Adaptive cabin suspension systems of commercial vehicles: a review of the state-of-art and future trends

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Abstract: This paper reviews past studies on active and semi-active cabin suspension systems of commercial vehicles and highlights future research potentials. The development history of the cabin suspension is firstly introduced. Then, the three standard configurations on the market of the cabin suspension are discussed and compared, known as front, rear, and full cabin suspension systems. After that, an overview of cabin suspension control strategies in the literature is presented. Specifically, skyhook control, various optimal control, road adaptive control, and their combined approaches are discussed and compared. After thoroughly summarising past studies, some research topics which deserve further investigation are introduced.

Keywords: cabin suspension; adaptive suspension; skyhook control; optimal control; road adaptive control; cabin configuration.

Reference to this paper should be made as follows: Lu, Y., Khajepour, A., Liu, Y. and Zhen, R. (2022) 'Adaptive cabin suspension systems of commercial vehicles: a review of the state-of-art and future trends', *Int. J. Heavy Vehicle Systems*, Vol. 29, No. 1, pp.33–47.

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1 Introduction

The first truck and passenger car emerged simultaneously at the end of the 19th century (Evers, 2010). Passenger cars and buses were designed for passenger transportation which require a high level of comfort, while trucks were developed to transport goods as efficient and durable machines (Gillespie, 1985). Truck drivers are constantly exposed to undesirable vibrations caused by uneven road surfaces, especially in long-distance transportation. Extensive research has been done on lower back problems experienced by truck drivers as a result of vibrations created during driving on uneven roadways, braking, turning manoeuvres, and engine operations (Deprez et al., 2005). Quantitatively, intensive low-frequency vibrations from 0.5 to 10 Hz are transmitted to the driver seat if the road induced vibrations are in the frequency range of 2–20 Hz (Giliomee and Els, 1998; Hostens and Ramon, 2003). As a result, drivers suffer from motion injuries, such as neck and back pain. Statistically, male truck drivers are four times more likely to suffer from a herniated disk than the average male (Griffin, 1990). According to Deprez et al. (2005), lower back pain is a major cause of industrial disability in middle-aged workers and accounts for 20% of all work-related injuries. Furthermore, constant vibrations can also lead to driver fatigue and possibly have further implications on driving safety. Unsurprisingly, the negative impact on the economy is substantial. Work-related injuries experienced by truck drivers in the US results in an estimated loss of $90 billion per year (Deprez et al., 2005). The European Parliament continues to work on regulations to restrict the harm of whole-body vibration. One of the results is the Machinery Directive 89/392/EEC and its amendments of 1996 which force vehicle manufacturers to develop vibration isolation techniques to reduce the effects of noise and vibration to the lowest possible level (Donati, 2002).

Many technologies have been introduced in commercial vehicles to reduce harmful vibrations transmitted to drivers, such as seat suspension systems, cabin suspension systems, and enhanced ergonomic layouts of the cabin interior (Caffaro et al., 2017). Most seat suspension systems are designed to isolate vertical vibrations only, but operators are exposed to vibrations in all three planes. As a result, cabin suspension systems have received a lot of attention over the past two decades as they can eliminate vibrations in vertical, roll, and pitch directions.

Cabin dynamics, as well as driver's comfort during braking, accelerating and steering manoeuvres, have improved significantly over the past few decades. In the 1920s and 1930s, the first sleeper berth was developed (National Transportation Safety Board, 2014) to accommodate drivers frequently needing to pass the night in their trucks. Cabins were initially welded to the chassis frame, which resulted in an uncomfortable ride experience. No further changes were made to the truck cabin suspension until the 1960s. The rubber mounts used between the chassis frame and the cabin substantially improved ride comfort. In the same period, the first tilt cabin was invented. It is still one of the standard configurations used today because the tilt structure greatly facilitates the drive-line inspection (Evers, 2010). During the 1970s and 1980s, various steel and air springs were used to refine the cabin suspension design. Looking back at history, truck manufacturers put a lot of attention and effort toward enhancing drivers' ride comfort.

