Review

Review on Seat Suspension System Technology Development

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Abstract: This review will focus on the necessity for developing seat vibration control systems as a part of manufacturers' investigation into finding innovative methods to increase the comfort and safety of the vehicles' drivers. Operators of either on-road or off-road vehicles are regularly subjected to an extended variety of various vibration levels, especially at low frequencies. Considering that exposure to such vibration in long term has some damaging effects on driver's health, many comprehensive investigations have been carried out and researchers have proposed several measures for estimating discomfort and the suitability of various vehicles' seats such as those of trucks, cars and agricultural vehicles in operating condition. Active, passive and semi-active suspension systems are employed in vehicle seats to alleviate the harmful and damaging effects due to the transmitted vibration to the human body. In order to improve riding comfort, the operator's body displacement and acceleration must be reduced. According to the research, active suspension control systems are the best choice to reduce the transmitted vibration to the drivers' body and provide the best ride comfort in comparison with passive and semi-active systems.

Keywords: seat suspension system; vibration control; drivers' health; ride comfort; passive suspension; active suspension; semi active suspension

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1. Introduction

Nowadays, considering the advancement of different technologies, motor vehicle manufacturers have concentrated on the research to find new techniques to promote the safety and comfort of the ground vehicle operators [1]. Plenty of investigations have been carried out and researchers have proposed several criteria for estimating discomfort and the fitness of various vehicles' seats such as those of trucks, cars and agricultural vehicles in operating condition [2]. One of the challenging tasks for engineers in automotive industries is the design of the suspension system. It is crucial to design reliable, safe and convenient seats to eliminate road excitation, since transmitted vibrations to the driver's body may cause some damaging effects on their health and efficiency [3].

Truck drivers and operators of any earth-moving machine during their operation will experience a wide range of vibrations, most often originating from road surface unevenness [4]. The vibration felt in a typical earth-moving machine vehicle usually happens at frequencies from 0 to 20 Hz [5]. The results for operators are the lack of concentration, tiredness and reduction of the effectiveness of the work being conducted [6]. There is a direct link between vibration discomfort frequencies for heavy-duty vehicles and eigenfrequencies of the operator's body. Based on the conducted studies by Paddan [7], the vibration at low excitation frequencies (0.5–4 Hz) are the principal hazard causes for lumbago or a backache, which harmfully affect the mental and physical well-being of operators and travellers and decrease their working performance [8]. Most passive suspensions in normal seats are not able to isolate these low-frequency vibrations [9]. It is fully identified that vertical vibration at lower frequencies is the most dominant vibration to the driver's body which influences the ride

comfort and safety [10]. However, in order to lower the vertical vibration acceleration felt by the human body, a seat suspension system is required.

Automotive seats must provide drivers of a broad range of sizes with seating over relatively long periods of time and isolate vehicle vibration and shock transmitted to the drivers [11]. To satisfy these conditions, there has been extraordinary progress in automotive seat design during the past decade. Targets have been developed to maximize seat quality and performance and decrease driver's stress during long operating hours. An essential part of the improvement is the driver's seat, so research of seat suspension systems have become the focus of attention in all automotive and truck companies because the driver's body is connected to the vehicle by the seats and all of the vibration is transmitted to the driver's body through the seats [9,12,13].

Three methods of vibration isolation are applied to the vehicle's seats in order to decrease transmitted vibration from vehicles seat to operators' body, namely, passive [14,15], semi-active [16], and active [17,18] vibration control systems. Active vibration control is a method for decreasing unwanted vibration where some sort of sensor is adopted to measure the motion, force, acceleration, and other parameters related to vibration signals and a powered actuator is applied to generate a force to resist the unwanted motion. Passive vibration control does not employ any sensors or actuators and does not use any power; however, mechanical parts are utilised to damp undesired vibrations. The mechanical parts include spring blades, shock absorber, air cushion, etc. Semi-active systems with specific types of dampers present a better performance than passive systems and worse performance than active control systems.

All of the mentioned methods are extensively examined in order to determine the main advantages and disadvantages and to find the best solution for vibration isolation. In order to enhance vehicle seat suspension performance, active and semi-active suspensions are more efficient ways as many investigations have been implemented by researchers about these systems over the previous years. In 1974, Karnopp [19,20] started to examine the main advantages of passive, active and semi-active suspension systems and compared their performances. Based on the obtained results, the active and semi-active systems are much more efficient than the conventional passive seating system. Nonetheless, the increased price and complexity of active systems only justify their application in cases when the performance is critical, while the semi-active system can produce notable performance gains for the small extra cost [21]. The passive and active seat suspension is shown in Figure 1.
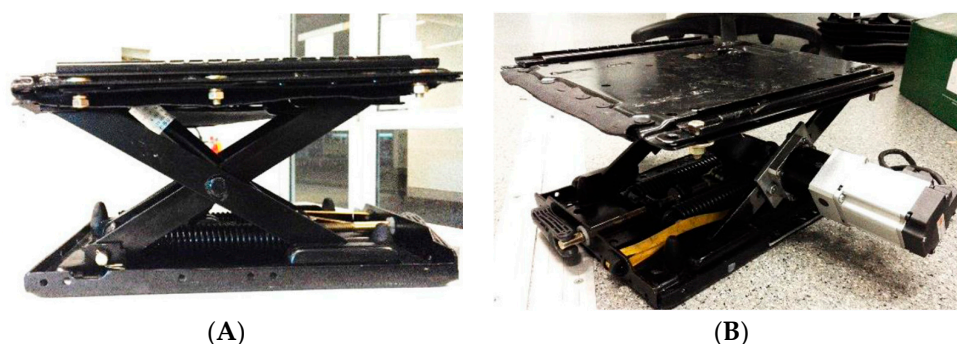

(A)   **(B)**

Figure 1. Prototype of passive seat suspension (**A**) and active seat suspension (**B**) [22].

