of the air spring suspension," *Journal of Mechanical Science and Technology*, vol. 36, no. 4, pp. 1719–1727, 2022.

[26] L. Q. Sun, Z. X. Li, X. F. Shen, and J. Y. Zhu, "Simulation and test study on dynamic characteristic of air spring with auxiliary chamber," *Applied Mechanics and Materials*, vol. 341, pp. 391–394, 2013.

[27] J.-J. Chen, Z.-H. Yin, S. Rakheja, J.-H. He, and K.-H. Guo, "Theoretical modelling and experimental analysis of the vertical stiffness of a convoluted air spring including the effect of the stiffness of the bellows," *Proceedings of the Institution of Mechanical Engineers- Part D: Journal of Automobile Engineering*, vol. 232, no. 4, pp. 547–561, 2018.

[28] Z. Yin, J. Jiang, and W.-B. Shangguan, "Complex stiffness model of an air spring with auxiliary chamber considering inertial effects of gas in connecting pipeline," *Proceedings of the Institution of Mechanical Engineers- Part D: Journal of Automobile Engineering*, vol. 237, no. 1, pp. 145–158, 2023.

[29] M. Bianchi, L. Branchini, A. De Pascale et al., "Application and comparison of semi-empirical models for performance prediction of a kW-size reciprocating piston expander," *Applied Energy*, vol. 249, pp. 143–156, 2019.

[30] D.-C. Wu, B. Bahrami Asl, A. Razban, and J. Chen, "Air compressor load forecasting using artificial neural network," *Expert Systems with Applications*, vol. 168, Article ID 114209, 2021.

[31] Z. Lin, Q. Wei, R. Ji, X. Huang, Y. Yuan, and Z. Zhao, "An electro-pneumatic force tracking system using fuzzy logic based volume flow control," *Energies*, vol. 12, no. 20, p. 4011, 2019.

[32] X. Sun, Y. Cai, S. Wang, Y. Liu, and L. Chen, "A hybrid approach to modeling and control of vehicle height for electronically controlled air suspension," *Chinese Journal of Mechanical Engineering*, vol. 29, no. 1, pp. 152–162, 2016.

[33] P. K. Wong, H. Wang, and J. Zhao, "Robust finite-time fault-tolerant control for vehicle height and posture regulation with air suspension system subject to actuator faults, uncertainties and external disturbance," *Nonlinear Dynamics*, vol. 111, no. 11, pp. 10113–10130, 2023.

[34] L. Gao, G. Yang, W. Li, and B. Li, "Measurement of mass flow rate and evaluation of heat transfer coefficient for high-pressure pneumatic components during charge and discharge processes," *Flow Measurement and Instrumentation*, vol. 45, pp. 391–403, 2015.

[35] P. Righettini, H. Giberti, and R. Strada, "A novel in field method for determining the flow rate characteristics of pneumatic servo axes," *Journal of Dynamic Systems, Measurement, and Control*, vol. 135, no. 4, Article ID 41013, 2013.

[36] X. Zhang, Y. Lu, Y. Li, C. Zhang, and R. Wang, "Numerical calculation and experimental study on response characteristics of pneumatic solenoid valves," *Measurement and control*, vol. 52, no. 9-10, pp. 1382–1393, 2019.

[37] L. Yang, R. Wang, R. Ding, W. Liu, and Z. Zhu, "Investigation on the dynamic performance of a new semi-active hydro-pneumatic inerter-based suspension system with MPC control strategy," *Mechanical Systems and Signal Processing*, vol. 154, Article ID 107569, 2021.

[38] Z. Sun, Y. Shi, N. Wang, J. Zhang, Y. Wang, and S. Xu, "Mechanism and optimization of a novel automobile pneumatic suspension based on dynamic analysis," *Electronics*, vol. 10, no. 18, p. 2232, 2021.

[39] L. Xu, "Mathematical modeling and characteristic analysis of the vertical stiffness for railway vehicle air spring system," *Mathematical Problems in Engineering*, vol. 2020, Article ID 2036563, 12 pages, 2020.

[40] M. Y. Wu, H. Yin, X. B. Li, J. C. Lv, G. Q. Liang, and Y. T. Wei, "A new dynamic stiffness model with hysteresis of air springs based on thermodynamics," *Journal of Sound and Vibration*, vol. 521, Article ID 116693, 2022.