In general, the human body is sensitive to the disturbance frequency in the range of 4–8 Hz (Fritz et al., 2005). According to Hiromatsu's research (1993), the resonance frequency of the chassis frame vibration is generally around 2 Hz, and the resonance frequency caused by the frame bending is around 6 Hz. Thus, the disturbance frequency higher than 1 Hz should be eliminated in order to maintain a good ride comfort. The natural frequency of the conventional passive cabin suspension cannot be lower than 2 Hz because of the mechanical limitation on the stroke length which can only suppress the disturbance frequency higher than 5 Hz (Hiromatsu et al., 1993). Hence, it is necessary to develop controllable suspension systems in order to eliminate vibrations in the frequency range from 1 Hz to 5 Hz. In this paper, several representative active and semi-active cabin suspension systems are reviewed and discussed.

The rest of the paper is organised as follows: Section 2 introduces three standard cabin configurations designed and used in recent years; Section 3 gives a thorough review and discussion of the adaptive cabin suspension systems in the literature; and Section 4 summarises the past studies and recommends future research topics.

2 Cabin suspension configurations

Compared to a passenger car, a truck usually has two suspension systems, the primary and the secondary (cabin) suspensions (Cole, 2001). The secondary suspension system mainly acts as a vibration isolation system between the cabin and the rest of the vehicle. It is designed to improve ride comfort by minimising undesired vibrations in the cabin without compromising the vehicle handling and stability performances. In general, there are three types of the cabin suspension arrangements: front, rear, and full (Tong and Amirouche, 1998). In the USA, most tractor semi-trailers are equipped with the rear cabin suspension, and the full cabin suspension is commonly used in Europe (Roy, 2015).

2.1 Front cabin suspension

In the front cabin suspension system, as shown in Figure 1(a), the front side consists of springs and shock absorbers. The rear part is pinned to the chassis frame which allows small pitch and vertical movements. However, this arrangement is hard to install, because the flexible control linkages are needed and the crashworthiness results in additional constraints on the front cab isolators (Flower, 1978). Nevertheless, the front cabin suspension system can effectively attenuate vertical vibrations and reduce the fore-aft motion. It can be considered by cabin-over-engine (COE) tractor manufactures as an alternative option to the full suspended cabin suspension.