The human body is sensitive to vibrations and the feeling of the vibration is different depending on the frequency and the direction of the vibrations [9]. By using a frequency weight, the feeling can be translated from the vibration in space to how it is felt inside the driver's brain where discomfort is recognised. The frequency weight is offered in ISO-2631 [23] and divides the sensitivity into two directions, horizontal and vertical [24]. The horizontal sensation function is used for both lateral and longitudinal accelerations. In ISO-2631, the human filter is presented as a transfer function with various sensitivities for different frequencies. In a vibrating system with only one frequency, the experienced discomfort can simply be measured by multiplying the acceleration magnitude with

the corresponding sensitivity weighting factor for that frequency [17]. In real life, the vibration mechanisms are more complex and it is impossible to define the signal using one frequency and one amplitude. By using Fourier transform, the signal can be converted to a series of trigonometric functions in the frequency domain. These trigonometric functions can be filtered individually for each frequency and amplitude and then transformed back to the time domain where an RMS value can be estimated [25]. Considering the direct relationship between the vibration exposure levels and the driver's health, it is clear that the ride comfort is fully dependent on the frequency, amplitude and exposure time duration of the transmitted vibration [26]. According to the frequency-weighting curves for single-degree-of-freedom (DOF) system vibration described in ISO 2631-1, the driver's comfort is most seriously affected by 5–8 Hz translational vibration along the *z* axis (Heave motion), 1–1.25 Hz translational vibration along the *x* and *y* axes, and 0.8 Hz rotational vibrations around three axes [27].

Usually, the isolation of the vertical vibration, which is confirmed to have the greatest vibration amplitude and affects drivers' comfort in vehicles, is recognised in designing seat suspension [28]. The whole human body system is a complex dynamic system with sophisticated mechanical characteristics. During operation of any land vehicle, the severe vibration generated by bumpy roads and the operation of the machineries generate a load which is transferred to the seat; thus, the operators regularly feel Whole Body Vibration (WBV) [29–31]. To assess human vulnerability due to transmitted vibrations in vehicles, ISO 2631-1 [23] is always utilised, which has set different ways for the analysis of Whole Body Vibration and presents guidance on the possible impacts of vibration on health, comfort, attention, and motion illness.

The objective of obtaining a biodynamic model for a seated body is to be able to predict the performance of seat design and support the suspension control system configuration [32]. Biodynamic modelling of the seated human body has attracted considerable attention in recent years, and many mathematical models ranging from 1-DOF to 11-DOF have been offered [33,34]. These models are obtained from different modelling methods, such as lumped-mass models, finite element models, and multi-body models. The lumped-mass body model can be expressed in the frequency domain as a transfer function or in the time domain as a differential equation of motion. A linear 4-DOF model of a seated human body to investigate whole-body vibration was studied by Zhou [35]. In order to model the human body seating system, Zhou prepared a model for the human bodies which contained four mass segments: the head, upper trunk, lower trunk, and thighs. Complex head–neck–torso models studying both vertical motion and rotation of the seated human body were proposed in [36–39]. However, the multiple-DOF modelling in 3D space, in particular, when studying the multiple-DOF vibrations, has not been investigated to date [40]. In addition, the model parameters should be modelled in terms of various driver bodies and postures. So, real-time classification of model parameters should be extended [41]. An innovative seating solution is vital to reach a comfortable ride, and therefore reduce driver exhaustion, by effectively decreasing undesired vibrations [42]. Vehicle seating systems have been used to reduce vibration transferred from road disturbances. However, vibrations from the driver of vehicles and machine tools have not been fully studied for most of the currently available seating systems because these vibrations may come from various directions rather than just from vertical and fore-and-aft motions [43]. Furthermore, the driver is the most significant vehicle occupant when the physical and psychological effects of vehicle vibration on the body are considered, especially in the case of commercial vehicles [44]. A driver's biodynamic responses to vehicle vibration should be focused when designing seating systems. However, combining a human body biodynamic model with a seating system design has also not been fully discussed in research to date [45]. In studies on seating systems, Because the frequency range plays a vital role in vehicle ride comfort, the head acceleration or a rigid driver and passenger body acceleration usually is considered as a performance index to evaluate ride comfort [46]. However, neither a sprung mass acceleration nor rigid body acceleration can accurately show human bio-dynamical characteristics. Studies [47–49] show that it is essential to involve a complex biomechanical model of the human body in a seated position to get a good insight into ride comfort as an essential parameter when designing a seating suspension. It is seen in

preliminary work towards this purpose that developing an integrated model that incorporates the vehicle chassis suspension, the seating system, and a human body model, and designing an integrated control system, will be important in attempts made to promote human ride comfort and safety [50,51]. Therefore, the multiple-DOF vibration reduction seating system together with the human-in-the-loop control strategy will be an innovative seating solution.

The Whole Body Vibration in terms of the body frame *x-y-z* is described in Figure 2, where the three translational vibrations are along the *x*, *y*, and *z* axes; the three rotational vibrations, which are also described as roll, pitch, and yaw motions, are around the three axes.
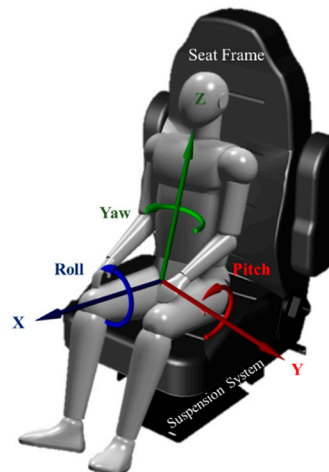

Figure 2. Whole body vibration of the seated human body.

It can be noticed that the most sensible frequencies for humans are close to those of translational vibration along the *x* and *y* axes, and those of the three rotational vibrations; however, the translational vibration amplitudes along the *z*-axis are larger than the vibration amplitudes in other DOFs at the sensitive frequencies [52]. This implies that when designing a multiple-DOF seat suspension, the yaw vibration control, which would have the weakest impact on ride comfort comparing with the vibration in other DOFs, could be neglected in order to decrease the complexity of the seat suspension configuration; the translational vibration along the *z*-axis could be decoupled from other DOFs in order to clarify the vibration control [53].

The simple vehicle seat form contains an isolation system and a seat frame, as given in Figure 2. Various techniques which have been applied in seating system designs by different researchers are explained in the following sections.

2. Passive Vibration Control Systems

Most seat suspensions utilise a passive mechanism to reduce the effect of the vehicle vibration which are created by uneven road surface on the human body. The passive suspension as a conventional suspension system contains a sprung mass with a damping shock absorber to regulate unwanted vibrations [54]. The basics of passive vibration control are shown in Figure 3 to present the fundamental concepts. A passive control system can absorb structural vibrations and remove energy from the dynamic system without an external energy source. The method is to connect the structure to elements and materials with damping characteristics that overcome vibrations. A passive system is regularly implemented with springs and dampers with time-invariant stiffness and damping coefficients [55].
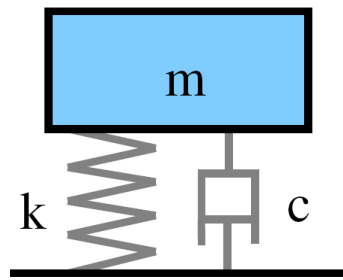
Figure 3. Single-degree-of-freedom system [56].

