

High-speed elevators – aerodynamic challenges and vibration performance: A comprehensive review

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ABSTRACT

As urbanization intensifies and high-rise buildings dominate skylines, the demand for high-speed elevators continues to rise. This review explores their aerodynamic characteristics and vibration performance, focusing on safety, comfort, and efficiency. Key aerodynamic aspects include drag reduction, ventilation optimization, and pressure management, supported by innovations in cabin design and hoistway configurations to enhance airflow and reduce noise. Vibration issues, caused by rail irregularities, aerodynamic forces, and structural dynamics, are addressed through advanced damping systems and smart technologies, such as AI-based monitoring and digital twins. Sustainable practices, including energy-efficient materials and designs, further enhance performance. Improving comfort is inseparable from enhancing the efficiency and safety of high-speed elevators, and the integration of aerodynamic solutions, advanced vibration systems, and interior design innovations represents a fundamental step towards meeting the future demands of ultra-tall buildings. Future innovations may draw on biomimetics for cabin shapes, optimized structures to minimize drag and pressure fluctuations, and improved vibration control algorithms that balance cost and sustainability. The research was selected based on its novelty, direct relevance to the topic, diversity of methodologies, and practical importance.

Keywords: high-speed elevators, aerodynamic drag reduction, cabin design optimization, piston wind and ventilation, ride comfort and vibration control, CFD and experimental validation.

INTRODUCTION

High-speed elevators have become a pivotal element in the infrastructure of tall buildings, as it represents the main means of ensuring vertical movement efficiently and safely. With the increasing high constellations and the complexity of operating requirements, the aerodynamic and vibrating challenges are highlighted not only to influence the efficiency of the system, but also extend to the comfort and safety of passengers [1].

Early literature focused on improving the basic mechanical aspects, such as strengthening the steering components or adjusting the dimensions of the cabin, but these traditional approaches proved their limitations when dealing with super speeds. The numerical simulation (CFD) was a

major tool in most recent studies, as it enabled the modeling of the air flow and the resulting forces. However, excessive dependence on theoretical modeling without field experimental realization raised questions about the ability of these results to generalize in realistic operating environments [2]. Research review also showed two main trends: (i) depends on direct engineering solutions such as adding the edges fairings to reduce air resistance and noise, (ii) heading towards smart and advanced solutions, such as biometric designs, multi-targets, and digital twinning.

Despite this progress, most studies dealt with each axis in isolation from the other (cabin, hoistway, vibrations) without building an integral framework that links them. In addition, a clear gap has emerged in neglecting the

standards of human comfort as an essential element in evaluating performance, as attention was often focused on physical indicators (such as clouds or acceleration of the cabin) without direct linking to the experience of sensory and psychological passengers. Also, the dynamic interaction between the building and the elevator, especially in the high-rise constellations, did not have sufficient study despite its importance in inflating vibrations.

An accurate methodology has been adopted in choosing previous studies, as it was taken into account that the chosen research is relatively recent (most of the years 2023–2024) to ensure that technical developments are paid, with reference to some older studies when needed to cover the theoretical basis. The choice was also based on the criterion of direct link with the topic of research, as it included studies that dealt with the aerodynamic characteristics of high-speed elevators and the performance of vibrations in them, whether in terms of design or in terms of proposed technical solutions. In addition, the diversity of the methods of research selected between CFD, practical experiments (air tunnel, laboratory tests), and analytical models, were taken to ensure the comprehensiveness of the issue coverage from its theoretical and applied angles. As for the classification, studies have been organized within three main axes according to their topics: this classification allows the presentation of an organized and clear vision, and reflects comprehensiveness in dealing with the subject that combines modernity, scientific link, and practical applications. Based on the foregoing, this research aims to provide a comprehensive review of the aerodynamic characteristics and the performance of vibrations in high-speed elevators, with a focus on analyzing previous studies according to major axes of the design of the cabin and HoistWay as well as the performance of vibrations. This review seeks beyond merely summarizing the literature, as it works to compare different curricula, highlight the size of the associated effects and restrictions, and to determine research gaps and future trends, which provides valuable visions of engineers, architects and researchers working in the field of vertical transport.

AERODYNAMIC CHARACTERISTICS

The high-speed elevators' aerodynamic properties are crucial in enhancing passenger safety and comfort in super-tall buildings. The operation of ultra-high-speed elevators generates significant aerodynamic forces, adversely affecting the elevator shaft's structural integrity and passengers' comfort [3-5]. These forces are susceptible to various parameters, including the hoistway blockage ratio and the design of ventilation holes within the shaft [6]. Numerous numerical and experimental studies have been conducted to analyze these parameters.

Design of the elevator cabin

The design of the elevator cabin in tall buildings is no longer just an external form, but rather a decisive factor in controlling air resistance and noise caused at high speeds. With the expansion of high-speed elevators, the increased scientific interest in studying the relationship between the shape of the cabin and the characteristics of the flow within the elevator well, in pursuit of improving energy efficiency, comfort and safety. During the tracing of the research path in high-speed elevatics, it reveals a remarkable systematic and cognitive development during the last decade, from simplified preliminary studies to advanced mathematical frameworks. Early research efforts, as in the works of [7], and [8], began focusing on describing the effect of simple engineering elements – such as the dome or streamlined cover – on air resistance, using two or 3D numerical simulations. Despite the success of these studies in showing the explicit relationship between the height of the cover or the curvature of the dome and the reduction of the strength of the clouds, it was characterized by excessive reduction and its total dependence on theoretical modeling without experimental achievement. Later, research has taken a more related approach to the practical aspects. Studies has dealt with the relationship between aerodynamics and energy consumption [9], indicating that the various forms of deflectors affect differently depending on the speed of operation, which provided a qualitative addition to energy efficiency considerations. On the other hand, [10] moved to a new systematic systematic path (POD and DMD), intense effort to build low-ranking

