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Horizontal vibration and control methods in high-speed elevator car systems: a review

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Abstract: Horizontal vibration in high-speed elevator car systems has been a serious problem affecting the riding feeling, and it may threaten the safety and stability of the elevator system. This review aims to provide a comprehensive overview of the causes of horizontal vibration, focusing on factors such as the car and guide system, aerodynamic characteristics, and the performance during starting and stopping processes. Subsequently, various models of high-speed elevator car systems were discussed in detail, taking into account structural excitations and aerodynamic effects. Finally, a thorough analysis of vibration suppression methods, addressing both passive and active controls, was presented. Compared to passive control, active damping control technology has been shown to offer a more flexible and efficient approach to vibration suppression by leveraging real-time feedback and dynamic adjustments of control forces. To enhance the suppression of horizontal vibration, further research into intelligent control strategies with self-learning capabilities, as well as the integration of intelligent materials, appears promising.

Keywords: horizontal vibration; high-speed elevator; passive control; active control

1. Introduction

With the acceleration of global urbanization, the prevalence of super high-rise buildings, particularly in metropolitan areas, is on the rise. As a critical mode of transportation, the demand for high-speed elevators with a lifting velocity above 2 m/s is increasing rapidly. However, featured by greater lifting velocities and enhanced transportation capacities, high-speed elevator systems are facing several serve technical challenges. Notably, it has been observed that for lifting velocities exceeding 3 m/s, the horizontal vibration acceleration of the car system is significantly greater than that of low-speed elevators [1–3].

When the frequency of elevator vibrations approaches the sensitivity range of the human body (1–2 Hz), passengers may experience both physical and psychological discomforts, including dizziness and palpitations [4,5]. On the other hand, horizontal vibrations have negative effects on the safety and stability of the elevator system. Prolonged exposure to horizontal vibrations can lead to wear and tear on connecting components, thereby deteriorating their accuracy and lifespan. For this reason, elevators become more easier to breakdown, which can even result in serious safety incidents [6]. Therefore, effectively suppressing horizontal vibrations in the car system has been regarded as a critical issue in the field of high-speed elevator research.

In this work, the causes of horizontal vibration in high-speed elevator car systems and their vibration reduction control technologies are systematically reviewed. By conducting an in-depth analysis and summarizing existing research findings, the paper explores the key factors influencing horizontal vibration, including the car and guide system, aerodynamic characteristics, and the performance during starting and stopping processes. The characteristics of passive and active vibration reduction methods are also evaluated in detail. Finally, major conclusions and perspectives on the horizontal vibration in high-speed elevator car systems are provided at the end of the paper.

2. Horizontal vibration

This section explores the influencing factors of horizontal vibrations in high-speed elevator systems, including the structure of the elevator car system, characteristics of the guiding system, aerodynamic properties, and starting and stopping performance. By analyzing the effects of these factors on vibrations, the aim is to provide a theoretical foundation and design guidance for enhancing the safety and comfort of elevators.

2.1. Structure of high-speed elevator car systems

Figure 1 shows the overall structure of the high-speed elevator car system. The composition of high-speed elevator car systems is illustrated in Figure 1(a), which primarily consists of the car cab, car frame, and roller guide shoes, among other components. As depicted in Figure 1(b), the car cab is connected to the car frame using rubber elements to mitigate vibrations, and it is propelled by the friction between the traction ropes and the guiding pulleys. In the guiding system, T-section guide rails are installed along the hoistway wall of the elevator, while roller guide shoes are positioned at both the top and bottom of the car frame, working in conjunction with the guiding pulleys. The guiding pulleys are secured to the guide rails by elastic elements.

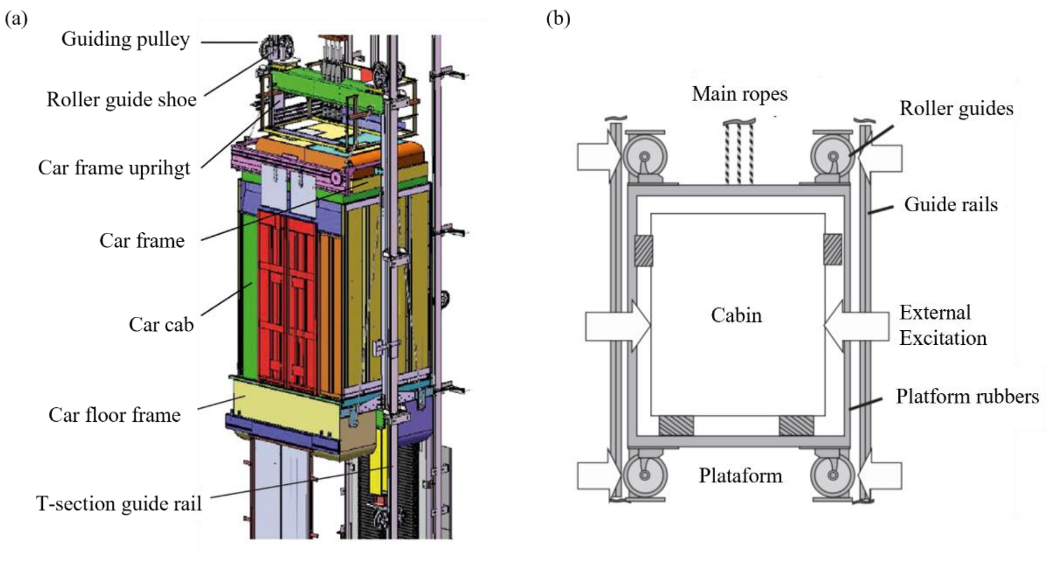


Figure 1. Overall structure of the high-speed elevator car system (a) Schematic diagram of elevator car system; (b) Schematic diagram of the cabin structure.