A conventional suspension system was chosen by Maciejewski et al. [6]. The proposed system includes a shear guidance mechanism, an air-spring, a hydraulic shock-absorber and buffers. The geometry of the seating system is shown in Figure 4. The damped vibration effect is given by the spring force coupled with the shock-absorber force. Amplification of vibration in the 0–2 Hz frequency range was mentioned [57]. At the greater frequencies, the desired performance of the seat suspension was given and vibrations transmitted by the seat were decreased significantly [58]. The pneumatic and nonlinear elements provide a condition to increased vibro-isolating features of the suspension. This kind of system is known by a relatively simple adjustment of stiffness and damping of the pneumatic suspension by setting air pressure. By adjusting the pressure inside the air spring chamber at different loads, a constant static deflection can be forced. Consequently, regulating the air pressure would lead to a change in the stiffness of the suspension system as well as its eigenfrequency [59]. Incorporating an additional air reservoir culminates in a decrement in the system stiffness and as a result lowers the natural frequency of the system. The air-spring has minimal damping; therefore, this sort of element employed to suspension systems needs an external shock-absorber. A damping force can be caused by airflow throttling between the added air reservoir and the air-spring. According to the obtained results by Maciejewski et al. [6], the modified seat suspension outstandingly promotes the vibro-isolating characteristics of the seat in the 0–4 Hz frequency range. For bigger frequencies, vibro-isolating features of both seats (conventional and modified) are nearly the same [60]. The best performance of the modified seat suspension in comparison with normal passive seats (approximately 1.3 Hz) was taken at the resonance frequency. The study by Maciejewski et al. led to a good agreement between the desired reduction in transmitted vibration to the driver's body and the opposing necessity for the reduction of seat suspension travel.
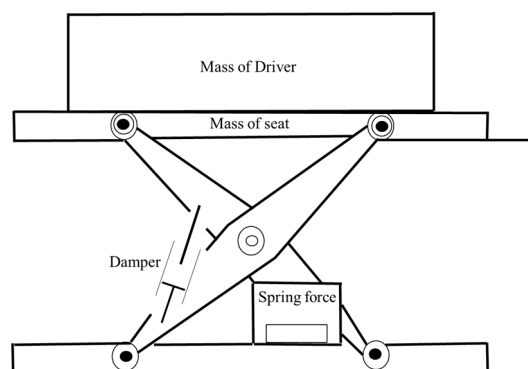

Figure 4. The main parts of the passive seat suspension [6].

3. Semi Active Vibration Control Systems

The vibration transmissibility of passive vibration isolation systems is low in some frequencies, especially in the low-frequency range. The main objective of implementation of the semi-active seat suspension systems is to find a way to reduce vibration transmissibility in the low-frequencies, in addition to the high performance at high frequencies. Semi-active suspension measures the stiffness

and damping characteristics of the isolation system and makes it possible to control the vibration in a broad vibration frequency range [61,62]. Furthermore, if the stiffness matrix of the system is positive definite, then the semi-active control systems are unconditionally stable. Besides this, semi-active systems are more efficient because of their lower power consumption in comparison with other active control systems. Adjustable damping and stiffness features in semi-active suspensions have resulted in this system having been applied in broad industrial fields such as vibration control of high-precision machinery [63], automotive suspensions [64], helicopters [65], engine mounts [66] and earthquake-response suppression [67]. Vibration isolation by semi-active control can be enhanced by employing controllable stiffness and damping systems. Semi-active devices manipulate the stiffness of the structure very quickly to turn uncontrollable stiffness systems into governable systems, and this feature makes it possible to decrease the vibration transmissibilities. With the advancement of magnetorheological (MR) or electrorheological (ER) dampers, semi-active control of seat suspension has been developed to enable variable damping force and has less power consumption than active control systems [14,68].

Oil and ferrous particles (20–50 microns in diameter) are the main components of Magnetorheological fluids [68], as shown in Figure 5. When a magnetic field is applied on the MR fluids, it affects their main characteristics, and their properties could be immediately changed or rearranged within a very short time (Millisecond). The main benefit of applying MRF Dampers is their quick response to the force variation (over 100 times per second faster response than the passive system). Furthermore, they are active and fully adjustable without consuming external power. Besides this, there are no moving parts in this system. The main disadvantage of the MRF dampers is the high cost of construction.
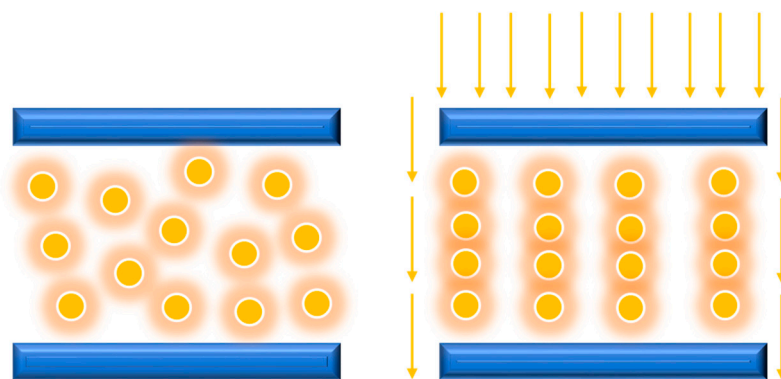

Figure 5. The mechanism of magnetorheological (MR) fluid [68].

In 2005, Gavin and Alhan [69], by implementing a series of experiments on an ER semi-active damping system, showed that using controllable damping devices is a smart way to provide low-transmissibility systems. Based on their obtained results, the minimum damping of the system is the most important parameter that regulates the acceleration transmissibility, and the controllable damping and stiffness provides more efficient vibration insulation.