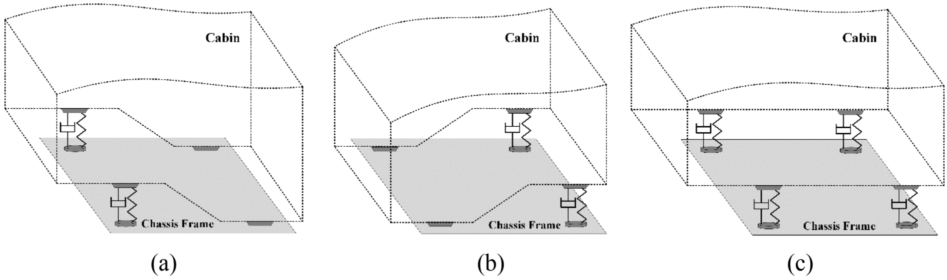
2.2 Rear cabin suspension

The rear cabin suspension configuration, as shown in Figure 1(b), is widely used in the commercial vehicle industry because it is rather easy to install. Normally, the cabin's forepart is pinned to the chassis frame, while the rear part is equipped with coil or air springs and shock absorbers. The guiding mechanism usually includes transverse arms, a Panhard rod, and/or two lateral dampers (Gross and Van Wynsberghe, 2001). Note that the suspension damping property is mainly constrained by stroke length, and the stiffness is highly related to cabin's vertical and pitch natural frequencies (Roy and Law, 2016). In general, the natural frequency of the cabin suspension with air springs often lies in 1~1.4 Hz (Patricio, 2002), and that with steel springs lies in 1.8~3 Hz (Foster, 1978). Moreover, the rear cabin suspension attenuates the backslap since the cabin is partially decoupled from the frame bending, but it increases vertical vibrations at the same time (Flower, 1978). Due to the relatively low roll stiffness, the truck steering manoeuvre results in additional roll motion, as well as increased pitch motion when braking or accelerating. This results in a major drawback of the cabin suspension system which is the poor attitude behaviour. In early years, the roll motion was limited by using a stiff anti-roll-bar; however, this was once again a source of discomfort for the driver (Evers, 2010). Based on this configuration, the tilt cabin gains a lot of attention in industry which is easy to install and facilitates the drive-line inspection. A useful review of the tilting cabin mechanism can be found in Dadhania et al. (2016).

2.3 Full cabin suspension

In an effort to further improve heavy-truck drives' ride comfort, the full (4-point) cabin suspension system emerged. As shown in Figure 1(c), all the four corners are installed with coil (Jiang et al., 2019) or air springs (Groß and Jolibert, 2001) and dampers. Its guiding mechanism generates a small radial movement which causes the fore-aft movement (Gross and Van Wynsberghe, 2001). Nowadays, lateral shock absorbers are sometimes used in addition to stabilisers in order to further optimise cabin's roll dynamics (Lin et al., 2012; Ahmadian and Patricio, 2004). Air springs are widely used in the full cabin suspension system. In this case, the height levelling system is required, which normally consists of external valves, linkage component, and pipelines to connect between airbags and air supplies. It is able to maintain a constant suspension natural frequency despite changes in the cabin load. Besides, the cabin titling function can be achieved by using a front tilting arrangement (Jain, 2007), by which the cabin can be tilted up to 45 degrees for chassis maintain purposes (Achanta et al., 2020). The full-floating arrangement provides the best ride quality because of its potential for improving ride comfort in vertical, roll, and pitch directions. Meanwhile, it improves crash safety and reduces the dynamic forces at mounting points (Gross and Van Wynsberghe, 2001). Hence, the full cabin suspension system is frequently equipped in heavy vehicles nowadays (Ribeiro et al., 2013) and upgraded to various adaptive suspension systems.

Figure 1 Cabin suspension configurations: (a) cabin front suspension; (b) cabin rear suspension and (c) cabin full suspension



(a) (b) (c)

3 Adaptive cabin suspension systems

Although the passive full cabin suspension system shows great potentials in improving ride comfort and various tuning methods have been investigated by researchers (Jiang et al., 2019; Dengfeng et al., 2016; Gu et al., 2013; Zhao et al., 2016), yet the overall cabin dynamics can be further optimised by applying advanced control systems. The control methodologies that have been applied to cabin suspension systems in the literature can be classified into three main categories: skyhook control, optimal control, and road-adaptive control. These controllable cabin suspension systems are thoroughly reviewed and discussed in this section.

3.1 Skyhook control

In the early 1970s, Karnopp (1983) introduced the concept of the semi-active suspension system based on the well-known skyhook control. Because of its performance and computational efficiency, the skyhook control law is also widely used in adaptive cabin suspension systems. Based on the actual cabin suspension system shown in Figure 2, the concept of the skyhook theory is that the cabin is connected to an imaginary sky through a damper c_{sky}, and a spring k_s installed between the cabin and the chassis frame, as shown in Figure 3.