models with high mathematical efficiency to analyze air pressure patterns, which allowed reduction in the cost of the account, and if it remained away from providing direct design solutions. In the same direction in [11], and [12], distinguished its research by dual – experimental and numerical verification – by studying the effect of TOE Guards on reducing air disorder and noise, adding a process of credibility that most previous studies missed. In 2024, studies expanded to include multiple trends [13], presented an advanced mix of simulation and experiences to study the effect of three-SEDED arc fairings, and they proved that the increase in the diameter of the curvature reduces the surface pressure and the fluffy swells, with a reduction of air resistance by a rate of 60.13%, with average experimental error that did not exceed 10%, which strengthened the credibility of the results although the study is that the study did not eat spectral noise. In the same context, [14], dealt with the relationship between the elevator shape and the dynamic dynamic noise in the cyclic space, explaining that the increase in the direction surfaces reduces the side forces by 57.6% and withdrawal by 34.65%, with noise focus in the range of 500–1000 [15], also introduced a bombish approach inspired by the shape of the Boxfish, which showed a decrease in the clouds of 71.5% and an improvement in the stability of vibration. These three studies represented a turning point by combining experimental verification, spectral analysis of sound, and biological designs. The research, such as [16], combined high-resolution simulation (CFD) and the NURBS parameter, which allowed the resistance to a rate of approximately 39% in a simulation environment closer to industrial conditions. This work is a shift from the mere description of the problem to building an integrated digital design framework, capable of absorbing engineering complexity and physical restrictions on the environment of the elevator well. Despite this gradual development, the majority of research is still bound by excessive dependence on numerical simulations, and a large-scale industrial deficiency, which leaves an existing gap between theoretical models and practical application. Hence, the future trend must be based on integrating innovative biological designs with smart algorithms to improve and reliable industrial experiences, in order to achieve a balance between lowering clouds and

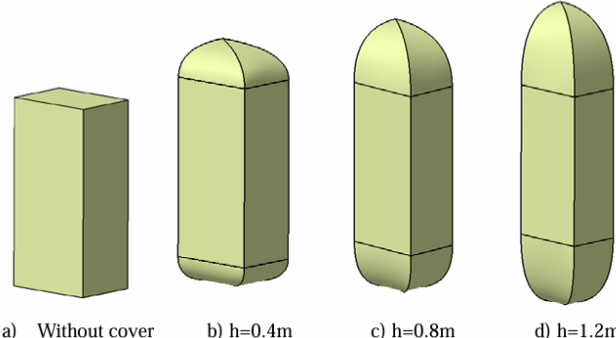
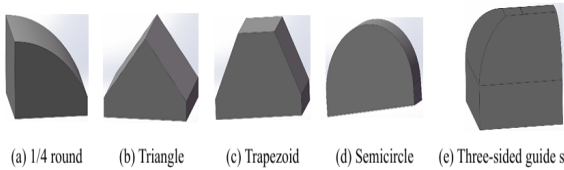
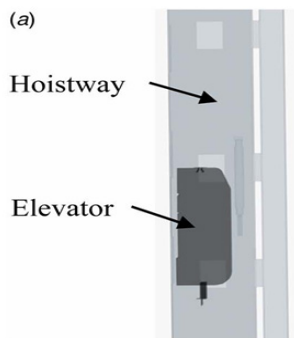
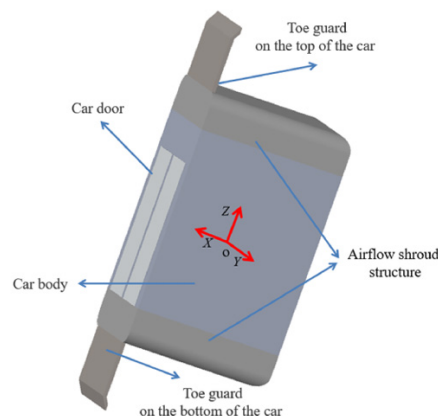
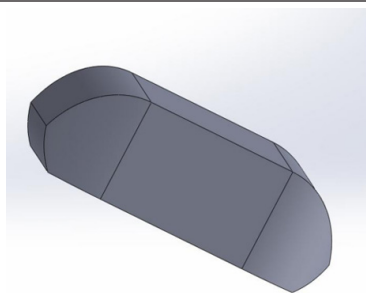
noise and ensuring the safety and comfort of passengers in high -speed elevators. Table 1 displays a summary of the most important tools and methods used and the most prominent results reached by previous research.