The development of the magnetorheological fluid (MRF) dampers—with MRF being very sensitive the magnetic field and having low power consumption—motivates researchers to use them in order to make semi-active seat suspension systems [70]. There are many numerical and experimental investigations about semi-active seat suspensions by using MR dampers. Choi and Han [71] applied MR dampers to reduce vertical seat vibration. Another study was done by Choi and Wereley [72], where they examined the application of MR dampers that were implemented on helicopter crew seats and they reported the advantages of using a semi-active suspension system in comparison with passive systems. In order to decrease the effect of ground vehicle crashes, Bai and Wereley [73] studied semi-active magnetorheological energy absorbers of MR seat suspension in the crash. They found that the performance of semi-active seat suspension control systems partially depends on the damping force performance of MR dampers. The schematic of the MR damper is shown in Figure 6 [74].
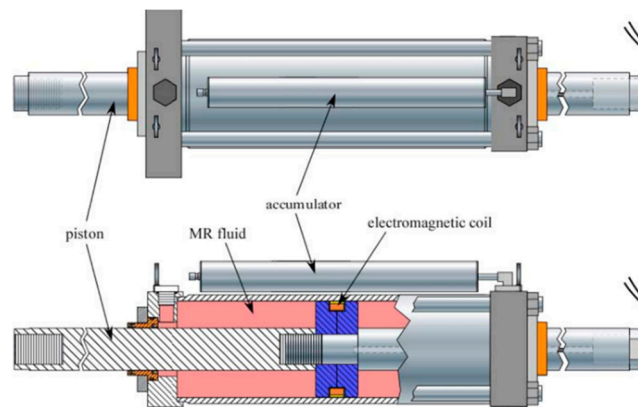
Figure 6. Schematic of the magnetorheological (MR) damper [74].

As previously mentioned, the main disadvantage of the MR dampers is the high cost of construction because of the price of the MR fluid [15,75]. In linear MR dampers, large amounts of magnetorheological fluids are needed to fill the MR fluid tank, but in a rotary damper, the required amount of MR fluid is much smaller and the cost of construction will be decreased substantially. The less MR fluid there is, the lower the cost of construction becomes [76].

One of the restrictions of using linear dampers is sealing the system [77]. As the working mechanism of the linear MR damper fully depends on the pressure difference between the two sides of the piston, it means the pressure of at least one side is high and therefore needs good sealing. On the other hand, in a rotary MR damper, the need for sealing is eliminated since the pressure in rotary dampers is quite low; thus, it is much simpler to solve the sealing problem [78]. The other problems of linear MR dampers such as sedimentation and hard adjustment are solved in rotary dampers. Compared to a linear MR damper, the rotary MR damper generates a significant reduction displacement and device compactness and requires less space for the configuration [79]. A rotary MR damper is shown in Figure 7.
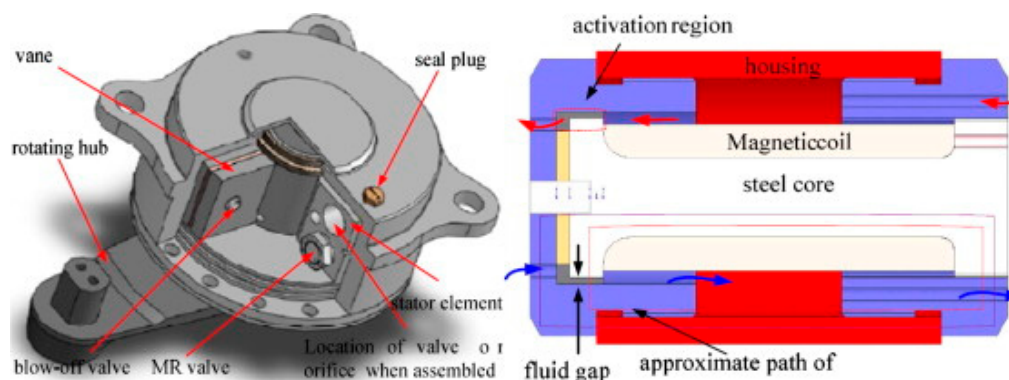

Figure 7. The structure of a MR rotary damper [79].

A novel seat suspension structure by employing a rotary MR damper was proposed by Sun et al. [80]. The structure of the proposed seat suspension system is shown in Figure 8. Based on their study, the MR rotary dampers have many advantages compared with linear MR dampers.
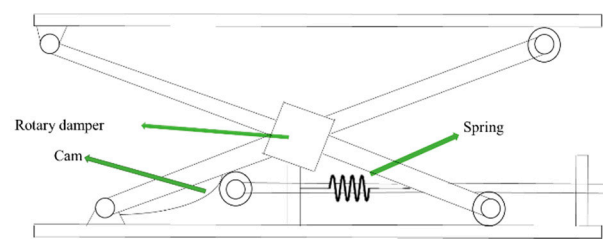
Figure 8. The structure of the seat suspension with rotary MR damper [80].

Based on the implemented experimental tests by Sun et al., they considered transmissibility as a parameter, which is the ratio of affected response acceleration to excitation acceleration. The transmissibility ratio shows whether the suspension system is efficient or not. They offered a comparison between passive and semi-active seat system acceleration and explained that the acceleration amplitude in the semi-active case is considerably decreased in comparison with passive ones. According to the obtained results in the semi-active state, the seat acceleration had the minimum value, which verified that the semi-active rotary MR damper-based seat suspension was much more efficient in decreasing the vibrations. The experimental results, as given in Figure 9, proved that the semi-active system by utilizing MR damper can efficiently decrease the transmissibility and presents the best performance over a wide frequency range.
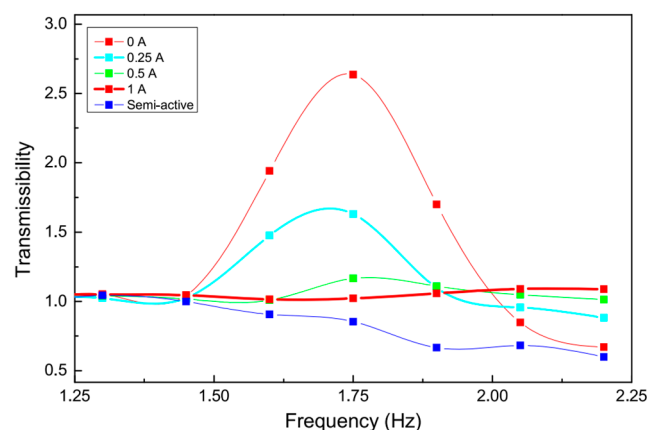

Figure 9. The experimental results of the transmissibility of the seat with MR damper [80].