[41] Y. Zheng, W.-B. Shangguan, and S. Rakheja, "Modeling and analysis of time-domain nonlinear characteristics of air spring with an auxiliary chamber," *Mechanical Systems and Signal Processing*, vol. 176, Article ID 109161, 2022.

[42] Z. Qi, F. Li, and D. Yu, "A three-dimensional coupled dynamics model of the air spring of a high-speed electric multiple unit train," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 231, no. 1, pp. 3–18, 2017.

[43] M. A. Spiroiu, "Railway vehicle pneumatic rubber suspension modelling and analysis," *Materiale Plastice*, vol. 55, no. 1, pp. 24–27, 2018.

[44] P. Pintado, C. Ramiro, A. L. Morales, A. J. Nieto, and J. M. Chicharro, "The dynamic behavior of pneumatic vibration isolators," *Journal of Vibration and Control*, vol. 24, no. 19, pp. 4563–4574, 2018.

[45] I. Mendia-Garcia, N. Gil-Negrete Laborda, A. Pradera-Mallabiabarrena, and M. Berg, "A survey on the modelling of

air springs–secondary suspension in railway vehicles," *Vehicle System Dynamics*, vol. 60, no. 3, pp. 835–864, 2022.

[46] E. Verron, R. E. Khayat, A. Derdouri, and B. Peseux, "Dynamic inflation of hyperelastic spherical membranes," *Journal of Rheology*, vol. 43, no. 5, pp. 1083–1097, 1999.

[47] E. Verron, G. Marckmann, and B. Peseux, "Dynamic inflation of non-linear elastic and viscoelastic rubber-like membranes," *International Journal for Numerical Methods in Engineering*, vol. 50, no. 5, pp. 1233–1251, 2001.

[48] A. V. Eitzen, U. Weltin, T. Brüger, T. Steinweger, and M. Flamm, "Modelling of cord-rubber composites of bellow air-springs," *Constitutive Models for Rubber VIII*, pp. 649–654, CRC Press, 2013.

[49] E. Verron and G. Marckmann, "An axisymmetric B-spline model for the non-linear inflation of rubberlike membranes," *Computer Methods in Applied Mechanics and Engineering*, vol. 190, no. 46–47, pp. 6271–6289, 2001.

[50] X. Li, Y. He, W. Liu, and Y. Wei, "Research on the vertical stiffness of a rolling lobe air spring," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 230, no. 4, pp. 1172–1183, 2016.

[51] X. Li and T. Li, "Research on vertical stiffness of belted air springs," *Vehicle System Dynamics*, vol. 51, no. 11, pp. 1655–1673, 2013.

[52] F. J. De Melo, A. B. Pereira, and A. B. Morais, "The simulation of an automotive air spring suspension using a pseudo-dynamic procedure," *Applied Sciences*, vol. 8, no. 7, p. 1049, 2018.

[53] N. Oda and S. Nishimura, "Vibration of air suspension bogies and their design," *Bulletin of JSME*, vol. 13, no. 55, pp. 43–50, 1970.

[54] M. Berg, "A three–dimensional airspring model with friction and orifice damping," *Vehicle System Dynamics*, vol. 33, no. sup1, pp. 528–539, 1999.

[55] A. Alonso, J. G. Gimenez, J. Nieto, and J. Vinolas, "Air suspension characterisation and effectiveness of a variable area orifice," *Vehicle System Dynamics*, vol. 48, no. sup1, pp. 271–286, 2010.

[56] J. Sun, "Calculation of vertical stiffness of air spring with FEM," in *Proceedings of the 4th ANSA and μETA International Conference*, BETA CAE System USA, Inc, Thessaloniki, Greece, June, 2011.

[57] S. Wenku, J. Wan, H. Ying, Y. Weimin, Y. Hao, and L. Zubin, "Finite element analysis of an air spring concerning initial pressure and parameters of cord fabric layer," in *Proceedings of the 2009 Asia-Pacific Conference on Computational Intelligence and Industrial Applications (PACIIA)*, vol. 1, pp. 496–499, IEEE, Wuhan, China, November, 2009.

[58] A. R. Bhise, R. G. Desai, R. N. Yerrawar, A. C. Mitra, and R. R. Arakerimath, "Comparison between passive and semi-active suspension system using matlab/simulink," *IOSR Journal of Mechanical and Civil Engineering*, vol. 13, no. 04, pp. 01–06, 2016.