Figure 2 Quarter-cabin model

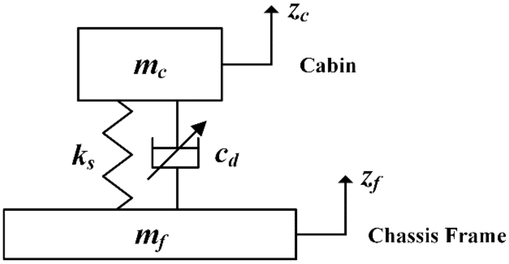
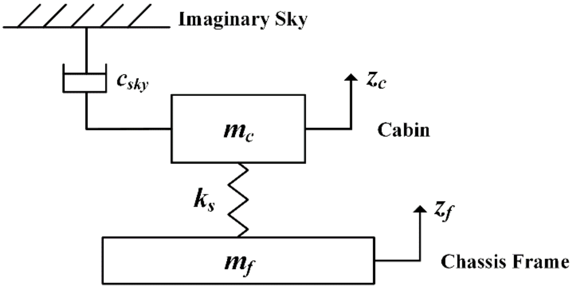


Figure 3 Skyhook control theory



This control law consists of two states, in which the damping coefficient c_{sky} changes according to the sign of the product of the cabin and frame velocities:

$$\begin{cases} c_{sky} = c_{max}, & \text{if } \dot{z}_c(\dot{z}_c - \dot{z}_f) \geq 0 \\ c_{sky} = c_{min}, & \text{if } \dot{z}_c(\dot{z}_c - \dot{z}_f) < 0 \end{cases}$$

In this way, the damping coefficient c_{sky} switches between the high-state and the low-state, then the corresponding force generated by the imaginary damper equals to

$$F_d = c_{sky} \cdot \dot{z}_c$$

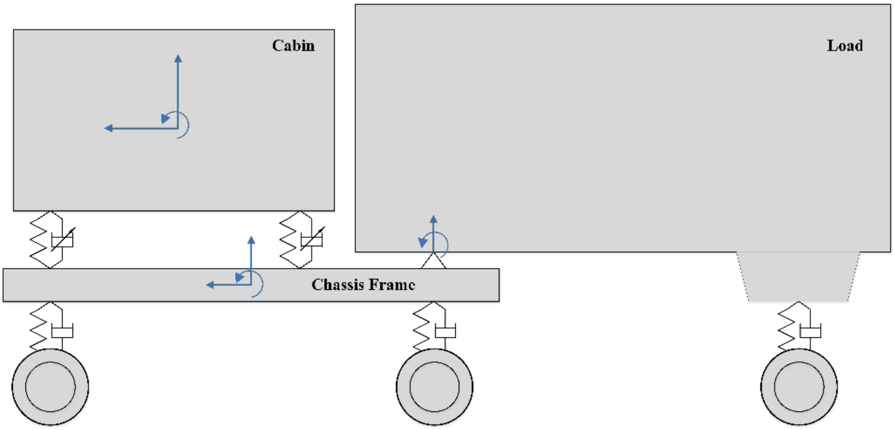
This amount of force F_d should be provided by the actual damper which is installed between the cabin and the chassis frame. Hence, the actual damping coefficient c_d can be calculated by

$$c_d = \frac{F_d}{\dot{z}_c - \dot{z}_f}$$

This comfort-oriented control law focuses on reducing the sprung mass acceleration, by generating a damping force proportional to the absolute sprung mass velocity. Several modified skyhook controllers have been introduced in the literature, namely modal skyhook, no-jerk skyhook, and a classic skyhook controller applied on a self-powered active cabin suspension system. The skyhook approach is often considered a benchmark in the literature due to its popularity and efficiency.

Tong et al. (1999) introduced a skyhook based semi-active cabin suspension to achieve optimal vertical and pitch dynamics. In this suspension system, the cabin was supported by both front and rear suspensions that consisted of passive springs and adaptive dampers, as shown in Figure 4. A 3-axle tractor semi-trailer equipped with a separated cabin were modelled as an 8 DOFs system. The simulation results showed that with the skyhook controller, the driver's absorbed power dropped by 30%, and both vertical and pitch accelerations were also reduced. With the addition of a controllable seat suspension system, more than 60% of the driver's absorbed power could be reduced. The authors also mentioned that the skyhook cabin suspension, although more costly, provided better vibration isolation performance than the skyhook seat suspension.