2.2. Effect of the car and guide system

The design of the elevator car is crucial for the dynamic performance of elevators. Firstly, the mass distribution of the elevator car and its coupling methods with the guide rail system determine the system's vibration characteristics [7]. Ideally, a uniform mass distribution within the car and a highly stiff connection structure with the guide rail are necessary to suppress the occurrence of asymmetric vibrations. However, due to inevitable errors in manufacturing and installation processes, issues such as uneven quality distribution or loose connections frequently arise during actual operation. There are the following errors in the installation process of elevator guide rail, including parallel error, horizontal error, straightness error and perpendicularity error. These problems can lead to significant horizontal vibrations at high speeds, adversely affecting passenger comfort and system stability. Horizontal vibrations in high-speed elevator systems significantly impact passenger comfort, system stability, and safety. Particularly at high speeds, aerodynamic disturbances within the shaft can exacerbate vibrations, making them difficult to suppress using traditional control methods. Compared to vertical or torsional vibrations, the swaying sensation caused by horizontal vibrations is more easily perceived by passengers and can lead to structural wear and fatigue damage. Therefore, addressing horizontal vibration issues is crucial for enhancing the performance of high-speed elevators, ensuring safety, and improving the riding experience. Thus, accurate measurement and adjustment are required when installing the elevator guide rail to ensure that the installation quality of the guide rail meets the standard requirements. The amount of vibration acceptable for comfort depends on many factors that vary with different applications. The standard (ISO 2631–1:1997, IDT) gives the influence range of vibration acceleration on passenger comfort, as shown in Table 1.

Table 1. Seven phases of high-speed elevation operation state.

Vibration degree (m/s^2)	Passenger comfort level
< 0.315	Do not feel uncomfortable
0.315-0.63	A little uncomfortable
0.5-1	Quite uncomfortable
0.8-1.6	Uncomfortable
1.25-2.5	Very uncomfortable
>2.0	Extremely uncomfortable

In the guide system, the precision of the fit between the guide shoes and the guide rails is crucial. Traditional sliding guide shoes often generate significant noise and horizontal vibrations due to their high friction. To address this issue, rolling guide shoes have gained popularity in recent years [8]. At present, the main types of high-speed or ultra-high-speed rolling guide boots on the market are: (1) magnetic suspension guide boots, (2) active control rolling guide boots, and (3) passive control rolling guide boots after parameter optimization. Among them, the magnetic suspension guide shoe subverts the traditional type and principle of rolling guide shoe, and replaces the contact roller with non-contact magnetic suspension, which can be regarded as the technical extension of sliding guide shoe. In addition, the active control of the rolling guide shoe is to add an actuator to the roller of the rolling guide shoe. By controlling the actuator, the parameters such as the contact force between the roller and the guide rail are actively controlled. In contrast, the passive control of the rolling guide shoe is to optimize the design and adjustment of the key parameters of the rolling guide shoe (such as spring stiffness, damping coefficient, *etc.*), thereby improving the vibration reduction performance of the rolling guide shoe. However, the application of rolling guide shoes requires higher manufacturing accuracy and installation quality of the guide rails. Furthermore, to ensure the long-term stability of the system, more attention should be paid to the material selection for the guide shoes and the fatigue life of the rolling elements [9]. Additionally, the connection stiffness between the elevator car and the guide rail has a direct impact on the anti-vibration performance of the elevator [10,11]. If the connection stiffness is insufficient, the car may experience resonance, leading to a significant increase in vibration amplitude, and even endangering the safety of the elevator. Therefore, in the design process, it is necessary to optimize the structural design of the car and guide system by improving the overall stiffness of the system.

Previous studies have demonstrated that maintaining an appropriate distance between the car and the guide rail can effectively prevent excessive impact and vibrations[12]. Actually, a gap that is too large can cause the car to sway and collide, resulting in significant horizontal vibrations. Conversely, a gap that is too small may increase the friction force, leading to accelerated wear of both the guide rail and guide shoe, and ultimately causing vibration problems. The manufacturing accuracy of the guide rail is also a critical factor in its performance. High-precision guide rails are characterized by excellent straightness and smoothness, and their surface roughness must be strictly controlled to minimize friction between the car and the guide rails. By employing modern manufacturing technologies, such as CNC machining and high-precision measurement techniques, the manufacturing accuracy of guide rail can be significantly improved. Additionally, the installation quality of guide rail plays a vital role in influencing horizontal vibration. Improper installation can result in uneven joints or bending of the guide rail, causing the car to bounce or swing, which can substantially increase the amplitude of horizontal vibration [13,14]. Therefore, to ensure the long-term accuracy and stability of the guide rails, regular inspection and maintenance are essential, particularly in correcting guide rail straightness and repairing surface wear.

2.3. Effect of aerodynamic characteristics

At high lifting velocities, aerodynamic phenomena—such as pressure gradients, vortices, and turbulence—are generated by the motion of airflow in the hoistway. The behavior can lead to uneven gas distribution around the elevator car, resulting in aerodynamic instability and horizontal vibrations [15]. The aerodynamic effects are influenced not only by lifting velocity but also by the cross-sectional shape of the hoistway, the surface roughness of the car, and the pressure in the hoistway [16]. In high-speed elevators, the increased gas velocity in the narrow gap between the elevator car and the hoistway can induce turbulence, which may cause lateral oscillations and vibrations of the elevator car due to increased resistance and local pressure fluctuations. For the natural ventilation shaft, strong convection will produce a large pressure difference, resulting in car vibration and noise problems. Although the mechanical ventilation shaft can control the turbulent flow up and down the car to a certain extent, the operation stability will decrease with the increase of maintenance interval. Furthermore, as the elevator car passes through narrow areas or corners in the hoistway, the changes in airflow can produce significant aerodynamic impacts and then exacerbate horizontal vibrations. This phenomenon is particularly pronounced at high lifting velocities, as the amplitude of pressure fluctuations is proportional to the square of the operating velocity.

