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# Research Development on the Comfort of Human Taking the Elevator

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## Abstract

The safety and comfort of the elevator have an important influence on the human body. The vibration depression measurement of vertical and horizontal vibration along with noise cause of the elevator has been summarized then. Till now, the study on the vertical vibration usually focused on of different degrees of freedom model establishment due to its dominant role at low speed. The horizontal vibration is mainly generated at the high-speed operation of the elevator. The vibration control method has been changed from passive and active control in some existing research. Then the elevator vibration control system had been improved. And the reasons of the elevator noise generation and reduction measurement have been introduced. Most all the researches are mainly about the establishment and improvement of the motion model but lack the comprehensive research model combined human and the elevator. In addition, the research on the safety and comfort of human is inadequate and there is no analysis on the ride comfort of human now. In the conclusion section the establishment of human-elevator comprehensive simulation and experimental model has been proposed. It provides a combination direction for the medical and engineering in the future work.

## Keywords

Elevator, Noise, Vibration Depression, Safety, Comfort

## 1. Introduction

With the development of the modernization of the city, the high-rise buildings have become the important symbol of the modern cities. As a vehicle for high-rise vertical buildings, the demand for elevators is increasing also which play an important role in the modern person's life [1]. Also the performance, ride safety and comfort requirements of elevators are required higher and higher. Under the premise of safety, the comfort is an important indicator of elevator riding as well. Because of the vibration and noise of the elevator mechanical system, the personnel comfort has been affected which limits the riding sense of the elevator [2].

The factors affecting the vibration of elevators and the research on noise at home and abroad have been described in this paper [3]. It is pointed out that both of the research direction and the deficiency of the research at home and abroad, providing some basis for restraining the vibration of the elevator and suppressing the noise in the future. At the same time, the problems affecting the ride comfort of elevators from different angles have been expounded either which provide the research direction for the humanized development of elevators [4].

## 2. Research Status of Elevator Vibration

The vibration of elevator has a great influence on elevator operation. According to the different factors, the vibration can be divided into two aspects: vertical vibration and horizontal vibration.

## 2.1. Vertical Vibration

The upper and lower running of the elevator is obviously influenced by vertical vibration. At present, the research of vertical vibration mainly includes: by analyzing the factors of vertical vibration of the elevator such as rotating imbalance, Zhang Changyou has put forward the dynamic vibration absorber on both sides of the car roof wheel through dynamic simulation analysis, as to achieve the effect of vibration reduction [5]. Liu Xihua has established a 7-DOF model with a traction ratio of 1:1 as shown in Figure 1. Among them, $m_1$-$m_5$ is the equivalent mass, counter-weight mass, the car, car frame and the accessories mass of the traction machine, the traction machine base and the guide wheel; $k$ and $c$ are respectively the rigidity and damping of the weighing beam and the anti-vibration pad, the torsional rigidity and the damping of the traction machine, the rigidity and the damping of the rope head spring, and the equivalent rigidity and damping of the trailing wire between the counter-weight and the tensioning wheel, between the tractor and the car frame, the car frame and the tensioning wheel; $I$ and $R$ are respectively the equivalent rotational inertia and radius of the tensioning wheel and the traction sheave. In the dynamic model, the dynamic response of the elevator has been studied, and the vibration acceleration characteristics of the elevator system have been calculated under the influence of the rotation imbalance and the rigid inertia force of the elevator system. Studying on the effect of acceleration under two kinds of comprehensive conditions, differential equations have been established to solve the vibration characteristics under single excitation and integrated excitation. It has been concluded that the vibration study under the comprehensive excitation is more consistent with the actual situation [6].

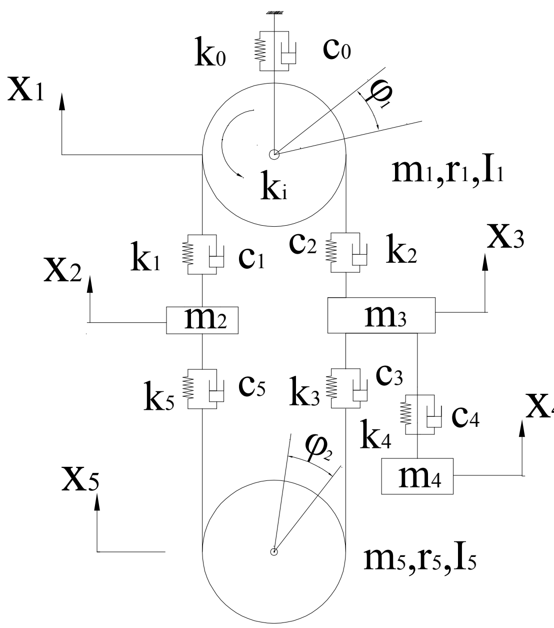


*Figure 1. Vertical vibration dynamic model of elevator with 7-DOF model for traction ratio of 1:1.*