Figure 4 Sketch of the truck with cabin suspension (see online version for colours)

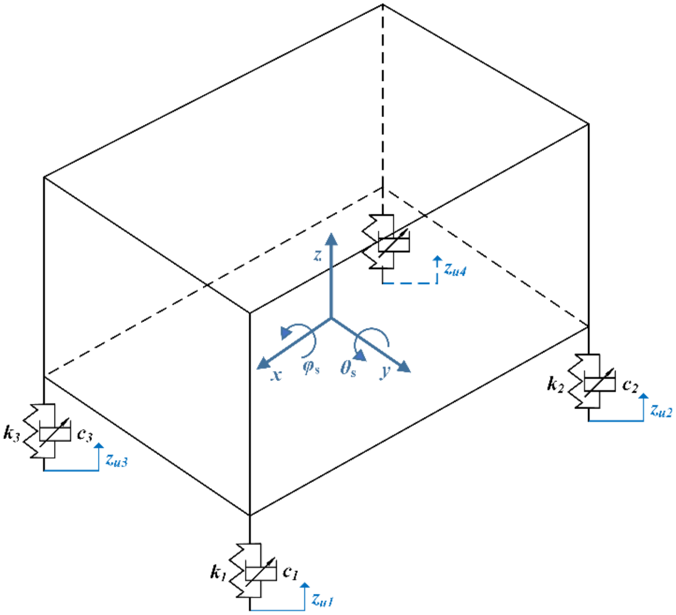


Nakano et al. (1999) designed a self-powered active cabin suspension system based on the traditional skyhook theory. An electric generator was installed in the primary suspension system to regenerate vibration energy and store it in a capacitor. The actuator installed in the cabin suspension achieved active vibration control by using the energy stored in the capacitor. Numerous simulations showed that the self-powered active cabin suspension system had better vibration isolation performance than a semi-active or passive system.

Marcu (2009) proposed a variation of the skyhook theory, named no-jerk skyhook, which was applied to a rear semi-active cabin suspension system of a class 8 Volvo VN 770 semi-truck. A controller called hierarchical semi-active control (HSAC) was developed and implemented to allow the no-jerk skyhook controller to adapt to different road conditions. The cabin was modelled as a 3-DOF rigid body. In the front, the cabin was mounted to the frame through bushings which were modelled as relatively stiff spring and damper on each side. In the rear, the suspension system contained two air springs and two dampers. The corresponding bond graph model was introduced in Marcu's work. The simulation results showed that the proposed controller was most effective in low frequency range (3~5 Hz), but there were no benefits at high frequency ranges (above 10 Hz). The laboratory testing also showed that the no-jerk skyhook controller significantly improved the ride comfort around its natural frequency, especially when dealing with transient excitations. The no-jerk policy provided noticeably smoother control signals than the classic skyhook law. Nevertheless, Marcu's analysis mainly focused on the cabin's vertical motions. The roll and pitch dynamics were not fully considered which were sources of discomfort because of the cabin's high centre-of-gravity location.

Ekberg and Hansson (2015) applied the modal skyhook theory for optimising 4-point cabin active and semi-active suspension systems. As shown in the Figure 5, each strut consisted of a spring and an adaptive damper. The modal skyhook was developed based on the motion of the cabin's centre-of-gravity instead of simply relying on the deflection velocity at four corners. This method was then implemented in ADAMS/Car for analysis. In some cases, the roll angle barely changed with an individual skyhook controller, but vertical acceleration and pitch angle were considerably suppressed. The modal skyhook controller could flexibly reduce cabin roll and pitch angles by tuning its user-defined parameters. Overall, the simulation results showed that the overall performance of the modal skyhook was much better than that of the traditional skyhook, especially in terms of the cabin's roll and pitch dynamics.