[59] C. Min, M. Dahlmann, and T. Sattel, "A concept for semi-active vibration control with a serial-stiffness-switch system," *Journal of Sound and Vibration*, vol. 405, pp. 234–250, 2017.

[60] N. Eslaminasab, O. Vahid A, and F. Golnaraghi, "Nonlinear analysis of switched semi-active controlled systems," *Vehicle System Dynamics*, vol. 49, no. 1-2, pp. 291–309, 2011.

[61] S. Nie, Y. Zhuang, W. Liu, and F. Chen, "A semi-active suspension control algorithm for vehicle comprehensive vertical dynamics performance," *Vehicle System Dynamics*, vol. 55, no. 8, pp. 1099–1122, 2017.

[62] H. Yuan, V. Nguyen, and H. Zhou, "Research on semi-active air suspensions of heavy trucks based on a combination of machine learning and optimal fuzzy control," *SAE International Journal of Vehicle Dynamics, Stability, and NVH*, vol. 5, no. 2–0011, pp. 159–172, 2021.

[63] R. Faraj, C. Graczykowski, and J. Holnicki-Szulc, "Adaptable pneumatic shock absorber," *Journal of Vibration and Control*, vol. 25, no. 3, pp. 711–721, 2019.

[64] A. M. Bazinenkov and V. P. Mikhailov, "Active and semi active vibration isolation systems based on magnetorheological materials," *Procedia Engineering*, vol. 106, pp. 170–174, 2015.

[65] R. N. Khamitov, G. S. Aver'yanov, and A. B. Korchagin, "Operational processes in a dual-chamber pneumatic shock absorber with rapid switching," *Russian Engineering Research*, vol. 29, no. 10, pp. 974–978, 2009.

[66] K. Hiramoto, T. Yao, and K. J. U. P. Toida, *Air Damper*, USA, 1999.

[67] R. N. Khamitov, G. S. Aver'yanov, and A. B. Korchagin, "Pneumatic shock absorber with an active damping system," *Russian Engineering Research*, vol. 29, no. 9, pp. 871–873, 2009.

[68] G. Mikułowski, R. Wiszowaty, and J. Holnicki-Szulc, "Characterization of a piezoelectric valve for an adaptive pneumatic shock absorber," *Smart Materials and Structures*, vol. 22, no. 12, Article ID 125011, 2013.

[69] D. Lin, F. Yang, D. Gong, and S. Rakheja, "Design and experimental modeling of a compact hydro-pneumatic suspension strut," *Nonlinear Dynamics*, vol. 100, no. 4, pp. 3307–3320, 2020.

[70] T. Raparelli, A. Manuello Bertetto, and L. Mazza, "Experimental and numerical study of friction in an elastomeric seal for pneumatic cylinders," *Tribology International*, vol. 30, no. 7, pp. 547–552, 1997.

[71] N. J. Theron and P. S. Els, "Modelling of a semi-active hydropneumatic spring? damper unit," *International Journal of Vehicle Design*, vol. 45, no. 4, pp. 501–521, 2007.

[72] H. Safarzadeh, M. H. Djavareshkian, and A. Esmaeili, "Optimal design of magnetorheological fluid damper based on response surface method," *International Journal of Engineering*, vol. 28, no. 9, pp. 1359–1367, 2015.

[73] R. Ahamed, M. M. Rashid, M. M. Ferdaus, and H. M. Yusof, "Design and modeling of energy generated magneto rheological damper," *Korea-Australia Rheology Journal*, vol. 28, no. 1, pp. 67–74, 2016.

[74] I. Ballo, "Active vibration control systems for driver's seat of earth-moving vehicles," *Archives of Acoustics*, vol. 18, no. 2, pp. 183–195, 2014.

[75] M. Law, M. Wabner, A. Colditz, M. Kolouch, S. Noack, and S. Ihlenfeldt, "Active vibration isolation of machine tools using an electro-hydraulic actuator," *CIRP Journal of Manufacturing Science and Technology*, vol. 10, pp. 36–48, 2015.

[76] S. Razdan, P. J. Awasare, and S. Y. Bhave, "Active vibration control using air spring," *Journal of the Institution of Engineers: Series C*, vol. 100, no. 1, pp. 1–12, 2019.