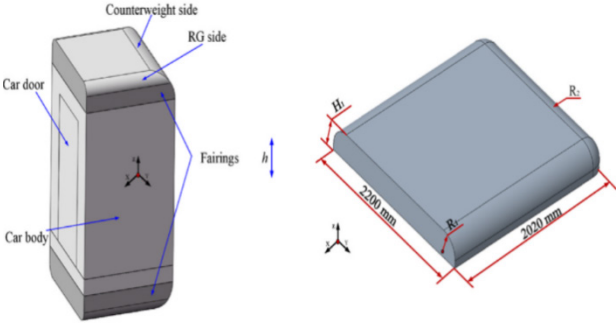
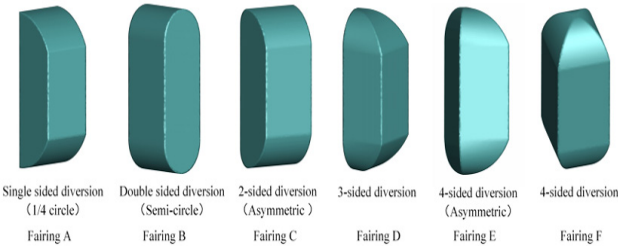
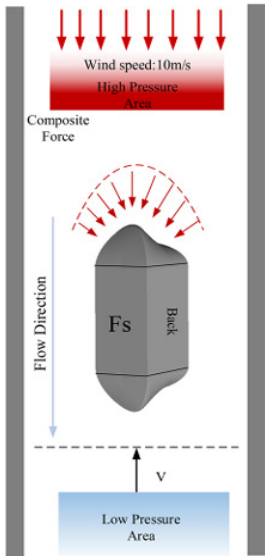
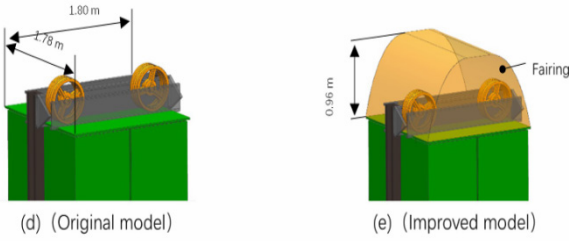
Aerodynamic forces are a major challenge facing modern elevator design, particularly with regard to cabin design and reducing drag forces that affect the overall elevator performance. In this context, the importance of studies focusing on understanding the effects of aerodynamic forces and how to improve elevator designs to reduce air resistance is highlighted. As discussed, complex aerodynamics (CFD) simulation techniques and modern analysis techniques such as SAS have been used to accurately evaluate these forces. For example, in Rogowski et al. [17], study, the effect of turbine interaction on aerodynamic forces was analyzed using advanced simulation models, reflecting the importance of these tools in simulating the effects of air on moving objects. This analysis can be directly applied to elevators in terms of reducing the drag caused by the air interacting with the elevator cabin. Czyż et al. [18] noted the increased aerodynamic drag in speedboats, highlighting the importance of careful engineering and component design to minimize adverse forces – a principle that can also be applied to elevators to reduce drag. As in Rogowski et al. [19], study, which examined the performance of the NACA 0018 wing under low-turbulence flow conditions, focusing on the behavior of lift and drag coefficients at low Reynolds numbers. This research reflects advances in the use of numerical tools to understand and optimize aerodynamic forces, providing valuable guidance for reducing air resistance in elevator cabin design.

Hoistway design, aerodynamic forces, and pressure dynamics during elevator operation

Research on the aerodynamic properties of high-speed elevators has witnessed gradual development. For example, during the period 2019–2024, it has moved from initial theoretical models to comprehensive models supported by field experiments. Yang et al. [20], conducted a valuable study on the aerodynamic properties of high-speed elevators using numerical simulation (CFD), demonstrating a quadratic relationship between aerodynamic forces and operating

Table 1. Summary of research on cabin design and its effect on elevator aerodynamic performance

Ref.	Year	Figure	Tools used and method	Mean results
[8]	2015	 a) Without cover b) $h=0.4\text{m}$ c) $h=0.8\text{m}$ d) $h=1.2\text{m}$	CFD (Fluent Software)	As the height of the diversion cover increases, the drag force on the elevator decreases. Pressure and velocity distributions improve with higher covers, leading to more uniform flow characteristics.
[9]	2022	 (a) 1/4 round (b) Triangle (c) Trapezoid (d) Semicircle (e) Three-sided guide shape	CFD (Fluent), Dynamic grid simulations	Deflector shapes significantly affect the elevator's aerodynamic performance and energy consumption under various speed conditions.
[10]	2023	 (a) Hoistway Elevator	CFD, POD, DMD	Modelling aerodynamic pressures using data-driven approaches (POD, DMD) in super high-speed elevators improves computational efficiency.
[11]	2023	 Car door Car body Toe guard on the top of the car Airflow shroud structure Toe guard on the bottom of the car	CFD	Finding that different toe guard configurations reduce drag and noise effectively.
[12]	2023		Surrogate models (RBF, EBF), NSGA-II algorithm, CFD simulations	The study focuses on the aerodynamic optimization of high-speed elevator fairings using a multi-objective optimization approach. The fairing's aerodynamic drag and yaw moment are optimized using surrogate models.

[13]	2024		RNG k- ϵ Turbulence Model, FVM, SIMPLEC Algorithm, Experimental Test	Disclosure areas of separation and swirls with higher accuracy, design d reduced clouds by 60.13%and the results are close, average error is less than 5%.
[14]	2024		large-eddy simulation Curle acoustic theory	Increasing the guide surface can significantly reduce the pressure difference between the upper and lower parts of the car. The number of guide surfaces, installation position and vertex offset significantly impact drag and lateral force.
[15]	2024		Bionic design, Numerical simulation	The study introduced a boxfish-inspired bionic flow guide for high-speed elevators. Compared to a traditional rectangular structure, the drag coefficient was reduced by 71.5%, and vibrations were minimized.
[16]	2025		CFD, NURBS curves, Genetic algorithm, multi-island genetic algorithm	Fairing is designed to improve aerodynamics by reducing aerodynamic resistance.

speed or distance from the shaft wall. However, the results were more descriptive than analytical, with some realistic elements excluded from the model, limiting the comprehensiveness of practical application and making the study closer to a

theoretical framework than to direct engineering solutions. In contrast, Qiao et al. [21], presented the unsteady flow resulting from the piston wind phenomenon based on the Bernoulli equation, with a sensitivity analysis of parameters related