Both ER and MR fluid are useful just for a small frequency range, and out of that range they will lose their efficiencies. To expand the efficient frequency range, in a study by Du et al. [24], they suggested MR elastomers (MREs). Conversely, from MR/ER fluids, magnetorheological elastomers (MREs) have controllable damping capabilities [81]. MRE is a kind of composite which is formed by magnetized particles scattered with the alliance in a solid polymer such as rubber. The elastic behaviour of an MRE grows monotonically based on the magnetic field. Simultaneous to the removal of the magnetic field, the MRE quickly returns to its primary status [82]. These unique characteristics of MREs have pointed to a variety of uses such as tuned vibration absorbers [83,84]. This novel vibration isolator has potential in utilisation where the reinforced vibration properties are wanted. Study of MRE isolators in vibration attenuation of structural systems has been done in [85–87], and a model of an MRE isolator has been constructed and experimentally examined in [88]. The efficiency of the MRE isolator depends on some significant parameters, like the relative MR effect, the material's strength and its life span. Figure 10 represents a schematic diagram of the mentioned MRE seat isolator using the fabricated MRE. As mentioned before, one of the restrictions of the MRF dampers is the cost of construction. According to the obtained results, MRE-based devices are comparatively low-priced and strong in comparison with other semi-active systems like MR dampers [81].
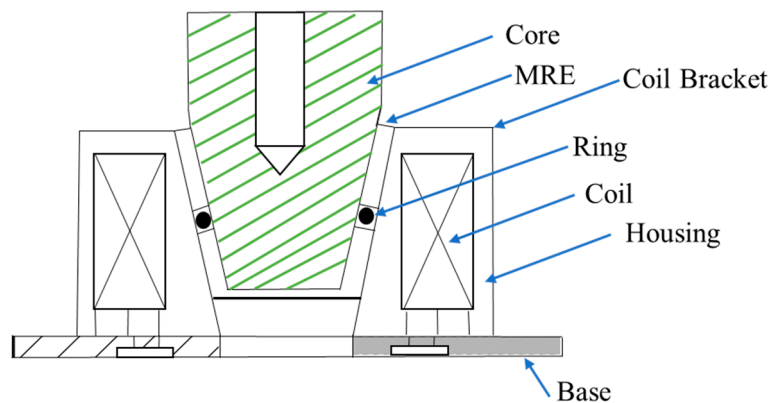
Figure 10. MR elastomer (MRE) seat isolator [81].

Another method to implement semi-active seat suspension is an energy regenerative seat suspension, which was suggested and built by Ning et al. [89]. The simplified layout of the regenerative seat suspension system is given in Figure 11. As shown, the vibration energy will be stored in a battery through a storage circuit. The regenerative shock absorber converts vibration energy into electrical energy through electromagnetic coupling and uses the electrical energy to generate electromagnetic damping force.
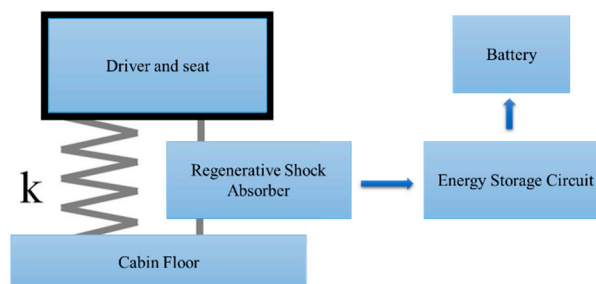

Figure 11. Schematic of the regenerative seat suspension system [89].

The mentioned system contains a changeable external resistance and a semi-active controller for vibration control. The schematic and prototype of this seat system is shown in Figure 12. The energy regenerative seat suspension consists of a pair of metal leaves that slide against each other and is located at the middle of the seat, and generator and a gear reducer ride on it. The rotary motions of the scissors structure generate energy and will directly be stored in the battery. An external variable resistor was assigned to measure the electromagnetic torque. A series of experimental and numerical evaluations were done to confirm the efficiency of the system and all of the obtained results were compared with passive seat suspension. Results showed that utilizing regenerative seat suspension fosters a 22.84% reduction in the total transmitted vibration comparing with passive system, and it clearly proves that a more comfortable ride will be experienced. Because the regenerative seat suspension shows a good performance, there is high potential to develop this system as a self-powered semi-active system.
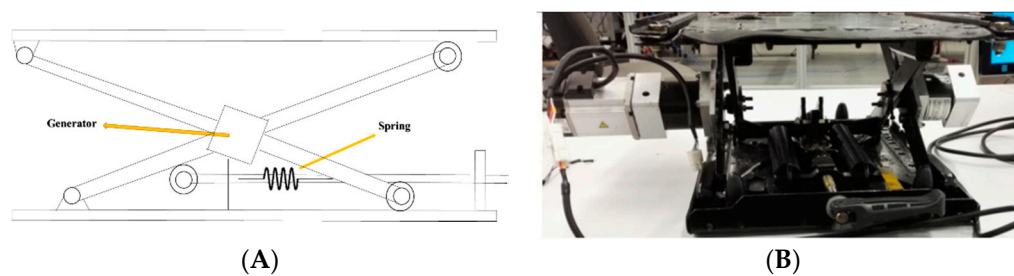
(A)　　　　　　　　　　　　　　　　　　　　　(B)

Figure 12. (**A**) Semi-active regenerative seat suspension schematic. (**B**) Seat suspension prototype [89].

4. Active Vibration Control Systems

Active suspensions are able to utilize external energy to power the system to reduce undesired oscillation through continuous control. The main goal of using the active suspensions is to reduce the effects of road conditions on the suspension travel, and bumpy road profiles do not change the efficiency of the suspension system [90]. The active suspension system is a more efficient vibro-isolating system but because of its high costs of construction and complex structure, they are applied infrequently. There are various methods for the implementation of active control systems to reduce vibration, such as using conventional linear actuators like hydraulic cylinders or linear motors, pneumatic actuators, and rotary and linear electro motors.

A system employing active vibration control has the opportunity to add and eliminate energy from the system through the use of actuators that apply force or torque to the structure. The advantage is that they are more robust and usually provide better performance. Many researches have been performed to enhance the ride comfort of passengers. The active system can generate force through the use of electric or hydraulic actuators according to the state of the system. Consequently, an external energy source is required, which results in active systems being larger, more energy-consuming and more costly than both passive and semi-active control systems. In addition to the increased complexity of the system, another disadvantage is the stability of the system in case of system failure due to faulty sensors. Time delay may occur in active suspension systems because of delay in data processing, sensors or some mechanical faults. In order to control the actuator time delay, various controllers such as Proportional Integral Derivative [91], Fuzzy [92] and Adaptive Neuro-Fuzzy Inference System (ANFIS) [93] are applied and tested to optimise the active suspension systems. In 2017, Puneet Gandhi et al. [94] designed the mentioned controllers in MATLAB for a half car active suspension model of 4 Degrees of Freedom (4-DOF) on the road of the ISO 8608 [95] random road profile. According to their obtained results, among the different controllers, the ANFIS-based controller presents the best performance in terms of 'settling time' and 'peak overshoot' in comparison with other controllers.