[77] B. Fu, R. L. Giossi, R. Persson, S. Stichel, S. Bruni, and R. Goodall, "Active suspension in railway vehicles: a literature survey," *Railway Engineering Science*, vol. 28, no. 1, pp. 3–35, 2020.

[78] E. Guglielmino, T. Sireteanu, C. W. Stammers, G. Ghita, and M. Giuclea, *Semi-active Suspension Control: Improved Vehicle Ride and Road Friendliness*, Springer Science and Business Media, Berlin, Germany, 2008.

[79] Y. Qin, F. Zhao, Z. Wang, L. Gu, and M. Dong, "Comprehensive analysis for influence of controllable damper time delay on semi-active suspension control strategies," *Journal of Vibration and Acoustics*, vol. 139, no. 3, 2017.
[80] M. Ahmadian and N. J. J. Vahdati, "Transient dynamics of semiactive suspensions with hybrid control," *Journal of Intelligent Material Systems and Structures*, vol. 17, no. 2, pp. 145–153, 2006.
[81] D. Karnopp, M. J. Crosby, and R. A. Harwood, "Vibration control using semi-active force generators," *Journal of Engineering for Industry*, vol. 96, 1974.
[82] S. M. Savaresi, E. Silani, and S. Bittanti, "Acceleration-Driven-Damper (ADD): an optimal control algorithm for comfort-oriented semiactive suspensions," *Journal of Dynamic Systems Measurement and Control*, vol. 127, 2005.
[83] M. Valášek, M. Novak, Z. Šika, and O. J. V. Vaculin, "Extended ground-hook- new concept of semi-active control of truck's suspension," *Vehicle System Dynamics*, vol. 27, no. 5-6, pp. 289–303, 1997.
[84] Y. Qin, M. Dong, R. Langari, L. Gu, and J. J. S. Guan, "Adaptive hybrid control of vehicle semiactive suspension based on road profile estimation," *Shock and Vibration*, vol. 2015, Article ID 636739, 13 pages, 2015.
[85] A. J. Nieto, A. L. Morales, J. M. Chicharro, and P. J. Pintado, "An adaptive pneumatic suspension system for improving ride comfort and handling," *Journal of Vibration and Control*, vol. 22, no. 6, pp. 1492–1503, 2016.
[86] A. L. Morales, A. J. Nieto, J. M. Chicharro, and P. Pintado, "A semi-active vehicle suspension based on pneumatic springs and magnetorheological dampers," *Journal of Vibration and Control*, vol. 24, no. 4, pp. 808–821, 2018.
[87] H. Liu, H. Gao, and P. Li, *Handbook of Vehicle Suspension Control Systems*, Institution of Engineering and Technology, Odisha, India, 2013.
[88] Y.-H. Shin and K.-J. Kim, "Performance enhancement of pneumatic vibration isolation tables in low frequency range by time delay control," *Journal of Sound and Vibration*, vol. 321, no. 3–5, pp. 537–553, 2009.
[89] P. Chang, D. Ki Han, Y. Shin, and K. Kim, "Effective suppression of pneumatic vibration isolators by using input–output linearization and time delay control," *Journal of Sound and Vibration*, vol. 329, no. 10, pp. 1636–1652, 2010.
[90] J. Xiao, B. T. Kulakowski, and M. Cao, "Active air-suspension design for transit buses," *International Journal of Heavy Vehicle Systems*, vol. 14, no. 4, pp. 421–440, 2007.
[91] R. Zhao, W. Xie, P. K. Wong, D. Cabecinhas, and C. Silvestre, "Robust ride height control for active air suspension systems with multiple unmodeled dynamics and parametric uncertainties," *IEEE Access*, vol. 7, pp. 59185–59199, 2019.
[92] Z. Yin, A. Khajepour, D. Cao, B. Ebrahimi, and K. Guo, "A new pneumatic suspension system with independent stiffness and ride height tuning capabilities," *Vehicle System Dynamics*, vol. 50, no. 12, pp. 1735–1746, 2012.
[93] S. Wang, Z. Lu, X. Liu, Y. Cao, and X. Li, "Active control of hydropneumatic suspension parameters of wheel loaders based on road condition identification," *International Journal of Advanced Robotic Systems*, vol. 15, no. 6, Article ID 172988141881742, 2018.