to distance and obstruction ratio. In the same year, Zhang et al. [22], presented a general model of airflow in an elevator shaft with multiple vents, explaining the effect of the number and dimensions of the vents on improving ventilation and reducing noise. Qiao et al. [23], also focused on analyzing the sensitivity of piston winds, emphasizing that the obstruction ratio and car speed are the two most influential factors in amplifying aerodynamic forces. In 2020, the scope of the research expanded to the applied side, with Cui et al. [6], studying the effect of blockage ratios on the aerodynamics of high-speed elevators, showing that increased blockage increases drag and lift and increases air turbulence behind the cabin. Meanwhile, Qiu et al. [24], presented an innovative approach by gradually partitioning the pressure curve inside the car, using the PSO algorithm to achieve multi-objective optimization that combines passenger comfort, energy efficiency, and aerodynamic stability. This represented a qualitative transition from theoretical analysis to practical application. In 2021, Zhang et al. [2], introduced 3D simulations using a multi-region dynamic partitioning method to study the effect of air vents on airflow, identifying optimal locations for vents in the middle of the shaft or on its upper and lower sides. In 2023, research expanded in three main directions: Liu et al. [25], presented a multi-parameter model and a general formula for the ventilation rate, with car speed and blockage ratio as the most important parameters. Sensitivity, which gave the research direct practical value in engineering design. Xu et al. [26], then relied on large eddy simulation (LES) and acoustics theory to analyze aerodynamic noise, demonstrating that vortex separation behind the car is the main factor in noise generation and that the sound pressure level is linearly related to car speed. Yang et al. [27], considered the entire operating phase (acceleration, constant speed, deceleration) and incorporated additional variables such as the blockage ratio and the height of the shaft and cabin, clearly revealing that the pressure resistance is the most influential factor in elevator vibrations and noise. In a more comprehensive move, in 2024, the studies evolved to include field verification. Zhang et al. [28], presented an advanced three-dimensional model for analyzing the aerodynamics at the cabin-counterweight intersection, reinforced with experimental verification to ensure the reliability of the results.

The study clearly demonstrated the influence of the blockage ratio and distance. The length depends on the change in aerodynamic forces, but it remains confined to the computational aspect rather than the practical aspect. Zeng et al. [29], expanded the scope of their research to include the vehicle-counterweight system, using an unsteady three-dimensional dynamic mesh-based model. They demonstrated that reducing the distance between the vehicle and the counterweight leads to a significant increase in drag and lift at the intersection moment, threatening operational stability. Thus, despite their contributions, these studies reveal a clear gap in the absence of direct applied solutions to reduce vibration and noise, highlighting the need for future studies more closely linked to practical design. Table 2 provides a summary of the above-mentioned research, including the most important results reached by researchers when studying the aerodynamic characteristics under the influence of aerodynamic force distribution, crane path design, ventilation location, and other factors.

VIBRATION PERFORMANCE

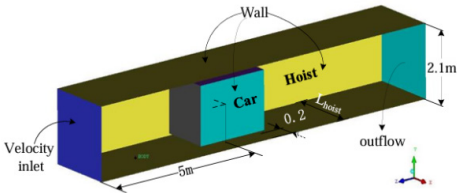
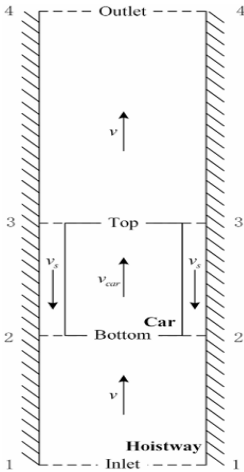
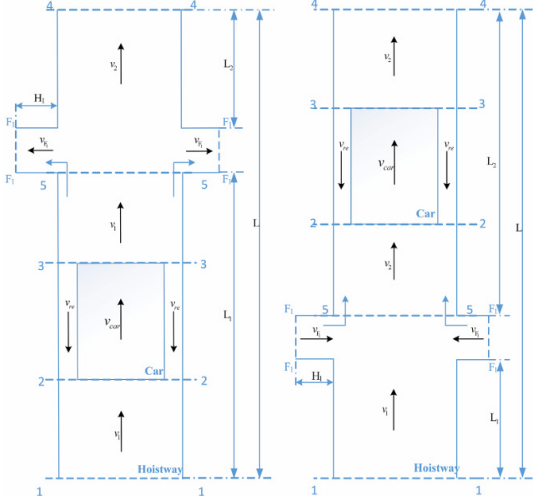
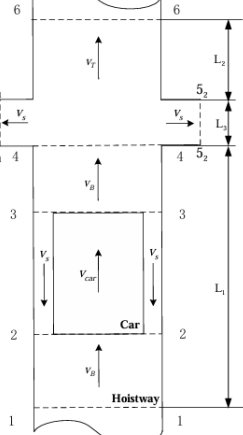
Vibration performance in elevators of high-speed is critical to passenger comfort and safety. The dynamics of vibrations experienced by elevator cars, particularly in ultra-high-speed systems, are influenced by various factors, including structural characteristics of the building, the design of the elevator components, and environmental conditions.

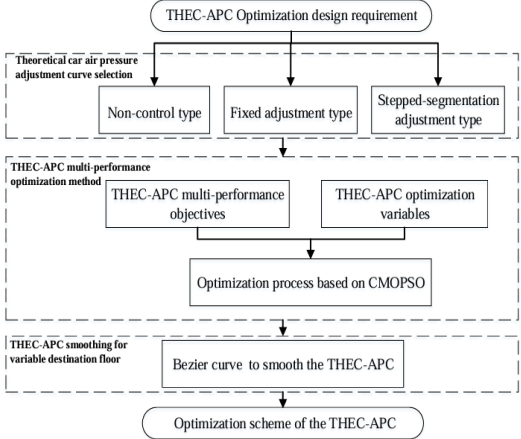
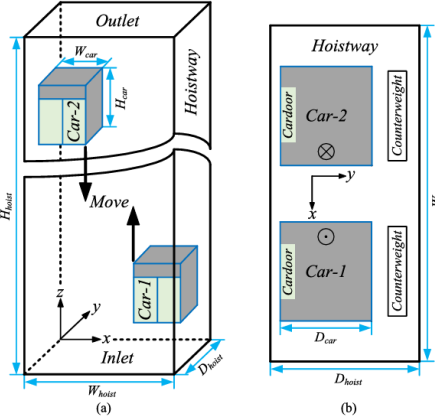
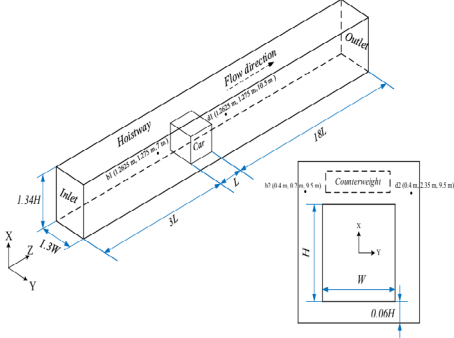
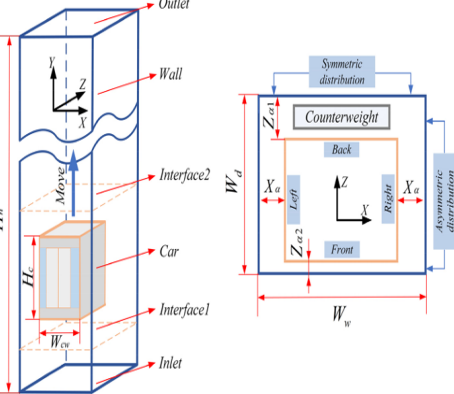
The elevator passengers are feeling cabin vibrations. Thinking of the cabin as a rigid body. All directions experience high-frequency delays up to 10 Hz. Their main sources are [30]:

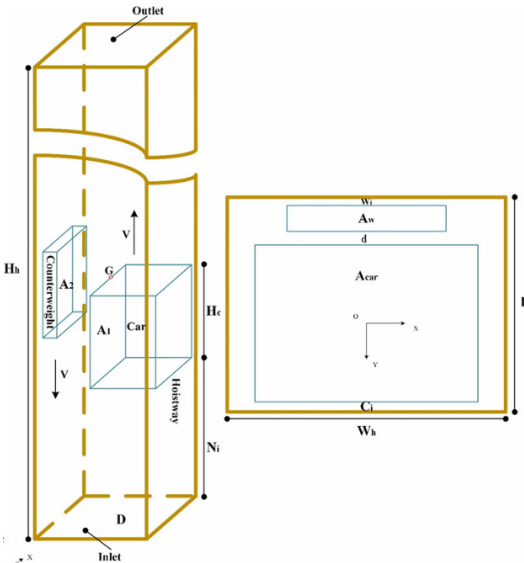
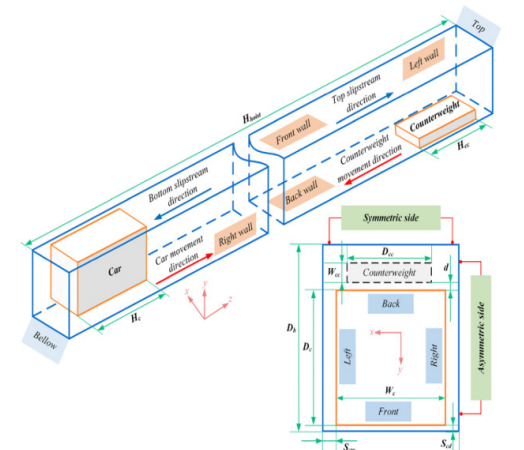
- the primary source of disturbance that affects riding comfort is the guide rails' unevenness,
- aerodynamic forces are produced while the elevator cabin moves through the hoistway,
- additional small causes of high-frequency disruption are the movement of passengers inside the cabin and forces exerted by the mechanism of the door.

The frequency content of low-frequency disturbance forces is less than 1 Hz. The suspension cables and the asymmetric cabin loads cause them. Compared to the high-frequency disturbance forces, their amplitudes

Table 2. Summary of research on elevator shaft design and its effect on aerodynamic forces and pressure distributions

Ref.	Year	Figure	Tools used and method	Mean results
[20]	2019		CFD, Fluent	Airflow patterns are greatly influenced by operating speed and the distance between the automobile and the shaft. Increasing pressure and turbulent kinetic energy with higher speeds.
[21]	2019		CFD (Fluent), Theoretical Analysis	A theoretical model was developed for car-induced unsteady airflow in elevators. It analyzes key parameters like airflow and ventilation rate, and its results are validated by experimental data.
[22]	2019		CFD (Fluent), Analytical Model	With the same cross-sectional areas, the increase in VH gradually reduced the weakening trend of the airflow in the hoistway.
[23]	2019		CFD, Analytical model	Larger ventilation hole areas effectively reduce the piston wind intensity. Small changes in vehicle length have a negligible effect.

[24]	2020	 Figure 1. Introductory paragraph of the proposed method.	PSO Algorithm, CFD	A stepped-segmentation approach was presented to alter air pressure curves, maximizing elevator comfort and energy consumption. The optimization improved the accuracy of air pressure regulation.
[25]	2023		CFD, Experimental validation, gray correlation analysis	The blockage ratio affects the Piston wind in the elevator hoistway, followed by the car speed, hoistway height, and frictional resistance coefficient, and is least affected by the car height.
[26]	2023		LES model, Curle acoustic theory	Vortex shedding, flow separation, and recombination are key factors in noise generation. The sound pressure level (SPL) increases with car speed, and car deflection angles influence noise characteristics.
[27]	2023		CFD Ansys flunt, RANS with k-ε RNG	The suction lift was reduced by 31% with deceleration and the ventilation increased by 52.6%, Compressive resistance is much greater than viscous resistance, and the height of the car has more effect on lateral lift, while the height of the well increases the total pressure.

[28]	2024		CFD, Dynamic Layering Method	Drag and lateral forces suddenly change as the car crosses the counterweight, with the blockage ratio having the most impact on drag.
[29]	2024		Fluent (CFD), MRDLC- CSM method	The blocking ratio increases with the pressure drag, and viscous drag has similar change trends at each stage, but the influence of pressure drag is more significant. The spacing significantly affects the car's aerodynamic characteristics during the intersection.

are significantly larger. The other causes directly impact the cabin structure or the cabin itself, whereas rail disturbances impact the cabin through the roller guide shoes.