Wu Limei has taken the traction elevator to carry on the dynamics model with a traction ratio of 2:1 as shown in Figure 2. Among them: $m_1$ - $m_6$ is the cage and the load, car frame and attachment, counter-weight and attachment, and the equivalent mass of the traction device, guide wheel, the car wheel and counter-weight wheel quality; $I$ is the equivalent rotational inertia of the traction device, guide wheel, the car wheel and counter-weight wheel; $R$ is the rope groove radius of traction sheave, crown wheel and counter-weight wheel; $k$, $c$ are respectively the rigidity and damping of the rubber, support beam and traction machine between the car and car frame. Then the dynamic model of elevator mechanical system had been analyzed and the time-varying system had been divided into a finite time invariant system for dynamic analysis. It has been concluded that the acceleration of the elevator varying greatly was at the beginning and braking stage. The change of acceleration has a great influence on vibration. And the elevator parameters have been optimized to improve the dynamic performance of the elevator furthermore [7].

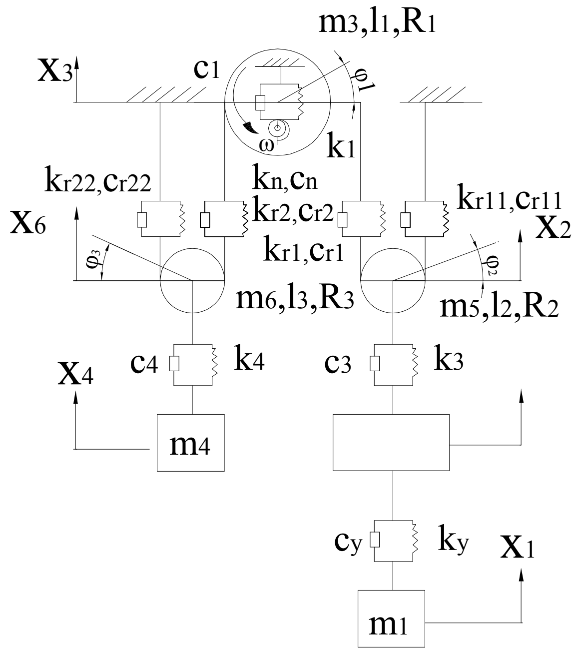


*Figure 2. Elevator dynamics model with 9-DOF of traction ratio 2:1.*

Yang Jincai et al. have established a single DOF vibration model through test data, and have analyzed the factors affecting the vibration and frequency of the system parameters [8]. R. M. CHI has established the three DOF model based on the single DOF harmonic vertical vibration. Taking the top boundary of a lifting rope the relation between the free vibration mode under uniform boundary conditions and the forced vibration under non-uniform boundary conditions has been analyzed, and the calculated values of relevant natural frequencies in two states have been compared then [9]. Dong-Ho Yang et al. have established the dynamic model of elevator rope coupling vibration analysis by energy method and Hamilton theory. The theoretical model proposed by the experimental test platform is validated to predict the vibration of elevator rope under various conditions [10]. Bao Jihu has taken the longitudinal vibration of the steel wire rope which has been changed the length as the test object and the ideal running curve of traction elevator obtained by five polynomial fitting has been used as output. And then Matlab software was used to simulate the condition. Finally it can be drawn the conclusion that the vertical vibration of the uplink is obviously higher than that of the downlink [11]. Vertical top hydraulic lift had been equivalent to the DOF spring-mass-damping mechanical model by He Wenhai shown in Figure 3. Among them, $m$ is the quality of the hydraulic elevator car and plunger; The hydraulic cylinder had been equivalent to a $m-k-r$ system with rigidity coefficient $k$ and damping coefficient $r$. The dynamic simulation of vertical vibration has based on Matlab/simulink software. By analyzing the forced vibration, non-excitation free vibration, random accompanying vibration and stable forced vibration, the main factors that influence the vibration are the stable and forced vibration, which provides the basis for vibration suppressing [12]. Angelo M. Tusset et al. have proposed to use the control of a magnetorheological damper (MR damper) to reduce the vibration of the elevator [13]. At present, the research on vertical vibration of the elevator is mainly on the modeling and analysis method, but the modeling precision under different structures has still been improved.