[94] E. Lanzilotta, D. Harty, and W. T. Larkins, "Ride height control system and method for controlling load distribution at target ride height in a vehicle suspension system," Google Patents WO2012024137A3, 2013.
[95] J. A. Peterson, "Active suspension and adaptive damping configuration," Google Patents, 2012.
[96] X. Xu, L. Chen, L. Sun, and X. Sun, "Dynamic ride height adjusting controller of ECAS vehicle with random road disturbances," *Mathematical Problems in Engineering*, vol. 2013, Article ID 439515, 9 pages, 2013.
[97] Q. Hu, W. Lu, and J. Jiang, "Design of a vehicle height and body posture adjustment hybrid automaton of electronically controlled air suspension," *International Journal of Adaptive Control and Signal Processing*, vol. 35, no. 9, pp. 1879–1897, 2021.
[98] J. Zhao, P. K. Wong, Z. Xie, C. Wei, and F. He, "Integrated variable speed-fuzzy PWM control for ride height adjustment of active air suspension systems," in *Proceedings of the 2015 American Control Conference (ACC)*, pp. 5700–5705, Chicago, IL, USA, July, 2015.
[99] T. Keleş, L. Güvenç, and E. Altuğ, "ECU controlled intelligent lift axle dropping and lifting system for heavy trucks," *Engineering Science and Technology, an International Journal*, vol. 22, no. 3, pp. 885–893, 2019.
[100] O. U. Acar, L. Güvenç, and E. Altuğ, "Hardware-in-the-Loop testing of automatic lift dropping system for heavy trucks," *Journal of Intelligent and Robotic Systems*, vol. 98, no. 3-4, pp. 693–703, 2020.
[101] Z. Gao, S. Chen, Y. Zhao, and J. Nan, "Height adjustment of vehicles based on a static equilibrium position state observation algorithm," *Energies*, vol. 11, no. 2, p. 455, 2018.
[102] X. Xu, K. Zhou, N. Zou, H. Jiang, and X. Cui, "Hierarchical control of ride height system for electronically controlled air suspension based on variable structure and fuzzy control theory," *Chinese Journal of Mechanical Engineering*, vol. 28, no. 5, pp. 945–953, 2015.
[103] H.-P. Schöner, "Automotive mechatronics," *IFAC Proceedings Volumes*, vol. 35, no. 2, pp. 1–5, 2002.
[104] B. Sreedhar and C. Deshmukh, *A Simplified Model of Air Suspension for Multi Body Simulation of the Commercial Passenger Vehicle*, SAE International, Warrendale, PA, USA, 2013.
[105] J.-L. Bouvin, X. Moreau, A. Benine-Neto, A. Oustaloup, P. Serrier, and V. Hernette, "CRONE control of a pneumatic self-leveling suspension system," *IFAC-Papers OnLine*, vol. 50, no. 1, pp. 13816–13821, 2017.
[106] X.-Q. Sun, Y.-F. Cai, C.-C. Yuan, S.-H. Wang, and L. Chen, "Fuzzy sliding mode control for the vehicle height and leveling adjustment system of an electronic air suspension," *Chinese Journal of Mechanical Engineering*, vol. 31, no. 1, pp. 25–13, 2018.
[107] G. Zepeng, N. Jinrui, L. Lian, and X. Xiaolin, "Research on air suspension control system based on fuzzy control," *Energy Procedia*, vol. 105, pp. 2653–2659, 2017.
[108] S. S. Sun, J. Yang, H. X. Deng et al., "Horizontal vibration reduction of a seat suspension using negative changing stiffness magnetorheological elastomer isolators," *International Journal of Vehicle Design*, vol. 68, no. 1/2/3, pp. 104–118, 2015.
[109] X. Sun, Y. Cai, C. Yuan, S. Wang, and L. J. Chen, "Vehicle height and leveling control of electronically controlled air suspension using mixed logical dynamical approach," *Science China Technological Sciences*, vol. 59, no. 12, pp. 1814–1824, 2016.
[110] X. Sun, Y. Cai, L. Chen, Y. Liu, and S. Wang, "Vehicle height and posture control of the electronic air suspension system using the hybrid system approach," *Vehicle System Dynamics*, vol. 54, no. 3, pp. 328–352, 2016.
[111] C. Yin, D. Zhao, J. Zhang et al., "Body height robust control of automotive air suspension system using finite-time

approach," *Asian Journal of Control*, vol. 24, no. 2, pp. 859–871, 2022.