To effectively mitigate the horizontal vibrations caused by aerodynamic effects, the optimized design of the hoistway and the elevator car should be thoroughly considered through structural modifications and the installation of aerodynamic damping devices. Jing *et al.* [17] compared the effects of various hoistway structures on aerodynamic forces and pressure. Their findings indicated that the aerodynamic issues could be alleviated by incorporating ventilation holes in the hoistway, with the aerodynamic resistance being influenced by the position and cross-sectional area of these holes. Chen *et al.* [18] investigated the impact of deflectors on aerodynamic performance, revealing that the installation of a suitably designed deflector on the elevator car can significantly reduce drag and vibration, effectively eliminating the vortex at the rear of the car. Compared with other deflectors in Figure 2, they found that trapezoidal or semi-circular deflectors are preferable for high-speed elevators. Inspired by the structure of boxfish, Zhang *et al.* [19] proposed a pneumatic drag reduction method for high-speed elevators in Figure 3. Their research demonstrated that, compared to the conventional rectangular car, the drag coefficient of the novel design was reduced by 71.5%, while the Strouhal number improved by 38.5%. Additionally, the vibration was diminished by shortening the tail vortex and increasing the shedding frequency. Beyond these methods, the effects of installing toe guards at both the top and bottom of the elevator car on aerodynamic characteristics were also examined. By analyzing the flow field, including velocity distributions, pressure, and vorticity intensity, Zhang *et al.* [20] concluded that the drag force was significantly reduced, where the resistance could be decreased by a shorter height of the toe guard.

(a) 1/4 round (b) Triangle (c) Trapezoid

(d) Semicircle (e) Three-sided-guide shape

Figure 2. Different types of deflector models

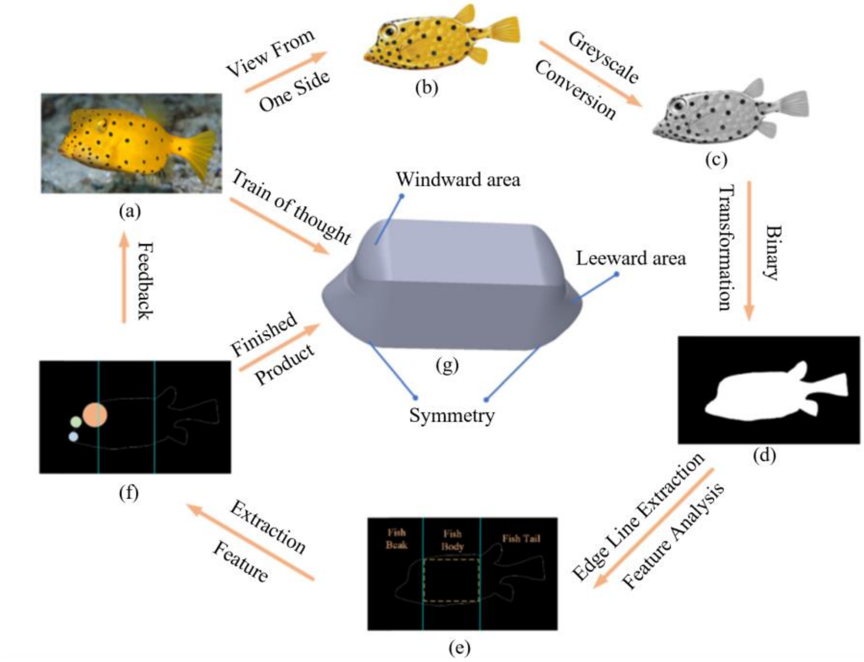


Figure 3. Analysis flow chart. (a) Boxfish; (b) side view; (c) grayscale image; (d) binary image; (e) contour; (f) extract feature; and (g) boxfish-inspired bionic flow guide model.

2.4. Effect of the starting and stopping performance

During the start-stop process of an elevator, variations in acceleration and deceleration can generate inertial forces that are transmitted to both the guide system and the elevator car. This transmission may lead to complex nonlinear dynamic responses, particularly in high-speed elevators.

When the elevator begins its operation, the motor's drive system generates initial torque, leading to the acceleration of the elevator car. Caused by the uneven acceleration and fluctuations in speed, the forces exerted on the elevator are usually unsteady that the possibility of vibration is increased. During the startup stage, horizontal vibrations are typically presented by periodic changes in displacement and acceleration. Research indicates that the horizontal vibration acceleration of the car is proportional to the elevator's acceleration; thus, greater acceleration results in more pronounced horizontal vibrations [21]. Additionally, during the initial startup, the car may undergo lateral displacement that the relative motion between the car and the guide rail will be induced, thereby amplifying vibrations. To mitigate the horizontal vibrations generated during the startup process, it is essential to optimize the acceleration curve in the design to prevent abrupt changes in acceleration. Furthermore, enhancing the quality distribution of the elevator car and increasing the overall stiffness of the guide rail system can effectively reduce the impact of inertial forces on the system.

During the braking process, strong friction occurs between the brakes and the wheels. This friction not only decelerates the elevator but also induces vibrations [22]. The elevator braking system represents a typical nonlinear mechanical problem, wherein variations in friction force can lead to relative motion among different components of the elevator system [23]. The type of vibration can be divided into three stages: (1) Startup stage: By imposing pressure on the brake, a sudden increase in friction can generate initial vibrations in the system. (2) Stable stage: Once the brake fully contacts the wheel, the friction force will be gradually steady, and the vibrations may diminish or stabilize. (3) Release stage: Upon releasing the brake pressure, a decrease in friction will trigger the second vibration. More specially, seven operation states of high-speed elevator were concluded by Qiu [24], which was shown in Table 2. It is worth noting that the dynamic behaviors of braking process including the smoothness and response speed is sensitive to the braking methods. For example, mechanical braking may induce serve instantaneous impacts, whereas electromagnetic braking offers a smoother deceleration process, thereby reducing the occurrence of horizontal vibrations [25].

Table 2. Seven phases of high-speed elevation operation state.