One of the most prominent components that transmit these vibrations to the cabin is the grippers, which form the link between the rails and the passengers. These vibrations are studied through their dual impact on user comfort, where they lead to a feeling of instability, dizziness, or sensory discomfort when moving at high speeds, reducing ride comfort. They also affect the structural system of the elevator and the building, where they cause wear on the rails and increase noise and dynamic stresses, reducing the life of the system components and affecting the elevator's efficiency. Studies have addressed multiple strategies for reducing these impacts, including the use of hydraulic or electromagnetic

gripper shoes. For example, [31], showed that the use of guide shoes with a hydraulic damping mechanism reduced horizontal vibrations by 21–27% compared to conventional systems. It also significantly improved passenger comfort during the journey and reduced wear rates on the rails, thus extending the system's operational life. [32], also developed a system based on electromagnetic steered shoes integrated with intelligent control algorithms (such as Sparrow Search Optimization). The results showed that this system significantly reduced vibration amplitude and responded more quickly to sudden changes in load or elevator speed, providing greater passenger comfort and improved building stability. Incorporating these technical innovations into high-speed elevator systems not only contributes to improving passenger comfort and safety, but also enhances

elevator sustainability by reducing the need for periodic maintenance and extending the life of structural components.

Types of vibrations

As mentioned, vibrations in high-speed elevators are a fundamental challenge in mechanical engineering, as they significantly impact passenger comfort and system efficiency. Therefore, they are divided into two main types: (i) vertical vibrations resulting from the elevator's ascent and descent movements, (ii) horizontal vibrations, which have the greatest impact on passenger comfort. Horizontal vibrations significantly affect stability and balance within the elevator, and their intensity increases with increasing elevator speed, leading to passenger comfort problems such as dizziness and nausea. Given the importance of this issue, an increasing number of studies have addressed the analysis of these vibrations and provided solutions to improve their performance through mathematical models and advanced control techniques.

Several recent studies have demonstrated significant progress in understanding and analyzing the horizontal vibrations of high-speed elevators, addressing the various factors influencing this phenomenon. Studies presented a complex dynamic model of elevator vibrations [33], focusing on the effect of the interaction between the movement ropes and the elevator itself, as well as defects in the guide rails. However, the study did not adequately consider the effects of wind or environmental changes that may affect elevator performance in real-world environments. While [34], provides a detailed analysis of the properties of governing in elevator withdrawal systems, highlighting the impact of the load on natural frequency and solidity. The results indicate that the increase in the load leads to improving damping, which enhances the system performance. However, the study reveals a noticeable effect of the direction of the elevator movement, where the damping is greater when moving down, which opens the way for more research on the effects of different directions on the efficiency of the system. In contrast, [35], examined the effect of wind on high-speed elevators, showing that the effect increases with building height. However, this study relied on a simple wind model and did not incorporate the complex interaction

between wind and elevator geometry, which may limit the accuracy of predictions in many cases. [36], presented an innovative approach based on fluid-solid interaction to analyze horizontal vibrations, integrating aerodynamic forces with mechanical dynamics, contributing to an accurate model. However, the study did not address sudden changes in air movement or the effects of extreme weather, a significant limitation of this model. Study of dynamic models for analyzing elevator vibrations under different conditions that dealt with the vertical vibrations of the elevator using the central block division model [37], explaining the effects of the elevator movement and the emergency arms on its performance. While study [38] dealt with crosses of a high-speed elevator under the influence of air disorders, focusing on the effects of aerodynamics using CFD simulation. Despite the importance of the results reached in improving the understanding of the dynamics of elevators, both studies lack adequate dealing with practical challenges in realistic systems, such as the effects of changing urban environments and various elevators. On the other hand, presented a joint study on the effect of wind and guidance systems on horizontal vibrations [39], demonstrating the effect of elevator speed on the resulting vibrations. However, this research ignored other environmental influences, such as changing weather or sudden temperature changes that may affect elevator materials. Zhang et al. [40], presented an innovative solution for controlling horizontal vibrations using neural algorithms and fuzzy logic, and their results demonstrated the effectiveness of the control in reducing vibrations. However, the proposed model was limited to theoretical models without studying practical application under real-world conditions or emergency situations, which is a weakness of this study. Studies explored an active shock absorber control system for high-speed elevators, and their results demonstrated its effectiveness in reducing vibrations [41]. However, these techniques were not integrated with conventional elevator mechanical systems, representing a gap in real-world applications. On the other hand, a study of the symbolism method for lowering vibrations [42], dealt with the use of new techniques to control vibrations, such as “jerk” and upgrading the speed control unit using the vertical ban filter. This approach addresses the effects of vibrations caused by the

mechanical system frequencies of the elevator that interfere with engine vibrations frequencies. Although this study provides innovative and effective solutions, the point that can be criticized is that the method relies heavily on knowing the natural frequencies of the mechanical system of the elevator. In the event of changes in these frequencies or non-optimum operating conditions, proposed solutions may be exposed to deficiencies. Hence, the need to develop smart systems that are able to adapt to changes in the work environment without the need for a continuous adjustment in software or devices. Thus, most subsequent studies, including [43–50], focused on control systems (such as LQR, slip control, and predictive control), which aim to directly reduce acceleration and displacement. These systems have proven effective in simulation, but they suffer from limitations such as the need for high-resolution sensors and increased complexity in field implementation. In contrast, a recent trend has emerged, represented by [51] the use of digital twins. This approach does not directly reduce vibration, but rather builds a live dynamic model of the elevator, enabling prediction of vibrations before they occur and providing recommendations for adjusting operation or maintenance. The advantage of this approach is that it enhances the ability to diagnose early, but it remains limited if not integrated with active control systems. Therefore, it can be said that development in this field is moving toward integrating digital twins with active control systems, so that the system becomes capable of prediction, preventative treatment, and immediate correction. This represents the future of vibration management in high-speed elevators. In other words, vibration management in high-speed elevators has shifted from traditional mechanical solutions (such as rail optimization) to hybrid, intelligent solutions that combine hydraulics, electromagnetism, and advanced algorithms.