[112] K. Cao, Z. Li, Y. Gu, L. Zhang, and L. Chen, "The control design of transverse interconnected electronic control air suspension based on seeker optimization algorithm," *Proceedings of the Institution of Mechanical Engineers- Part D: Journal of Automobile Engineering*, vol. 235, no. 8, pp. 2200–2211, 2021.

[113] H.-J. Gilsdorf, J. Kuhnel, and M. Hurrlein, "Vibration damper and pneumatic suspension system," Google Patents, 1997.

[114] E. L. Jensen, W. C. Kruckemeyer, T. A. Miller, R. G. Smith, and M. L. Oliver, "Pneumatic self leveling suspension damper," Google Patents, 2003.

[115] A. A. Mazhei, A. A. Uspenskiy, and V. G. Ermalenok, *Dynamic Analysis of the Hydro-Pneumatic Front Axle Suspension of Agriculture Tractor*, SAE International, Warrendale, PA, USA, 2006.

[116] E. Zheng, X. Zhong, R. Zhu et al., "Investigation into the vibration characteristics of agricultural wheeled tractor-implement system with hydro-pneumatic suspension on the front axle," *Biosystems Engineering*, vol. 186, pp. 14–33, 2019.

[117] G. Rene, "Combination chassis frame and pneumatic suspension for vehicles," Google Patents, 1959.

[118] C. Lühmann, T. Höppner, and O. Jurk, "Pneumatic suspension," Google Patents, 2003.

[119] C. M. Ho, D. T. Tran, and K. K. Ahn, "Adaptive sliding mode control based nonlinear disturbance observer for active suspension with pneumatic spring," *Journal of Sound and Vibration*, vol. 509, Article ID 116241, 2021.

[120] M. Repela and P. Zak, "Suspension control valve arrangement for a pneumatic suspension system of a commercial vehicle," Google Patents, 2021.

[121] B. Qin, R. Zeng, X. Li, and J. Yang, "Design and performance analysis of the hydropneumatic suspension system for a novel road-rail vehicle," *Applied Sciences*, vol. 11, no. 5, p. 2221, 2021.

[122] T. Wen-Peng, D. Jian-Ming, and X. Xin-Xin, "Modelling and characteristics of hybrid coupling hydro-pneumatic suspension for a seven-axle vehicle," *Proceedings of the Institution of Mechanical Engineers- Part D: Journal of Automobile Engineering*, vol. 235, no. 7, pp. 1892–1901, 2021.

[123] A. J. Nieto, A. L. Morales, J. M. Chicharro, and P. Pintado, "An adaptive pneumatic suspension system for improving ride comfort and handling," *Journal of Vibration and Control*, vol. 22, no. 6, pp. 1492–1503, 2016.

[124] L. X. Longa, L. V. Quynh, N. V. Liemb, B. V. Cuong, and H. A. Tand, "A comparison of ride performance of hydro-pneumatic suspension system with those of rubber and leaf suspension systems," *IOP Conference Series: Materials Science and Engineering*, vol. 914, no. 1, Article ID 012037, 2020.

[125] J. De Temmerman, K. Deprez, I. Hostens, J. Anthonis, and H. Ramon, "Conceptual cab suspension system for a self-propelled agricultural machine—Part 2: operator comfort optimisation," *Biosystems Engineering*, vol. 90, no. 3, pp. 271–278, 2005.

[126] F. Caffaro, C. Preti, M. Micheletti Cremasco, and E. Cavallo, "Three-axial evaluation of whole-body vibration in agricultural telehandlers: the effects of an active cab-suspension system," *Journal of Occupational and Environmental Hygiene*, vol. 14, no. 10, pp. 758–770, 2017.

[127] L. X. Long, D. V. Ha, L. Van Quynh, B. Van Cuong, and V. T. Hien, "Performance evaluation of a novel hydro-pneumatic suspension system of a heavy truck on ride comfort," *E3S Web of Conferences*, vol. 304, Article ID 01009, 2021.

[128] V. Q. Le, "Comparing the performance of suspension system of semi-trailer truck with two air suspension systems," *Vibroengineering Procedia*, vol. 14, pp. 220–226, 2017.