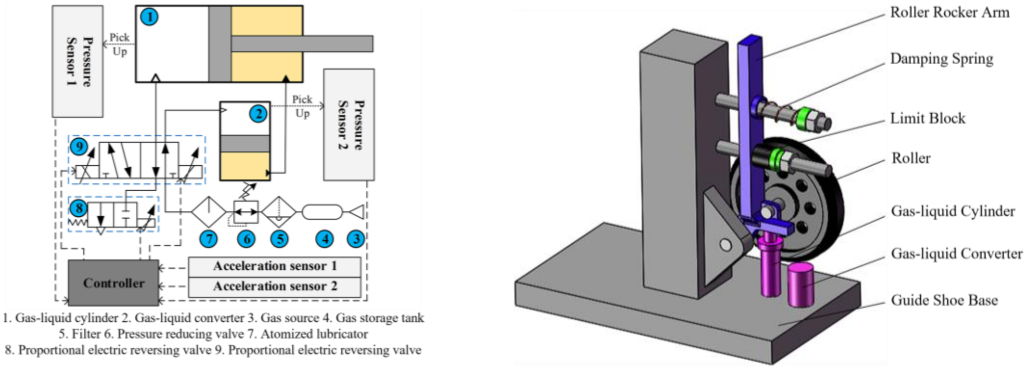
Phase	Time Used	Description
1	t_1–t_0	Acceleration increases to $a_e = -a_{\max} > 0$
2	t_2–t_1	Acceleration remains constant.
3	t_3–t_2	Acceleration reduces to $a_e=0$. Velocity increases to $v_e = -v_{\max} > 0$
4	t_4–t_3	Acceleration remains constant.
5	t_5–t_4	Deacceleration decreases to $a_e = a_{\max} < 0$
6	t_6–t_5	Deacceleration remains constant.
7	t_6–t_7	Deacceleration increases to $a_e = 0$. Velocity increases to $v_e = 0$

The hysteresis and instability of control strategies can result in uncontrollable vibration frequency and amplitude. To facilitate a smoother deceleration process, it is advisable to implement an efficient control system that adjusts the braking force in real time based on the speed and load of the elevator. Consequently, by employing adaptive control algorithms and predictive control techniques, intelligent control technology can be utilized to respond to the dynamic behaviors of the elevator system [26].

3. Model of high-speed elevator car systems

This section provides an overview of the structure of high-speed elevator systems and the vibration characteristics observed during operation. As elevator speed increases, irregularities in the guide rails and aerodynamic characteristics emerge as significant factors influencing horizontal vibrations. Researchers have proposed various mathematical models to examine the impact of rail defects, airflow disturbances, and other uncertainties on the dynamic characteristics of elevator systems. By establishing different vibration models and conducting experimental validations, the goal is to enhance the vibration resistance and safety of elevators. This section will discuss these research findings in detail and their important implications for the design of high-speed elevators.

The structure of the elevator, its aerodynamic characteristics, and its starting and stopping performance can all induce horizontal vibrations. Consequently, scholars have conducted extensive research on models of high-speed elevators. Diego Colon *et al.* [27] established a mathematical model for horizontal vibration that treats guide rail irregularities as random, uncertain excitations. To assess the robustness of the closed-loop system, polynomial chaos theory is employed to address these uncertainties. Case studies have demonstrated that the natural frequencies of the parked elevator are similar to those of the high-rise building. To mitigate the resonance between the building and the ropes, Crespo *et al.* [28] developed a mathematical model that incorporates the effects of stiffness related to the shoes and guide rails. Utilizing perturbation theory, Wang *et al.* [29] investigated the randomness of design parameters and formulated an expression for acceleration response, which can enhance the precision of models used in anti-vibration design. As depicted in Figure 4, He *et al.* [4] designed a gas-liquid active guide shoe equipped with a fuzzy neural network intelligent vibration reduction controller to address the inconsistencies between the elevator car and its frame, and establishing an 8-degree-of-freedom model for the elevator car system.



(a) Mechanism diagram (b) Schematic diagram

Figure 4. Gas–liquid active guide shoe.

Cao *et al.* [13] introduced a coupled vibration model for the rail and guide shoes using an equivalent model. Their investigation revealed that both roller eccentricity and surface roughness of the roller exhibit a linear relationship with vibration acceleration. To address the horizontal vibration of the elevator car caused by uncertain factors such as guide rail roughness, piston wind, and hoisting rope, Zhang *et al.* [30] developed a 5-degree-of-freedom vibration model in Figure 5 and designed an active car shock absorber, employing intelligent control based on back propagation neural networks. Additionally, they evaluated the influence of the guide rail's length, weight, and bending stiffness using the aforementioned model, thereby elucidating the relationship between structural properties and dynamic characteristics [7]. Furthermore, they established a non-linear model of the elevator car system grounded in Hertz contact theory and calculated the average response of random vibration using the orthogonal polynomial approximation method [8,31]. In Figure 6, by considering the excitation amplitude H and distance of adjacent brackets Δl, Song [11] established four types of guide rail excitations, where the displacement excitation and excitation period were sinusoidal, triangular, stepped, and pulsed models, respectively. Through developing a six-degree-of-freedom dynamic model that integrates the rails, shoes, and cabin, they indicated that reducing stiffness and straightness errors, along with increasing cabin weight, could effectively suppress horizontal vibrations. It is worth noting that different elevator space vibration models can be established based on varying assumptions. For instance, some researchers assume that the model system is linear, while others consider it to exhibit nonlinear behavior. It is important to note that when addressing nonlinear systems, additional degrees of freedom may be necessary to accurately capture complex dynamic behaviors. Moreover, some researchers neglect certain forces or influences in their models, such as air resistance or friction, which also reduces the degrees of freedom. Therefore, it is explained that there are different degrees of freedom in the content of the above researchers.

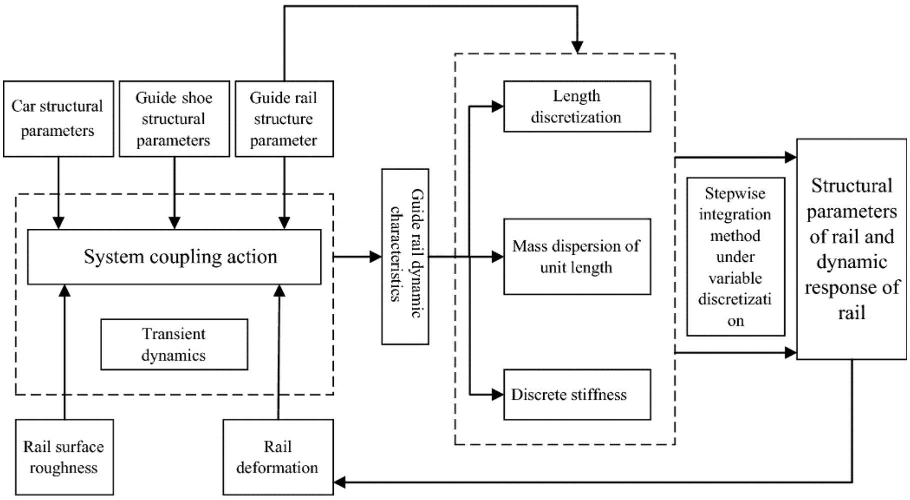


Figure 5. Analysis method of dynamic characteristics of guide rail.