In 2012, Du et al. [96] designed an integrated seat suspension system by applying a controller in order to enhance suspension performance and achieve better ride comfort. Their model consists of a quarter-car suspension, a seat suspension, and 4-DOF driver body and a feedback controller as shown in Figure 13. By employing a static output feedback controller, the driver head acceleration in bumpy road conditions experienced a substantial decrease, and because of the reduction in head acceleration, the integrated seat suspension system could provide better performance in terms of ride comfort in comparison with other seat suspension systems.

Negative-stiffness elements have been known as novel mechanisms for improving vibration damping. This method of isolation employs a revolutionary concept in low-frequency vibration isolation. Danh and Ahn in 2014 [12] analyzed this mechanism comprehensively and incorporated an active pneumatic system to isolate the vibrations by applying negative stiffness for a vehicle seat in low frequencies, defining it as an active system with negative stiffness structures. Negative stiffness structure is used to decrease the absorbed vertical vibration energy by the seat. In the structure, the mass is displaced by some random amount from the primary position because of the action of the force that opposes the displacement. When the force has influence on the seat structure, it leads to

that two horizontal springs will be compressed and two vertical restoring moments act on the mass. The experimental results confirm that the isolation efficiency of the suggested system is better than that of the active system without negative-stiffness structures.
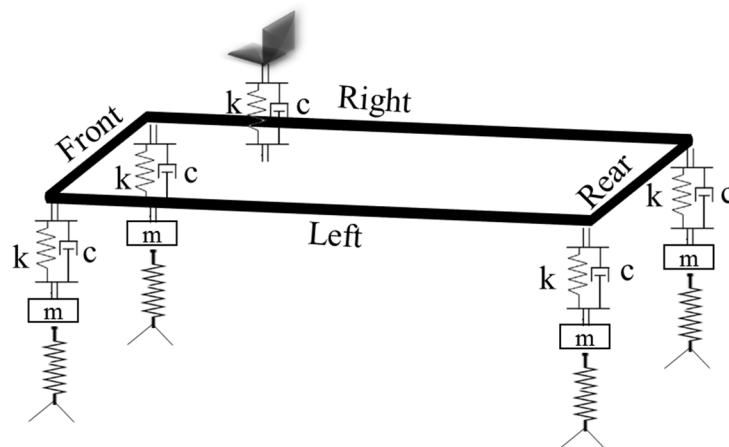

Figure 13. Integrated seat and suspension model [96].

In 2015, a project was performed by EKBERG and HANSSON [97] at the Department of Applied Mechanics at the Chalmers University of Technology in collaboration with Volvo Group Trucks Technology [98]. The main purpose of this research was to improve ride comfort by using active and semi-active suspensions, with a focus on the vertical dampers. They examined the effects of vertical dampers on the ride comfort feature of a commercial truck through the use of active and semi-active cab suspensions based on the principle of individual control of each damper separately. By this method, the restoring force mainly depends on the state of the suspension itself and is independent of the other dampers and the overall motion of the cab. The benefits of this method are that it is easy to implement and easy to overview. Figure 14 presents the truck coordinate system that was considered to study damping forces in the model coordinates, i.e., heave, roll and pitch. According to the obtained results by EKBERG and HANSSON, the active control systems improve the ride comfort regardless of the road profiles while the semi-active control systems principally work well for the road profile that induces low levels of vibration.
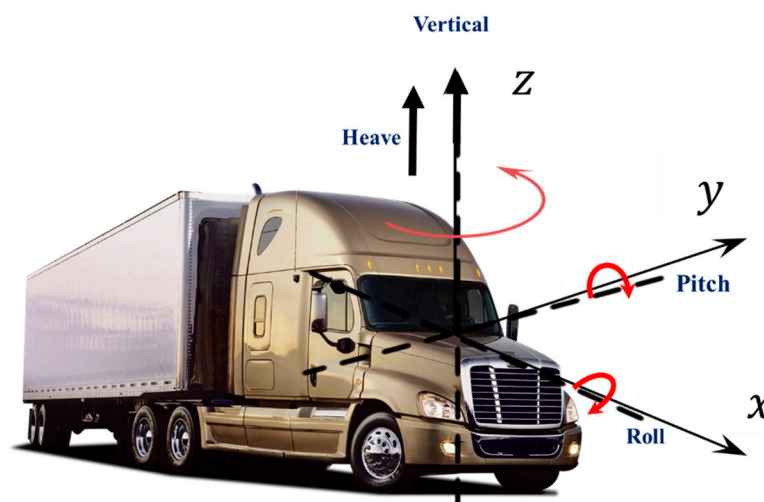

Figure 14. Pitch, roll and heave in Cab [97].

To apply a control suspension system, one of the main methods is the use of conventional linear actuators, e.g., hydraulic cylinders or linear electric motors to reduce the effects of vibration on the

human body [99]. However, one of the restrictions of this method is that they require to be fully maintained/powered and are usually expensive when large force outputs are needed. In order to overcome this limitation, Ning et al. [99] designed a seat suspension system that was able directly utilise a rotary motor to provide a reliable and efficient seat suspension system without maintaining the basic structure of the seat suspension. The idea of using an electric servomotor, as noted by Kawana and Shimogo [13], in order to reduce vibration in a truck seat was applied and they designed a ball screw mechanism as the actuator. Using an electric servomotor is simpler than implementing hydraulic or pneumatic actuators. Furthermore, its loading capacity and frequency span are appropriate for a seat vibration system. Ning et al. [99] used an electrical rotary motor to achieve this goal. These motors are applied in many industrial fields. It worth noting that other advantages of the rotary motor in comparison with linear actuators are lower price and ease of maintenance and control. By using a gear reducer, it is possible to increase a motor's torque output. Thus, a low-rated power motor can be used for active vibration control. A rotary-motor-based active seat suspension model is shown in Figure 15.
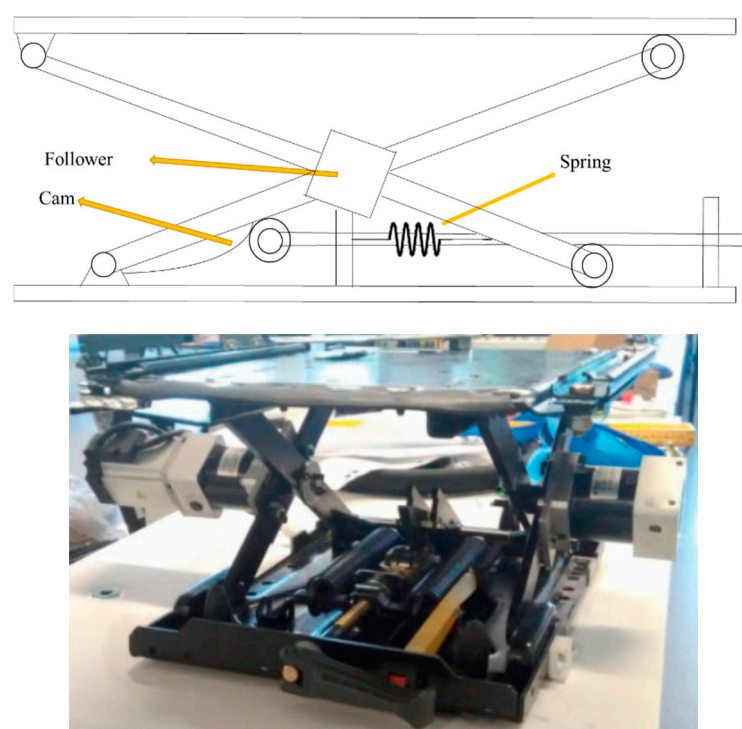