Table 3 shows the most important research that focused on vibration types, and the proposed solutions to reduce them.

In addition to cabin and hoistway design, vibration types, and control, drive technologies emerge as a key complementary factor. Recent studies [53, 54, 56] have shown that gearless traction systems with PM motors and VFD or S-curve control contribute to reduced mechanical effort and improved

passenger comfort. Although these studies do not constitute a major focus like the previous ones, their findings underscore the importance of integrating drive technologies with aerodynamic solutions to ensure integrated performance. Therefore, high-speed elevators are moving toward the use of gearless permanent magnet (PM) traction motors, due to their efficiency and quiet operation. In a study [52], presented a Gearless Traction Machine with a PM motor, which has proven reliable and capable of operating under severe operating conditions for extended periods. On the other hand, several researchers have relied on the use of phase-shifted linear synchronous motors (PMSLM) within S-curve-based VFD systems to achieve smoother traction speed control. Study demonstrated that this approach reduces jerk by up to 88% and improves passenger comfort [53]. Similarly, [54], developed a prototype using V/f control with an S-curve, demonstrating high efficiency in reducing motor gaps during stop-start and start-stop operations. Research has also highlighted machine-room-less (MRL) traction systems based on sleek, in-house PM motors. This design reduces the need for a large motor room and maximizes space utilization. Studies emphasized the importance of selecting the right motor within these systems to ensure optimal performance [55]. Finally, [56], discussed the historical developments in propulsion technologies, starting with Ward-Leonard systems to provide smooth speed control, through VVVF systems, and up to modern PM drives that reduced the need for special operating rooms and were embedded directly within elevator towers.

LIMITATIONS AND FUTURE DIRECTIONS

This review demonstrates that the study of the aerodynamic properties and vibration performance of high-speed elevators cannot be approached in isolation, but rather should be viewed as an integrated system comprising three main axes: cabin design, hoistway design, and vibration control mechanisms. Understanding the interrelationships between these axes is key to interpreting current challenges and proposing more efficient solutions. From the cabin design perspective, most studies have focused on improving aerodynamics using engineering

Table 3. Summary of research on vibrations in high-speed elevators and some strategies to reduce them

Ref.	Year	Tooles used	Method	Key result
[33]	2022	MATLAB/Simulink, Galerkin Method	The study uses the generalized Hamilton's principle to derive the kinematic vibration equation and solves it with the Galerkin method. The influence of perturbation frequency, irregularity type, and operating velocity on the vibration is analyzed.	This study models the horizontal vibration of high-speed elevators considering multi-component coupling, including the traction rope, car system, and guide rails. The model accounts for perturbations such as rope-sway, guide rail irregularities, and vibration inconsistencies. The results are verified with experimental data from a high-speed elevator.
[34]	2022	Experimental setup, test bench	Experimental analysis of vibration damping	Findings indicate that damping increases with elevator load and differs between upward and downward motion.
[35]	2021	MATLAB, Numerical simulations	Vibration modeling of elevator and building interaction under wind load	Findings indicated a correlation between wind pressure, building height, and horizontal vibration of elevator guide rails.
[36]	2022	CFD, FSI, MATLAB	The FSI model incorporates airflow in the hoistway, guide rail deviations, and dynamic parameters of the guide shoe.	It presents a fluid–solid interaction (FSI) model to analyze the horizontal vibration of a high-speed elevator car. The FSI method is coupled bidirectionally to represent accurately the interaction between the car and airflow, with experimental validation showing high accuracy.
[37]	2020	MATLAB, Experimental setup.	Centralized mass discretization model, vibration testing	Significant vertical vibration was found under emergency braking conditions, especially during upward motion.
[38]	2019	CFD, Newmark method	CFD-based simulation, vibration analysis	It found a significant impact of rotational angle and operating speed on vibration acceleration.
[39]	2019	Fluent, MATLAB, Newmark-beta method	The horizontal vibration dynamic model is solved using the Newmark-beta method, and dynamic responses are analyzed at different rated speeds.	Resonance occurs when the excitement frequency corresponds to the natural frequency of the system, which leads to an enlarged vibration capacity. The noticeable acceleration at speeds above 6 m/s is the result of this phenomenon, and not a cause of its occurrence.
[40]	2020	Finite Element Analysis, Numerical Modelling.	Discretization of differential equations, vibration modelling	Increased cord length reduces the normal frequency of the system, which makes its compatibility with the excitement frequency more likely, and thus increases the risk of resonance and the high acceleration of longitudinal vibration.
[41]	2018	MATLAB/Simulin, Neural networks	Active shock absorber modelling,intelligent control	Investigated intelligent control for suppressing horizontal vibration using active shock absorbers. The system showed significant improvement over traditional damping methods.
[42]	2019	Lagrange Approach, Harmonic Response Analysis.	The research uses the Lagrange approach to develop seven degrees of freedom dynamic model for the elevator system, followed by harmonic response analysis to evaluate vibration characteristics.	The study establishes a dynamic model for a high-speed traction elevator and conducts harmonic response analysis to investigate the elevator's vibration characteristics. The study identifies the significant effects of elevator car load, rubber stiffness under the car and tractor, and the lifting height on vibration. It also shows that increasing the rubber stiffness under the tractor can significantly reduce vibration amplitude.
[43]	2024	MATLAB/ Simulink,PD Controller	Use a six-degree-of-freedom dynamic model of the elevator car. Develops an adaptive control scheme.	The active shock absorber may cut oscillation time, peak acceleration, and vibration displacement by almost two-thirds.
[44]	2024	MATLAB/Simulink	6-degrees of freedom, LQR feedback control with prescribed performance	Proposed a transient response feedback control for horizontal vibration suppression in elevator systems, achieving reduction in horizontal vibration.