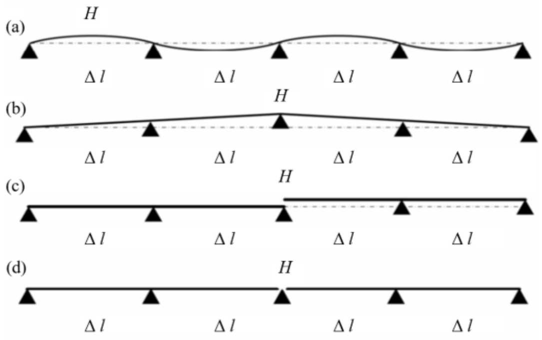


Figure 6. Four types of guide rail excitations: **(a)** sinusoidal excitation model; **(b)** triangular excitation model; **(c)** stepped excitation model; **(d)** pulsed excitation model.

The above models primarily focus on the impact of excitations, such as uneven guide rails and guide shoe defects, on the vibration of high-speed elevators. However, with the substantial increase in elevator operating speeds, the influence of aerodynamic characteristics in the hoistway on horizontal vibration should not be ignored. Through aerodynamic analysis of elevators, Zhang *et al.* [32] discovered that the disturbance effect of airflow in the hoistway on horizontal vibration becomes increasingly significant when the elevator operates at high or ultra-high speeds, emerging as a crucial vibration source that warrants attention. Building on Bernoulli's theory, For the piston effect in the hoistway of Figure 7, Liu *et al.* [33] proposed a multi-parameter theoretical formula during elevator ascent and descent. Here, cars 1 and 2 move opposite each other and the piston wind at different longitudinal planes was compared by dividing the hoistway into seven sections. During the operating, the airflow velocity v_{hoist} is increased to the piston wind speed w. In their analysis of the influences of lifting velocity, car height, hoistway height, blockage ratio and friction on this formula, they concluded that the blockage ratio is the most critical factor. Qiu *et al.* [14,24,34] highlighted that the coupling effect between the excitation of the guide system and the aerodynamic characteristics can exacerbate the horizontal vibrations of high-speed elevators. To accurately capture the dynamics of these horizontal vibrations, they developed a fluid-solid interaction model, which was validated at various speeds.

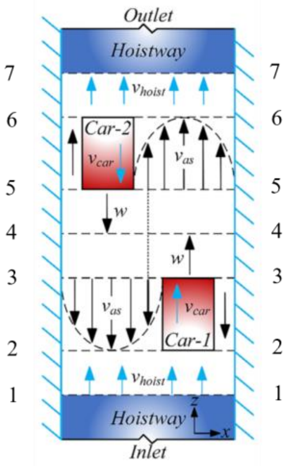


Figure 7. Schematic diagram of the piston effect in the hoistway.

4. Suppression of horizontal vibration

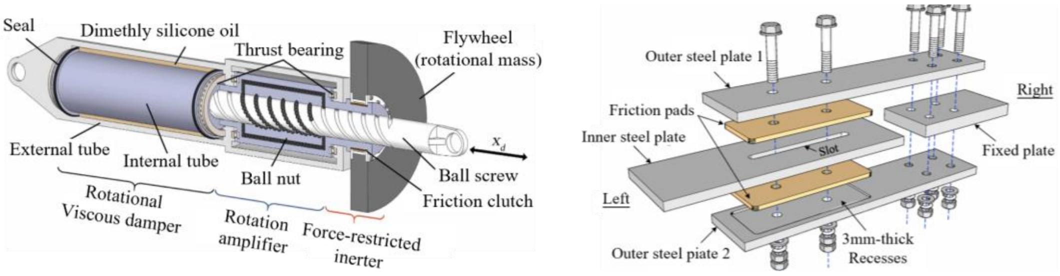
In high-speed elevator systems, the suppression of horizontal vibrations is crucial for enhancing system stability and passenger comfort. The main control technologies discussed in this section include passive control and active control. Passive control reduces vibration propagation by selecting appropriate materials and structural designs, utilizing dampers and vibration-damping pads. These measures are simple to implement and have low maintenance costs, making them widely used in elevator systems. In contrast, active control relies on real-time feedback and dynamic adjustments, achieved through the installation of sensors and controllers that monitor and respond to vibrations in real time. Actuators apply corrective forces based on commands from the controller, with common control algorithms including PID control and fuzzy logic control. The combination of these two control methods can effectively reduce horizontal vibrations in high-speed elevators, ensuring passenger safety and comfort.

4.1. Passive control

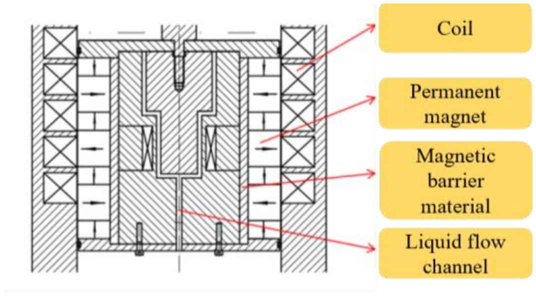
By selecting an appropriate structure and materials, horizontal vibrations can be suppressed through passive control methods, which include the use of dampers and the optimization of guide rails and car structures. Through adding energy dissipation devices or substructure systems, or structural treatment of some components, passive control can change the dynamic characteristics of the structural system [35]. Due to its straightforward implementation and low maintenance costs, passive vibration reduction technology is widely employed in high-speed elevator systems, and it plays a crucial role in enhancing system stability and passenger comfort [36]. In contrast, there are some problems in active control to suppress vibration. It is noteworthy that active vibration suppression necessitates complex modifications to the elevator system, leading to a high failure rate, intricate control algorithms, and significant energy consumption—factors that do not align with energy-saving and emission reduction policy requirements.