Figure 5 Three degrees of freedom cabin model (see online version for colours)



3.2 Optimal control

Optimal control strategies as well as other control methodologies have been applied to cabin suspension systems. They include linear quadratic regulator (LQR), acceleration driven damping (ADD) control, linear parameter varying (LPV), H_∞, and fuzzy logic.

In additional to the modal skyhook theory, Ekberg and Hansson (2015) also implemented the LQR for developing a 4-point cabin active suspension system. Specifically, an objective function J together with two penalty matrices Q and R were firstly formed as

$$J = \frac{1}{2}\int_0^\infty \left(x^T Qx + u^T Ru\right)\mathrm{d}t$$

which is based on the cabin system state-space model:

$$\dot{x}(t) = Ax(t) + Bu(t)$$

in which the optimal control signal u could be found by solving the algebraic Riccati equation.

In their work, the objective function contained the cabin's displacement, angles, and velocities in vertical, roll, and pitch directions. The control signals (damping forces) were calculated to minimise the terms in the objective function. The LQR controller was evaluated in ADAMS/Car. The active LQR controller was able to improve comfort by more than 30%, and cabin's roll and pitch dynamics could be adjusted by tuning penalty matrices. Overall, the active modal skyhook and the active LQR provided comparatively equal performances.

Van Iersel (2010) focused on minimising the undesired vibration of the cabin in the vertical direction. A 4 DOFs quarter-truck model was used with a variable rate damper in the cabin suspension, as shown in Figure 6. Two popular control theories were tried in his work: mixed skyhook and ADD control, and the LQ/LPV approach. The altered ADD algorithm was applied on a semi-active cabin suspension system as follows:

$$F_d = \begin{cases} F_{max}, & \text{if } \ddot{z}_c(\dot{z}_c - \dot{z}_f) \geq 0 \\ F_{min}, & \text{if } \ddot{z}_c(\dot{z}_c - \dot{z}_f) < 0 \end{cases}$$

which had a similar formulation as the 2-state classic skyhook theory. An interesting observation was that the traditional skyhook strategy performed better in low-frequency ranges, while the ADD algorithm acted better in high-frequencies ranges. Hence, the combination of these two methods had a greater potential for improving overall ride comfort. The proposed LQ/LPV strategy was inspired by H_∞ /LPV. The desired damping force was defined as

$$F_d = c_{nom}\left(\dot{z}_c - \dot{z}_f\right) + F_c$$

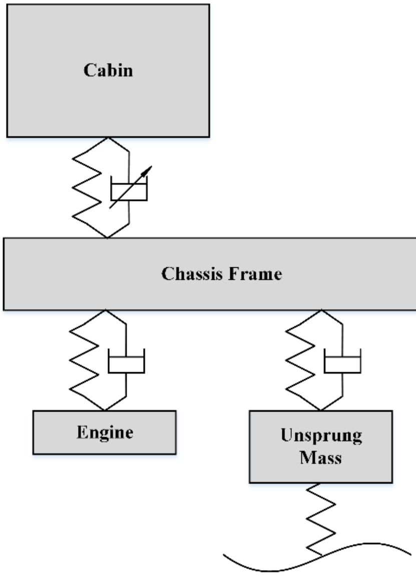
in which the additional force F_c was calculated by an LQ-optimal controller by solving the algebraic Riccati equation. An LPV parameter ρ was later introduced to capture the system's nonlinear characteristics which consisted of force boundaries and damper dissipativity constraints. With the proposed LPV parameter, the penalty matrix R of the LQ controller was re-defined as

$$R(\rho) = 1 \times 10^{-3} + \rho \cdot 10^{3}$$

by which the limitations and force change rate characteristics of semi-active dampers could be satisfied. For example, with increasing of ρ, the control force $F_c \rightarrow 0$ which caused the suspension acted as a passive system. The simulation results showed that the LQ/LPV strategy performed significantly better compared to the 2-state skyhook and ADD controllers. Additionally, the author also pointed out that those so-called clipped control strategies were not optimal for semi-active suspension systems. The constraints inherent to the semi-active dampers should be accounted during the control design process.