Figure 15. Active seat suspension configuration.

According to the obtained result from experimental evaluations on active seat suspension, which were done by Ning et al. [99], this system is able to overcome the vibration acceleration especially around the critical value (4 Hz). Considering that the vibrations with the greatest effect on human health in heavy-duty vehicles occur in the range of 3 to 5 Hz, active seat suspension could significantly enhance ride comfort.

As mentioned before, the idea of using an integrated seat suspension was investigated by Du et al. [96] and the results were explained. In 2018, Ning et al. [27] developed the integrated seat suspension system and tried to overcome the whole body vibration of vehicles, especially in heavy-duty ones, by designing a novel two-layer multiple-degrees-of-freedom (multiple-DOF) seat. In Figure 16, the simplified plan of the aforementioned two-layer multiple-DOF seat suspension design is shown. There are two main sections in this seat suspension: a top layer including two separately controlled rotational DOFs and a bottom layer to decrease the heave vertical motions. One of the main characteristics of this model is its ability to control the vibration of the driver's body in five DOFs, except for the yaw vibration, which interestingly has the smallest effect on

humans. The top-layer suspension is examined then its rotational stiffness and friction are recognized. In Figure 17, a constructed model of a multiple-DOF seat suspension is shown. Some experimental tests have been done in order to evaluate the interaction of the top layer and the bottom layer, and according to the obtained results, this interaction is small so it is obvious that by using this technique, the whole body vibration experienced a substantial reduction.
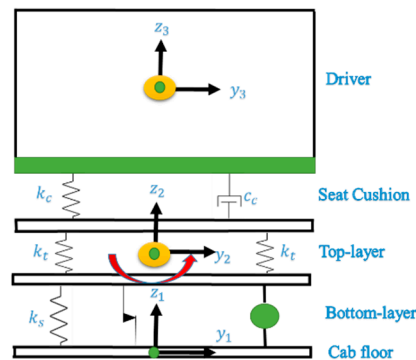

Figure 16. Schematic diagram of a two-layer multiple-degrees-of-freedom (multiple-DOF) seat suspension [53].
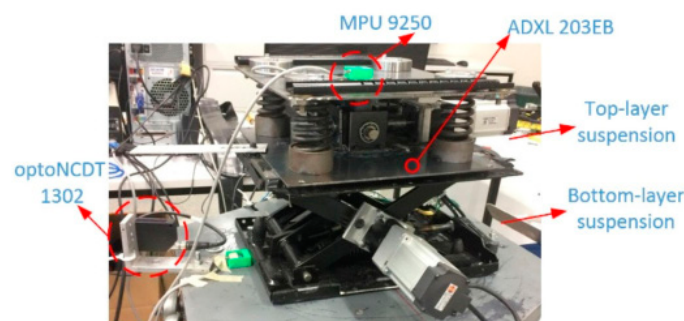

Figure 17. Multiple-DOF seat suspension prototype [53].

According to the obtained results by Ning et al. [27], when the fully controlled two-layer seat suspension is employed, the whole body vibration for roll and pitch direction decreases by 41.4% and 44.3% respectively. This multiple-DOF seat suspension will improve the driver's work condition and is effective in application.

The roll vibration will be fully transmitted to the driver's body in conventional single-DOF seat isolation systems and only the affected vibration in the vertical direction will be damped. A two-layer (integrated seat system) multiple-degrees-of-freedom seat suspension system was proposed by Ning et al. [53]. The efficacy of the multiple-DOF seat suspension system was examined by doing a series of both simulations and experimental test. The seat was constructed in two layers: the layer which is located on top of the seat is considered to be affected by vertical vibration in the z-axis, and the lower layer is designed for the roll vibration. A multiple-DOF seat suspension is shown in Figure 18, developed by Ning et al., presenting the bottom part of the multiple-DOF seat suspension as a mechanism for controlling the vertical vibration. As shown in Figure 19, a U-joint is connected to two actuators in the top layer.

In the structure of the U-joint, there are four springs in the four corners to provide rotational stiffness, which can be equal to two torsional springs in the universal joint.

An active multiple-DOF seat suspension was compared with a single-DOF active seat suspension and a conventional passive one to evaluate the impacts of transmitted vibration on health and ride comfort. Based on the collected measurement results, the total vibration of the active multiple-DOF active seat surface experienced a 29.8% vibration reduction, in comparison with the single-DOF active

one. The multiple-DOF seat suspension system could efficiently reduce the whole body vibration (WBV) of heavy-duty vehicle operators.
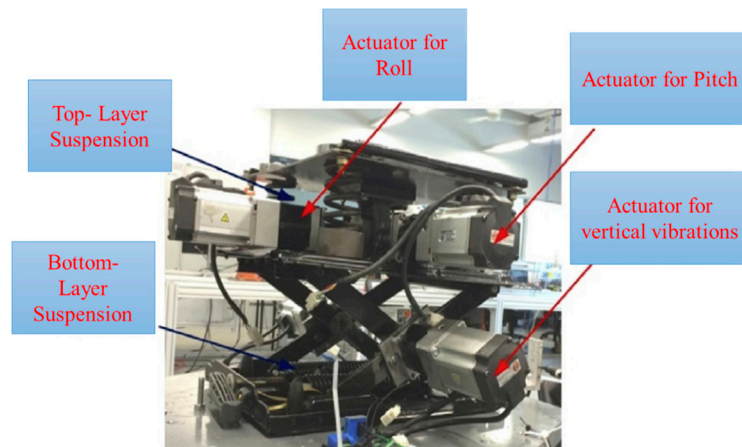

Figure 18. The prototype of multiple-DOF seat suspension [53].
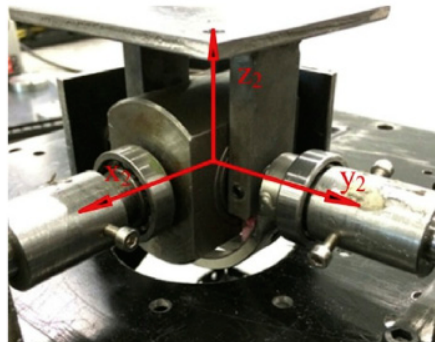

Figure 19. The geometry of universal joint [53].