Vibration damping pads, typically composed of elastic materials such as rubber, polyurethane, or elastic composites, are essential for reducing vibration propagation and absorbing impact energy. These pads are primarily installed at support points between the elevator car and the hoistway, as well as in the guide rail system and other critical contact surfaces. By creating an elastic isolation layer between the vibration source and the surrounding structure, damping pads can significantly diminish vibration transmission [12]. Furthermore, the performance of damping pads varies depending on their material composition and design, particularly in relation to high-frequency and low-frequency vibration control [9,12]. For instance, rubber materials are particularly effective in absorbing low-frequency vibrations, whereas polyurethane materials excel in managing vibrations in the mid to high-frequency range.

Dampers in Figure 8, including viscous dampers, friction dampers, and magnetorheological dampers, are usually employed to suppress the vibration amplitude of systems by consuming vibrational energy through internal friction or viscosity. Viscous dampers utilize fluid viscosity to absorb vibrational energy and are particularly effective for controlling low to medium frequency vibrations [37]. In contrast, friction dampers rely on the friction force consumption mechanism, which is straightforward and incurs low maintenance costs; however, their performance can be adversely affected by the wear of the friction surfaces [38]. Magnetorheological dampers, on the other hand, leverage magnetic fields to dynamically adjust fluid viscosity, allowing for real-time modulation of the damping effect, making them suitable for applications requiring dynamic adjustments [39]. To achieve optimal vibration reduction, the selection and configuration of these dampers should be tailored to the specific vibration characteristics of the elevator system.



(a) a viscous damper (b) a friction damper



(c) a magnetorheological damper

Figure 8. Structure of various dampers.

In addition to vibration damping pads and dampers, the introduction of inerters can also improve the damping effect. The inerter, a mechanical component initially proposed by Malcolm C. Smith, is designed to improve the performance of vibration control systems [40]. Its core function is to provide a reactive force that is proportional to the relative acceleration, thereby simulating the effects of inertia and introducing a new dynamic adjustment mechanism into the system. In recent years, both domestic and international scholars have developed a variety of inerter types, including but not limited to the ball screw inerter [41], fluid inerter [42], gear pump (hydraulic) inerter [43] and living hinge inerter [44]. Despite the continuous development and optimization of inerters, limitations still exist, including complex design, high manufacturing costs, and stringent requirements for service environments and installation accuracy [45].

By optimizing the material properties, cross-sectional shape, and support method of the guide rail, the stiffness and stability of high-speed elevator car systems can be significantly improved [46]. For instance, employing high-strength alloy or composite materials can markedly enhance the stiffness of the guide rail, thereby minimizing vibration propagation.

Additionally, optimizing the car structure, mitigating uneven mass distribution, and refining the connection method can further enhance the overall stability of the car and reduce vibration amplitude [5].

4.2. Active control

4.2.1. Active guide roller

Active vibration reduction control is characterized by real-time feedback and dynamic adjustment. By monitoring the external energy and structural response in real time, and automatically controlling the response of the structure under the action through the system, active control can protect the structure and equipment from damage [47]. The system primarily consists of active guide shoes and various control methods. As a crucial component connecting the elevator guide rail to the car, vibrations are transmitted through the guide shoe, which comprises sensors, controllers, and actuators. Several active vibration reduction devices have been widely utilized, including electromagnetic ω-actuators, magnetic suspension active guide shoes, and electromagnetic active rolling guide shoes [48–50].

Sensors are employed for the real-time collection of vibration data, which is subsequently converted into electrical signals. The commonly utilized types of sensors include accelerometers, velocity sensors, and displacement sensors [51]. Among these, accelerometers measure changes in system acceleration and can provide high-precision vibration data. Velocity sensors offer insights into the speed of system motion, aiding in the assessment of vibration intensity. Displacement sensors monitor changes in displacement within the system, addressing the limitations of both acceleration and velocity sensors. High precision and real-time response capabilities are foundational for sensors to play a pivotal role in active vibration reduction control.

The controller serves as the 'brain' of the active guide shoes, responsible for calculating feedback signals based on sensor data. Controllers typically employ various control algorithms to achieve vibration control, including Proportional Integral Derivative (PID) control, Linear Quadratic Regulation (LQR) control, Sliding Mode Control (SMC), and H_∞ control [52,53]. The PID controller optimizes system response by adjusting proportional, integral, and derivative gains, offering advantages such as simple implementation and ease of adjustment. The LQR controller minimizes the weighted cost function of the system to optimize control gain, making it particularly suitable for vibration reduction in linear systems. The SMC controller minimizes error by forcing the system to slide along the normal behavioural lines, making it suitable for both linear and non-linear systems. In contrast, the H_∞ controller is designed to manage uncertain systems and ensure robustness by optimizing performance indicators. Furthermore, modern controller may also integrate artificial intelligence algorithms to facilitate adaptation and optimization in complex dynamic environments.

According to the controller's instructions, actuators are capable of applying adjustment forces to modify the dynamic response of the system [54]. Typical actuators include electromagnetic, piezoelectric, and hydraulic actuators. Electromagnetic actuators offer high-frequency and high-precision control forces, making them suitable for precision vibration reduction applications. In contrast, piezoelectric actuators excel in low-frequency vibration control due to their rapid response and high efficiency. Hydraulic actuators, on the other hand, can deliver greater adjustment forces, making them ideal for scenarios involving high loads or large amplitude adjustments. To ensure effective vibration reduction, the selection of actuators should be based on the vibration characteristics and control requirements of the system.

4.2.2 Control methods

Classic feedback control methods, such as PID control, are among the most widely employed techniques for active vibration reduction. By continuously monitoring the system's vibration data, the PID controller can adjust its proportional, integral, and derivative signals to mitigate vibration. PID controllers demonstrate effective performance across numerous applications and are particularly well-suited for simple linear systems. However, when addressing complex dynamic systems or environments characterized by significant uncertainty, PID control may necessitate further optimization of its parameter settings or integration with alternative control strategies to enhance the system's damping effect. Zhang *et al.* [55] proposed a combined control method that integrates PID and BP neural networks, characterized by enhanced robustness and increased intelligence. Building on the fuzzy adaptive PID approach, Duan *et al.* [56] effectively controlled the motor running speed of elevators. Their method achieved precise speed regulation, significantly improving the stability and reliability of the elevator system. To address the vibrations associated with high-speed elevators, Tang *et al.* [57] introduced an optimized fractional-order PID control method, utilizing control cost and car performance as objective functions. Compared to a conventional PID controller, this innovative approach resulted in an approximate 25% reduction in vibration.