[129] K. Sim, H. Lee, J. W. Yoon, C. Choi, and S.-H. Hwang, "Effectiveness evaluation of hydro-pneumatic and semi-active cab suspension for the improvement of ride comfort of agricultural tractors," *Journal of Terramechanics*, vol. 69, pp. 23–32, Article ID 012037, 2017.

[130] W. Yue, S. Li, and X. Zou, "Investigation of semi-active hydro-pneumatic suspension for a heavy vehicle based on electro-hydraulic proportional valve," *World Journal of Engineering and Technology*, vol. 05, no. 04, pp. 696–706, 2017.

[131] N. V. Liem, Z. Jianrun, L. V. Quynh, and J. Renqiang, "Study of fuzzy control for cab's isolation system of heavy truck," *Vibroengineering Procedia*, vol. 10, pp. 309–314, 2016.

[132] J. L. Kolstad and F. L. Tagg, "Pneumatic suspension system," Google Patents, 1986.

[133] G. Tang, H. Zhu, Y. Zhang, and Y. Sun, *Studies of Air Spring Mathematical Model and its Performance in Cab Suspension System of Commercial Vehicle*, SAE International, Warrendale, PA, USA, 2015.

[134] M. A. Taylor and B. S. Puterbaugh, "Vehicle cab suspension system," Google Patents US6540038B2, 2003.

[135] M. L. Oliver, T. A. Bishop, E. L. Jensen, and W. C. Kruckemeyer, "Controlled truck cab suspension system," Google Patents WO2004018242A3, 2006.

[136] P. Li, Y. Wang, and W. Cheng, "Simulation analysis of cab mounting system of flat-head truck," *Journal of Physics: Conference Series*, vol. 1885, no. 4, Article ID 42013, 2021.

[137] T. B. Davis and W. E. Ott, "Cab suspension systems and associated methods of manufacture and use," Google Patents EP 3339067 A1 20180627, 2020.

[138] D. Ning, S. Sun, J. Zhang, H. Du, W. Li, and X. Wang, "An active seat suspension design for vibration control of heavy-duty vehicles," *Journal of Low Frequency Noise, Vibration and Active Control*, vol. 35, no. 4, pp. 264–278, 2016.

[139] R. P. Blood, M. G. Yost, J. E. Camp, and R. P. Ching, "Whole-body vibration exposure intervention among professional bus and truck drivers: a laboratory evaluation of seat-suspension designs," *Journal of Occupational and Environmental Hygiene*, vol. 12, no. 6, pp. 351–362, 2015.

[140] A. Heidarian and X. Wang, "Review on seat suspension system technology development," *Applied Sciences*, vol. 9, no. 14, p. 2834, 2019.

[141] I. Jiregna and G. Sirata, "A review of the vehicle suspension system," *Journal of Mechanical and Energy Engineering*, vol. 4, no. 2, pp. 109–114, 2020.

[142] M. W. Holtz and J. L. van Niekerk, "Modelling and design of a novel air-spring for a suspension seat," *Journal of Sound and Vibration*, vol. 329, no. 21, pp. 4354–4366, 2010.

[143] I. Maciejewski, L. Meyer, and T. Krzyzynski, "Modelling and multi-criteria optimisation of passive seat suspension vibro-isolating properties," *Journal of Sound and Vibration*, vol. 324, no. 3–5, pp. 520–538, 2009.

[144] C. Liu and K. Yu, "Superharmonic resonance of the quasi-zero-stiffness vibration isolator and its effect on the isolation performance," *Nonlinear Dynamics*, vol. 100, no. 1, pp. 95–117, 2020.

[145] M. Josee, S. Kazima, and P. Turabimana, "Review of semi-active suspension based on Magneto-rheological damper," *Engineering Perspective*, vol. 2, no. 2, pp. 38–51, 2021.

[146] L. Deng, S. Sun, M. Christie et al., "Investigation of a seat suspension installed with compact variable stiffness and damping rotary magnetorheological dampers," *Mechanical Systems and Signal Processing*, vol. 171, Article ID 108802, 2022.

[147] L. Deng, S. Sun, M. Christie, and W. Li, "Numerical study of rotary magnetorheological seat suspension on the impact protection," in *Advances in Applied Nonlinear Dynamics, Vibration and Control-2021*, vol. 1, pp. 1003–1017, Springer, Berlin, Germany, 2022.