Another active force control system suggested by Tahmasebi et al. [100] is the neuro active force control system. They believed this system was simple, effective and accurate. This system was designed and employed for an active seat suspension of heavy-duty vehicles likes trucks. They proved the efficiency of the neuro active force control system by doing a series of experimental tests and numerical simulations. According to the results, the neuro active force control mechanism as an intelligent control approach reduced the unwanted transmitted vibration in the driver's body.

Sliding mode control is a control scheme that changes the dynamics of a system by use of an intermittent signal. Sliding mode control is an efficient method to control nonlinear uncertainties in a system and are employed in suspension control systems. A sliding mode controller including a state observer for semi-active seat suspension was proposed by Choi and Han [49]. The terminal sliding mode controller gives some improved characteristics. Because of the improved performance of the terminal sliding mode controller in 2017, Ning et al. [22] designed a modified terminal sliding mode controller aimed for practical application. The results reveal that the frequency-weighted root mean squared (RMS) accelerations of the controlled active seat suspension had a 34.1% decrease compared with that of a passive seat suspension. The suggested control algorithm was confirmed in the simulation and experimental tests. Both the simulation and experimental results show the control algorithm effectiveness for practical application. Figure 20 presents the experimental test set-up.
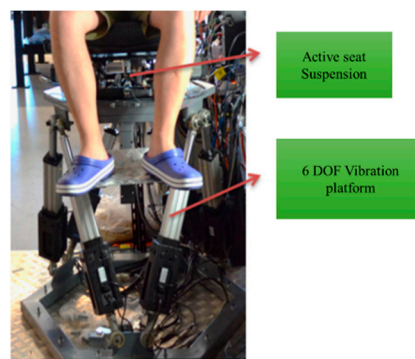
Figure 20. Experimental setup of active seating suspension system with a sliding mode controller [22].

5. Our Contributions

Our team has been working on a project which aims to develop an innovative 6-degree-of-freedom seating system for commercial vehicles, including heavy-duty trucks and equipment that are used principally in the construction of roads, bridges, ditches, and buildings, to maximise the reduction of undesired transmitted vibrations to the operator's body. We have designed, constructed and conducted experimental tests on an innovative active seat suspension system for the mentioned vehicles [99]. Our strategy to provide a safe and comfortable seat in the proposed seat suspension system is to apply a rotary motor that directly connects to the seat in order to generate the required active excitation force. It worth noting that use of the rotary motor does not need to modify the primary structure of the seat suspension. In order to amplify the generated torque of the motor, a gear reducer is utilised and makes it possible to get higher torque by employing an efficient and low-rated power motor. A static output feedback is schemed to permanently decrease seat vibration. It has been confirmed that this sort of seat suspension can obtain better ride comfort in the frequency range of 2–6 Hz in comparison with a passive seat suspension. One of the main goals of our design is to achieve a more cost-efficient active seat suspension that can be appropriate for heavy-duty trucks. A series of experimental tests have been done by our team and a 5-degree-of-freedom driver and seating system model to get the best vibration control has been developed [101]. Recently, an innovative strategy for examination of the driver seating system parameters from experimental vibration analysis has been designed. The parameter sensitivity investigation has been carried out regarding the arbitrary excitation frequency and system parameter adjustment. The maximum and minimum sensitive system parameters for the transmissibility ratio have been classified. The most efficient Proportional Integral Derivative (PID) controllers have been used to reduce the driver's body vibration. The evolved comfort and ergonomic seating system are expected to be broadly used in different types of earth-moving vehicles.

6. Conclusions

This paper presented a review of the recent development of the different seating systems for commercial vehicles such as trucks, buses, and earth-moving vehicles with a focus on state-of-the-art vibration control systems. Vibration directly affects drivers' health and performance. Designing a safe and comfortable seating system has become one of the main focuses of high-tech vehicle production companies.

A comprehensive discussion was done about the recent development of the novel control systems, and the pros and cons of all vibration control systems were presented. Passive vibration control systems might be the most dominant control system type for seats, but they are not as effective in reducing vibration, which has many damaging effects on the human body. Therefore, recent research focus has been on novel methods like active and semi-active control systems that can directly control vibration. These mechanisms might be more complex and expensive, and harder to maintain, but they are more efficient than traditional spring and damper systems.

As the active vibration control approach is associated with the reverse dynamics of the force actuator and the primary controller, studies about various methods of optimization of active control

systems—such as using motor, hydraulic and pneumatic actuators and servo motors—were reported. Advantage and disadvantages were compared and discussed. According to the acquired results, the integrated seat and suspension control system would provide the best performance in terms of ride comfort in comparison to other seat suspension systems, but it needs to be optimized to find the novel control algorithms and methods to improve the seating system performance.

The development and design of control systems in vehicle seating systems still have not overcome many obstacles such as the low frequency of transmitted vibrations to the operator's body because of the multidisciplinary nature of the environment where vehicles or trucks are operating. So our research team will try to find novel solutions to achieve a comfortable and ergonomic seating system for commercial vehicles. In Table 1, the advantages and disadvantages of three reviewed suspension systems are explained briefly.

Table 1. Comparison of the three seat suspension systems.

	Active	Semi-Active	Passive
Advantages	➢ Extensive range of force ➢ Compatible with any force and velocity ➢ Gaining better performance ➢ More efficiency	➢ Less implementation cost ➢ Lower energy use ➢ Simple control ➢ Simple design ➢ Easy to set up	➢ Simple design and configuration ➢ Lower price in comparison with other suspension systems
Disadvantages	➢ More power is needed ➢ Higher weight-to-power ratio ➢ Higher price ➢ Considerable modification should be done before setting it into the existing vehicle	➢ Damper limitation ➢ Narrow efficiency range ➢ Better performance than passive systems but performance is not as good as active systems	➢ Performance is not as good as active and semi-active systems

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