Robust control methods are also specifically designed to manage systems characterized by uncertainty and disturbances, thereby ensuring the stability of the system in the presence of these challenges. Among the various robust control techniques, H_∞ control is the most widely used, focusing on minimizing the worst-case gain of the system. Hu *et al.* [58] applied the "Eight-Maglev" topology structure to electromagnetic guide systems, taking into account the effects of load disturbances, parameter variations, and other uncertainties. They employed H_∞ robust control to achieve rapid tracking, enhanced robustness, and effective suppression of horizontal vibrations in the car. Compared to PID control, simulation results demonstrated that H_∞ control exhibits greater robustness and anti-interference capabilities. Cao *et al.* [59] proposed an H_2 robust controller utilizing a linear matrix inequalities (LMI) optimization technique to effectively mitigate horizontal vibrations induced by rail roughness. Their robust controller demonstrated a reduction in the maximum value of vibration acceleration by over 19%. Moreover, the effect of spring aging on the performance of the elevator car system was taken into account by Chen *et al.* [60, 61] They established the state-space equation of the elevator car system using the linear fractional transformation (LFT) method and then designed an H_2/H_∞ robust controller through linear convex optimization. By comparing the simulation results with those obtained from other methods, they concluded that the mixed control method demonstrates superior ability in suppressing vibrations.

The adaptive control method can automatically adjust its control strategy based on the real-time responses of the system, allowing it to adapt to changes in environmental conditions or system parameters. This approach is particularly effective for managing systems characterized by uncertainty and nonlinearity. Fateh *et al.* [62] developed a strategy for direct adaptive fuzzy control (DAFC) of hydraulic elevators by integrating adaptive control methods with fuzzy system theory to address parameter errors. This approach offers advantages over traditional adaptive fuzzy systems, including reduced computational costs and ease of implementation. Based on the dynamic characteristics of high-speed elevator car systems, a Takagi-Sugeno model was initially established by He *et al.* [63] Subsequently, they developed an adaptive sliding mode controller with fuzzy switching gain to mitigate the significant horizontal vibration induced by guide rail excitation. The results demonstrated that this novel method outperformed the linear quadratic regulator, presenting a promising option for active vibration reduction. Addressing the issue of inaccurate modeling of the car system due to load variations during high-speed elevator operation, Zhang *et al.* [64] employed the Takagi-Sugeno fuzzy method to develop an active control model. Then, they designed an adaptive gain H_∞ controller aimed at minimizing vibration amplitude through the parallel distributed compensation method. Their findings further confirmed that the adaptive gain H_∞ output feedback controller is effective in significantly reducing horizontal vibration. Wani *et al.* [65] introduced a response adaptive control system based on inter-story displacement (IDRA) aimed at determining control model parameters while effectively reducing the overall inter-story displacement response. The findings indicated that the IDRA control method surpassed the traditional clipped optimal control (COC) strategy in mitigating the inter-story response of the structure.

Sliding mode control (SMC) is a nonlinear control method that distinguishes itself from conventional control through its inherent control discontinuity. SMC operates by altering the structure of the controller—either the control law or the controller parameters—depending on the extent of deviation of the system state from the sliding mode surface. This approach ensures that the system functions in accordance with the predefined rules associated with the sliding mode. Based on adaptive fuzzy logic, Wang *et al.* [66] proposed a sliding mode controller to optimize the performance index of the sliding mode. Additionally, to optimize the effect of uncertainty on the car system, a fuzzy logic system was developed to approximate the uncertain disturbances in real-time, and a smooth hyperbolic tangent function was employed to compensate for the fuzzy errors. He *et al.* [63] designed and optimized an adaptive sliding mode controller using the quadratic index method. By adjusting the switching gain of the new controller, the horizontal vibrations of both the cabin and the elevator frame were reduced by more than 66% and 35%, respectively. Pang *et al.* [67] established a sliding mode control strategy with a variable rate reaching law to mitigate high-frequency chattering. Their findings indicate that ride quality can be enhanced by suppressing vehicle body acceleration. Gohari *et al.* [68] introduced a robust controller on the basis of sliding mode control, and proposed a new self-adjusting boundary layer strategy to prevent the occurrence of chattering. By using the effective control signals of each mode, the uncertainty of the system is extracted, and the robust control signals of the sensor and actuator uncertainty are determined, which not only suppresses the noise transmission, but also maintains the consistency of the system. In addition, by optimizing the position of the actuators, some researchers have not only improved the control performance of the system on the structural radiation sound, but also significantly reduced the basic control voltage of each actuator [69]. Darvishgohari *et al.* [70] used a hybrid control strategy to reduce the amount of sound propagation through a multi-layer double-bending sandwich shell with a piezoelectric layer and a shunt circuit. In addition, the results show that increasing the number of parallel circuits can effectively reduce the sound transmitted to the structure within the resonant frequency. Talebitooti *et al.* [71] studied the diffusion acoustic field of infinite double curved laminated shells of porous material sandwich composite materials in aerospace structures, and analyzed the propagation characteristics of the wave. The results of Sound Transmission Loss (STL) curve show that the porous material is effective in improving the performance of STL in the frequency domain above 500 Hz. It is worth noting that the influence of the change of the twist degree on the STL curve can be ignored. However, due to changes in volume Young's modulus and volume density, STL curves below and after 620 Hz exhibit different behaviors.