[148] I. Maciejewski, T. Krzyzynski, and H. Meyer, "Modeling and vibration control of an active horizontal seat suspension with pneumatic muscles," *Journal of Vibration and Control*, vol. 24, no. 24, pp. 5938–5950, 2018.

[149] D. Ning, S. Sun, H. Li, H. Du, and W. Li, "Active control of an innovative seat suspension system with acceleration measurement based friction estimation," *Journal of Sound and Vibration*, vol. 384, pp. 28–44, 2016.

[150] D. Ning, S. Sun, L. Wei, B. Zhang, H. Du, and W. Li, "Vibration reduction of seat suspension using observer based terminal sliding mode control with acceleration data fusion," *Mechatronics*, vol. 44, pp. 71–83, 2017.

[151] D. Ning, S. Sun, F. Zhang, H. Du, W. Li, and B. Zhang, "Disturbance observer based Takagi-Sugeno fuzzy control for an active seat suspension," *Mechanical Systems and Signal Processing*, vol. 93, pp. 515–530, 2017.

[152] Z. Gan, A. J. Hillis, and J. Darling, "Adaptive control of an active seat for occupant vibration reduction," *Journal of Sound and Vibration*, vol. 349, pp. 39–55, 2015.

[153] S. A. Ali, H. Metered, A. M. Bassiuny, and A. M. Abdel-Ghany, *Vibration Control of an Active Seat Suspension System Integrated Pregnant Woman Body Model*, SAE International, Warrendale, PA, USA, 2019.

[154] D. Xu, Y. Zhang, J. Zhou, and J. Lou, "On the analytical and experimental assessment of the performance of a quasi-zero-stiffness isolator," *Journal of Vibration and Control*, vol. 20, no. 15, pp. 2314–2325, 2014.

[155] N. Y. P. Vo and T. D. Le, "Static analysis of low frequency isolation model using pneumatic cylinder with auxiliary chamber," *International Journal of Precision Engineering and Manufacturing*, vol. 21, no. 4, pp. 681–697, 2020.

[156] K. K. Ahn, "Active pneumatic vibration isolation system using negative stiffness structures for a vehicle seat," *Journal of Sound and Vibration*, vol. 333, pp. 1245–1268, 2014.

[157] E. Palomares, A. J. Nieto, A. L. Morales, J. M. Chicharro, and P. Pintado, "Numerical and experimental analysis of a vibration isolator equipped with a negative stiffness system," *Journal of Sound and Vibration*, vol. 414, pp. 31–42, 2018.

[158] E. Haller, "Vehicle seat having a device for controlling a pneumatic suspension system," *Google Patents*, 2012.

[159] D. J. Gryp and M. H. Toomey, "Seat suspension assembly," Google Patents, 1998.

[160] D. L. Stephens, "Seat suspension," Google Patents, 1996.

[161] C.-M. Lee, A. H. Bogatchenkov, V. N. Goverdovskiy, Y. V. Shynkarenko, and A. I. Temnikov, "Position control of seat suspension with minimum stiffness," *Journal of Sound and Vibration*, vol. 292, no. 1-2, pp. 435–442, 2006.

[162] M. Lyashenko, P. Potapov, and A. Iskaliev, "Analysis of vibroprotection characteristics of pneumatic relaxation seat suspension with capability of vibration energy recuperation," *MATEC Web of Conferences*, vol. 129, Article ID 06018, 2017.

[163] I. Maciejewski, M. Zlobinski, T. Krzyzynski, and S. Glowinski, "Vibration control of an active horizontal seat suspension with a permanent magnet synchronous motor," *Journal of Sound and Vibration*, vol. 488, Article ID 115655, 2020.

[164] L. Tu, D. Ning, S. Sun et al., "A novel negative stiffness magnetic spring design for vehicle seat suspension system," *Mechatronics*, vol. 68, Article ID 102370, 2020.

[165] M. Al-Ashmori and X. Wang, "A systematic literature review of various control techniques for active seat suspension systems," *Applied Sciences*, vol. 10, no. 3, p. 1148, 2020.

[166] B. B. Mandal, A. Bhattacharjee, S. Prajapati, and S. A. Hussain, "A comparative study of transmissibility factors of traditional and pneumatic dumper seats using one-third octave band analysis," *Noise and Vibration Worldwide*, vol. 51, no. 10, pp. 167–175, 2020.