[45]	2023	MATLAB, least-squares method, Hankel-Toeplitz model	The Hankel-Toeplitz model of transverse vibration is derived by studying the phenomenon of hysteresis due to excitation and response. The least squares method is used to determine the parameters of the elevator system model by combining the measured vibration acceleration data of the high-speed elevator.	An active damping control strategy is designed in adaptive slip mode for instantaneous energy.
[46]	2022	MATLAB, JWPSO algorithm	LQR control with JWPSO optimization	Proposed a new optimization method (JWPSO) for LQR controllers, improving horizontal vibration control in elevators. Simulation showed superior performance compared to traditional methods.
[47]	2024	MATLAB/Simulink	Active vibration control, multi-objective genetic algorithm	suggested an active control technique for horizontal vibration suppression in high-speed elevators based on acceleration feedback.
[48]	2020	MATLAB/Simulink	Nonlinear predictive control, simulation	Explored nonlinear predictive control of horizontal vibration. The proposed control method reduced horizontal vibration more effectively than traditional PID controllers.
[49]	2021	Fuzzy neural network controller, Gas-liquid active guide shoe	A fuzzy neural network combined with gas-liquid active guide shoe; control is designed to mitigate horizontal vibration	The fuzzy neural network controller was used to reduce vibration acceleration under various loading conditions.
[50]	2021	The rey algorithm and back propagation (FA-BP) algorithm fuzzy neural network (FNN)	The dynamic model of a car system is constructed, and the FNN system-based non-parametric model of the MR damper is established with the original MR damper data collected from experiments	This paper proposes a new method for variable fuzzy control of semi-active steering shoes equipped with magneto-rheological (MR) dampers.
[51]	2024	Digital Twin (DT) technology, Support Vector Regression (SVR), Transfer Learning (TL)	The study combines digital twin modeling with transfer learning to predict horizontal vibrations of HSEs. A support vector regression (SVR) model is used for data-driven predictions based on the fused DT data.	Results indicate the TLDT model outperforms other prediction models, with improved accuracy for peak-to-peak and vibration acceleration values.

additions such as fairings or toe guards, or through biomimetic designs. These efforts have helped significantly reduce air resistance and noise, but they have often been limited to CFD studies and have not been supported by extensive field experiments. Conversely, some experimental studies have shown that simple, low-cost modifications may be more effective and feasible, raising questions about the balance between design complexity and economic feasibility. Regarding hoistways, the literature has shown that controlling the blockage ratio and adjusting the air vents play a key role in managing internal pressure and reducing piston wind. However, the results of studies have not always been consistent; while some studies have found the size of the air vents to be the most important factor, others have emphasized that the strategic location of these vents has a greater impact on internal stability. Importantly,

most of these studies were conducted under ideal operating conditions and did not fully simulate external influences, such as building flexibility or wind fluctuations, leaving a clear research gap. Moving on to vibrations, researchers have agreed that they represent the most sensitive aspect for passengers, directly impacting ride comfort. Their sources range from mechanical roughness in the rails, aerodynamic forces within the shaft, and structural effects of the building. In this context, innovative solutions have emerged, such as hydraulic and electromagnetic guided shoes, as well as active damping systems based on artificial intelligence algorithms. However, despite their technical feasibility, these solutions face challenges related to increased cost and maintenance complexity, as well as limited field trials to prove their sustainable performance. Even if you design a streamlined cabin and reduce

vibrations, an underdeveloped propulsion system can lose all the gains due to jerk or speed fluctuations. Additionally, smart propulsion technologies (such as S-curve + VFD or Digital Twin for the motor) help mitigate vibration and enhance passenger comfort, thus directly linking to the findings of the previous section.

From a broader perspective, one can trace the development of scientific research in this field. Until 2015, the focus was on purely mechanical solutions, such as optimizing the cabin shape or reducing rail roughness. After 2018, advanced numerical algorithms such as PSO and GA began to be incorporated into design optimization. Recent years (2020–2024) have seen a clearer shift toward integrating artificial intelligence, digital twins, and biomechanical solutions, reflecting the field's transition from piecemeal improvements to integrated, more intelligent systems.

However, common limitations remain among most studies, which can be summarized in points:

- Overreliance on numerical simulations and a lack of field experiments.
- Lack of integration of human comfort indicators (such as occupant psychological and sensory responses) into performance evaluation.
- Poor integration between cabin design, the hoistway and the building as a whole, as each axis has often been treated in isolation.

Based on these observations, several future directions can be proposed:

- The need to conduct field experiments in real operating environments to verify theoretical results.
- Incorporating human comfort measures as part of performance evaluation criteria, rather than relying solely on physical data.
- Developing integrated models that include the impact of building dynamics, not just the elevator as a standalone structure.
- Investing in artificial intelligence and digital twin technologies to create systems capable of predicting failures and controlling vibrations and pressures in real time.
- Researching low-cost, highly effective solutions to ensure industrial applicability alongside technical effectiveness.

From this comprehensive analysis, it becomes clear that the future of high-speed elevators will not stop at improving aerodynamic performance or reducing vibrations alone, but

will move towards an integrated system that balances safety, efficiency, comfort, and sustainability, so that the elevator becomes a harmonious element within both the building and its surrounding environment.

CONCLUSIONS

The study of aerodynamic and vibration characteristics in high-speed elevators should be approached as an integrated system encompassing cabin design, elevator track, and control mechanisms, rather than viewing them as separate axes. The literature also reveals an overreliance on numerical simulations, limited field experiments, and a lack of integration of human comfort indicators and building dynamics. Historically, research has evolved from simple mechanical optimizations to advanced numerical algorithms, and then, in the last decade, to artificial intelligence and digital twin technologies. Accordingly, the future direction requires enhancing practical testing, integrating comfort and sustainability criteria, and developing smart, low-cost solutions that ensure efficiency, safety, and passenger comfort simultaneously.

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