Hiromatsu et al. (1993) developed a fully active electromechanical cabin suspension actuated by an electric motor. The controller was designed based on H_∞ feedback control theory and tested on a full-scaled experimental platform and a real truck. The output torque of the motor was converted to a vertical force with a ball screw, together with an air spring in parallel. The control commands at all four suspension corners were augmented by applying frequency-weighted gains. The control signals were calculated by solving a standard feedback H_∞ problem aimed to minimise the given objective function under the worst possible disturbances. The robustness against cabin mass perturbation was confirmed on the Nyquist diagram. The experiment results showed that the proposed controller could eliminate cabin vibration and the effects from chassis frame bending. Moreover, this active suspension system could be economically produced by using 100 W class AC servo motors. It should be noted that this study only focused on the vertical dynamics of the cabin while excluding roll and pitch directions.

Figure 6 Quarter-truck model



Soliman (2008) developed a hybrid cabin suspension system based on a simple linear feedback control law whereby the vibration energy was stored in the capacitor and provided to the DC motor for cabin control. The proposed control system was simulated on a 9 DOFs half-truck model. As expected, the simulation results showed better ride comfort in terms of the cabin's vertical acceleration compared to a semi-active suspension system equipped with a two-state skyhook controller. Since the cabin suspension was modelled as a 1-DOF model, its roll and pitch motions were not considered in this study.

As an alternative to the damping control, some approaches have focused on the adaptive air spring stiffness control. Yan et al. (2008) introduced a genetic algorithm optimised fuzzy logic controller (GA-FLC) to improve the cabin's vertical dynamics by adjusting the rate of air springs. The control performance was evaluated by a nonlinear cabin suspension model built in ADAMS under four different road excitations. The simulation results showed that both the cabin's vertical displacement and acceleration were decreased by 30% to 40% after equipping the proposed GA optimised fuzzy controller. Moreover, Graf and Maas (2011) connected air springs and the air supply through fast switching valves. In this way, the mass flow of the compressed air was controlled, as well as the spring rate. By applying a hybrid skyhook and groundhook principle, the cabin accelerations in vertical, roll, and pitch directions were attenuated. According to their road tests with the phototype vehicle, the overall frequency-weighted acceleration (International Organization for Standardization, 1997) was reduced by 40%.

Instead of studying the cabin system of commercial trucks, several researchers have focused on the cabin development of vibratory rollers in vertical and pitch directions (Nguyen et al., 2020; Nguyen and Le, 2020). Nguyen et al. (2019) applied the PID-fuzzy control to the cabin isolation mounts of soil compactors. A 7-DOF nonlinear single drum vibratory roller was built to evaluate the control performance. The proportional, integral, and derivative gains of the PID were adjusted by the fuzzy control law. The performance of the proposed PID-fuzzy controller was evaluated via the weighted RMS accelerations and maximum PSD values of the driver seat's vertical motion and the cabin's pitch motion. The simulation results showed that the ride comfort could be remarkably improved in both vertical and pitch directions, especially in a low-frequency range below 4 Hz. Similarly, Jiao and Nguyen (2019) compared this PID-fuzzy controller against two different control approaches: the multi-objective genetic algorithm (MOGA), and the genetic algorithm based PID (GA-PID) controller. According to their simulation results, the fuzzy logic PID (FLC-PID) approach reduced the weighted RMS acceleration by around 30% in vertical direction and by more than 45% in pitch direction, which provided better control performance than GA-PID and MOGA approaches.