Fuzzy logic control is an intelligent control method that imitates human fuzzy reasoning and decision-making processes from a behavioral perspective. Zhang *et al.* [30] proposed a variable fuzzy control method utilizing semi-active guide shoes and magnetorheological dampers to mitigate elevator vibrations caused by uncertain factors. In this approach, data collected from experiments served as input for the fuzzy neural network, which subsequently fed back the trained data to the magnetorheological damper for active vibration reduction control. The results demonstrated a significant reduction in both the vibration acceleration and torsional acceleration of the elevator. He *et al.* [4] proposed an intelligent vibration reduction controller based on a fuzzy neural network to address the inconsistency between the car and its frame. By utilizing the Mamdani model, this fuzzy neural network control method demonstrated that the designed intelligent shock absorber can effectively reduce horizontal vibrations, achieving a reduction in vibration acceleration values of over 55%. Wani *et al.* [72] introduced two adaptive control strategies focused on response, aimed at reducing inter-story drift and acceleration responses. These strategies were combined with an algorithm for device placement to determine the optimal configuration and positioning of magnetorheological dampers, resulting in improved performance under varying intensities of ground motion.

5. Conclusions and perspectives

This section analyzes horizontal vibrations in high-speed elevator systems and their control technologies, finding that vibrations are primarily caused by the guiding system, aerodynamic characteristics, and dynamic starting and stopping performance. During high-speed operation, complex airflow disturbances can lead to unstable vibrations, affecting the stability of the elevator and the comfort of passengers. Although passive damping technologies can reduce vibrations through structural and material optimization, their effectiveness remains limited in complex environments.

Future research should focus on the application of artificial intelligence and machine learning, combined with the dynamic adjustment capabilities of smart materials, to develop adaptive vibration control solutions suitable for complex environments. This will enhance the damping effect of high-speed elevators and improve safety and comfort.

The horizontal vibration and vibration reduction control technology in high-speed elevator systems have been systematically analyzed in this work. Through the analysis of the causes, models, and vibration reduction techniques of horizontal vibration, the following main conclusions are summarized:

The horizontal vibrations in high-speed elevator systems primarily arise from the guide system, aerodynamic characteristics, and dynamic start-stop performance. Notably, the aerodynamic effects become particularly significant during high-speed operation, where complex airflow interference can induce unstable vibrations in the elevator car. The acceleration variations occurring during the start-stop process are transmitted to the system structure via inertial forces, leading to complex dynamic responses and horizontal vibrations. These vibrations not only compromise the stability of elevator operation but also diminish passenger comfort.

Passive vibration reduction control technology primarily depends on structural design and material properties. This includes the optimization of vibration reduction pads, dampers, guide rails, and car structures. The damping pad and damper effectively lower the system's vibration levels, thereby enhancing overall operational stability. The optimization of the guide rail and car structure significantly mitigates horizontal vibration by increasing system stiffness, balancing mass distribution, and improving connection means. However, passive vibration reduction technology remains limited when confronted with complex dynamic environments.

Active damping control technology offers a flexible and efficient approach to vibration suppression by utilizing real-time feedback and dynamic adjustments of control force. Central to this technology is the collaborative interaction among sensors, controllers, and actuators, alongside various control strategies, including PID control, robust control, adaptive control, sliding mode control, and fuzzy logic control. These active control methods can respond in real-time to changes in vibration in complex dynamic environments, optimizing the system's vibration reduction performance and significantly enhancing the operational stability and safety of high-speed elevators.

Although the control methods employed in the aforementioned studies have somewhat suppressed the vibrations of mechanical systems, their effectiveness is limited due to the absence of self-learning capabilities to address the random excitations present in high-speed elevator car systems. Consequently, artificial intelligence and machine learning technologies are emerging as critical areas for future development. Additionally, the advancement of intelligent materials with unique physical properties and dynamic adjustment capabilities allows for performance modification in response to stimuli, thereby facilitating effective vibration suppression. In vibration control for high-speed elevators, smart materials are considered an essential component of future vibration control technology due to their dynamically adjustable characteristics. They can respond to external stimuli (such as temperature, voltage, or stress) by altering their physical properties. Smart materials offer both active and passive vibration control functions, providing advantages in adapting to the complex dynamic environments of high-speed elevators. Specifically, the application of shape memory alloys (SMA) and piezoelectric materials in vibration control is particularly noteworthy. For example, embedding SMA in the elevator's guiding system allows it to absorb and suppress vibrations through deformation when vibration frequencies exceed a preset threshold, thereby enhancing the system's damping effect. Additionally, the high energy absorption capability of SMA materials can effectively reduce the impact during acceleration and deceleration in high-speed elevators, minimizing fatigue damage to the system. On the other hand, piezoelectric materials exhibit the electromechanical coupling effect, generating electric charges when subjected to mechanical stress, and vice versa. This property makes piezoelectric materials highly effective in active vibration control. When applied to high-speed elevator systems, sensors monitor vibration signals in real-time, and the control system can dynamically apply an electric field to adjust the deformation of the piezoelectric material, thereby counteracting disturbances caused by vibrations. Common control strategies include combining piezoelectric actuators with feedback control, using piezoelectric materials in the elevator car structure, guide rails, and dampers to respond to vibrations in real time and perform fine adjustments, ensuring smooth and comfortable elevator operation.

Moreover, the integration of artificial intelligence, machine learning with intelligent materials can yield highly adaptable vibration control solutions. By utilizing data-driven control methods alongside intelligent materials, intelligent vibration reduction systems can autonomously learn and modify control strategies in response to complex and dynamic environments, making them particularly well-suited for high-performance and demanding elevator systems. With the development of smart materials and control technologies, integrating SMA and piezoelectric materials within a single system can achieve more advanced vibration control. Using data-driven control algorithms and adaptive adjustments, these materials can autonomously respond to vibration changes in complex environments, providing more precise and efficient vibration suppression solutions for high-speed elevators. For example, by integrating SMA and piezoelectric materials into the guiding system, the system can utilize SMA to absorb vibrations at low frequencies and employ piezoelectric materials for active control at high frequencies, achieving a synergistic vibration reduction effect.

Authors’ contribution

Methodology, Shen Wei, Youjun Ye; validation, Lin Liu; formal analysis, Cao Zhixiang; investigation, Zhen Zhang; writing – original draft, Cao Zhixiang; writing – review & editing, Shen Wei, Zhen Zhang, Youjun Ye; supervision, Youjun Ye, Lin Liu. All authors have read and agreed to the published version of the manuscript.

Conflicts of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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