3.3 Road adaptive control

Previous research has showed that both active and semi-active cabin suspension systems could greatly improve ride comfort. However, their control gains and penalty matrices were fixed. In general, a controller with fixed parameters must be well-tuned in order to avoid harsh obstacles and high-level vibrations, which ultimately limits the damping potential under normal driving conditions (Hansson, 1996). Thus, an optimal controller with road-adaptive gain-tuning is a reasonable solution to resolve this issue (Hrovat, 1997). The adaptive gains are updated based on disturbances and/or suspension travel, which can be applied to different vehicle suspension models.

Van Iersel (2010) pointed out that the suspension deflection displacement had a significant impact on the driver's comfort, but the available working spaces were not fully used with fixed parameters. A road adaptive suspension control was then introduced by Van Iersel, which had been applied to his 2-state skyhook and LQ/LPV controllers. It showed that with different levels of road roughness (especially for lower ones), the proposed gain-adaptive semi-active suspension systems reached a better ride comfort with up to 45% improvement compared to non-adaptive ones. However, the proposed gain scheduling method under discrete obstacle conditions was not fully studied.

Hansson (1996) introduced a disturbance-adaptive active cabin suspension system for agricultural tractors based on a 1-DOF cabin model, whereby the vertical actuator force worked in parallel with a passive linear spring. This controller design was based on the time invariant state feedback theory. An adaptive algorithm based on varied parameters in the penalty matrices was applied. The gains of both controller and observer were adjusted according to the movements of the chassis frame. The controller feedback gains were then calculated with updated penalty matrices and chassis frame motions by iterating the Riccati equation. The gains in penalty matrices were dependent on suspension travel, so that the controller could always strive to find optimum solution based on the available suspension travel space. By simulating the proposed adaptive controller under different road profiles, the results showed that the active suspension performed better than the passive mode, and the adaptive methodology increased the control potential regardless of road conditions.

4 Summary and future trends

Adaptive cabin suspension systems based on various control theories were thoroughly reviewed and discussed. Undoubtedly, the past studies of cabin suspension systems have greatly contributed to enhancing truck drivers' ride comfort. The traditional skyhook control theory is efficient in improving cabin vertical and pitch dynamics, but it sometimes causes worse roll responses compared to the passive mode. Nevertheless, the skyhook concept is computationally efficient for real-time implementation and is often considered a benchmark system. Several advanced skyhook strategies led to greater adaptations, whereby the controller could give coordinated control signals instead of only focusing on the suspension relative velocity at each corner. Recent works mainly focus on optimal control strategies which have great potential to improve cabin dynamics in all three directions: vertical, roll, and pitch. However, the suspension mechanical limitation and semi-active damper dissipative constraint have not been fully considered and analysed in the design process. This results in the so-called clipped control, which is not the optimal solution for semi-active suspension systems. Researchers have tried to develop road-adaptive algorithms in order to optimise the control performance regardless of road conditions, however, simulation scenarios were not adequate. Finally, although the simulation results in the literature showed considerable improvements, very few have been validated by experimental testing.

Based on the review of previous work, some future research topics regarding the truck cabin adaptive suspension systems could be proposed:

- *Cabin three-directional vibration attenuation*: The majority of past studies aimed to reduce the vertical acceleration and, to a lesser extent, pitch vibrations. However, the tilt motions in roll and pitch directions are also main sources of discomfort. As such, control strategies that are able to improve cabin dynamics in all three directions should be developed for future suspension systems.
- *Advanced semi-active cabin suspension system*: The semi-active cabin suspension requires significantly less power than the active one, but further research is required to address the damper dissipative constraint and the suspension mechanical limitation when developing the control algorithm.
- *Road-adaptive cabin suspension*: Commercial vehicles may drive on various kinds of road, such as pavements, cropland, mining area, rough surfaces, etc. It is not possible to find a fixed-gain controller which can handle varieties of driving conditions. One potential solution is to adjust the parameters of the controller (such as objective functions, penalty matrices, gains, etc.) according to disturbances. This would require road classifiers to provide accurate disturbance information for the controller. In addition, proper gain-tuning rules should be developed to guarantee stable control performances on any kinds of road.

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