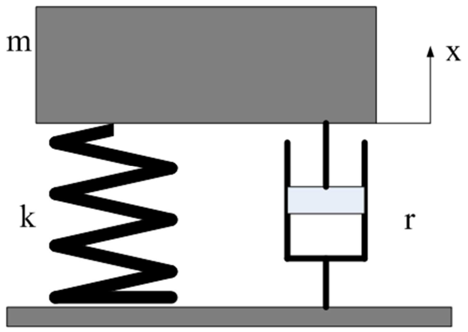


***Figure 3.*** *Equivalent of spring-quality-damping.*

## 2.2. Horizontal Vibration

When the elevator is running at high speed, the effect of air interaction between the car and the elevator shaft gradually increases, so that the horizontal vibration can not be neglected at high speed. At present, the researches on the horizontal vibration are as follows: Li Lijing et al., through the horizontal vibration model of the two DOF elevator car, have analyzed that the main reason that affects the horizontal vibration is the guide rail system [14]. Yin Jicai et al. has studied the force of the guide wheel on guiding boots through analyzing the horizontal vibration of the high-speed elevator bridge, and the model of the contact force between rolling guide boot and guide wheel had been established, converting the contact force of different guide rail excitation of the elevator into the contact force of guide wheel to guide wheel as shown in Figure 4, and the cylinder is in contact with the plane between rolling guide boot and guide rail. The axial length of cylinder is $L$. And a theoretical model has been established by simulation analysis in the paralle to the y-axis with a rectangular strip of width 2a. From relevant experimental verification, the vibration curve of experiment is consistent with the vibration curve of theoretical model, so as to help to reduce the horizontal vibration [15]. Guo Lifeng has established a 12 DOF nonlinear vibration system model by using the method of elevator car-guide coupling. Analyzed and studied from time domain and frequency domain, the rail installation system has been improved [16]. According to tunnel effect principle of the elevator, Duan Ying et al. have observed the distribution of the gas flow field around the elevator car as shown in Figure 5. Among them, $A$ is the cross-sectional area of elevator channel at both ends of the opening, channel and the car body. $P$ and $T$ are respectively the pressure at the box body and the gas temperature, the pressure and temperature at gas gap, the total pressure and temperature of the outside of the channel. $U$ is running velocity of the box, $V$ is gas flow velocity at the opening at both ends, and the air flow velocity at the gap of the box. $X$ is the displacement of the box. $L$ is the total length of the channel, and $L_0$ is the length of reserved space. The aerodynamic characteristics of high speed elevator had been tested, and surrounding flow field had been observed and analyzed under different conditions, obtaining the influence of tunnel parameters on horizontal vibration of the car [17]. Wang Wen et al. through the buildings in different frequency shaking situations, have calculated lateral vibration response of elevator suspended system and the effect of damping on vibration, which can be concluded that changing natural frequency to avoid resonance and changing distribution damping can effectively reduce the amplitude of the ropeit [18]. Through the research of active rolling guide boot, Utsunomiya has installed active guide boot to the bottom of the car, which can effectively reduce lateral acceleration of the car [19]. Feng Yonghui et al. have studied horizontal vibration of elevator car through rigid body dynamics and space dynamics model. Under the conditions of disturbance parameter uncertainty, position robust control force has been designed by using Lyapunoa method to reduce horizontal vibration. And the mathematical model of active guide boot and elevator car has been designed by using hydraulic elevator. It has been shown that active boot can effectively reduce horizontal vibration through simulation analysis [20, 21]. Liao Xiaobo et al. through experimental study, have established a mathematical model of an elevator and based on LQR control of active control strategy to simulate. The optimum values of some parameters have been obtained and corrected, which provides a feasible method for horizontal vibration test of elevators [22]. E. Esteban et al. using Kalman filter as observer, have proposed a dynamic model of elevator installation in the state space domain, which can better understand the behavior of the elevator system and optimize the design and installation [23]. Fu Wujun et al. have used ADAMS elevator as hypothesized prototype model. On this basis, the influence of guide rail, spring, rigidity and damping coefficient on lateral acceleration has been analyzed, and the optimum parameters have been obtained [24]. Bojan Z. Knezevic et al. have proposed a coordinate to the vibration problem. The speed controller was modified with software. And a new procedure was introduced for determining the EMS resonant frequency [25]. With the increase of elevator speed, the horizontal vibration has more and more influence on elevator performance. At present, the main research direction has been gradually shifted from passive control vibration reduction to active control vibration reduction.

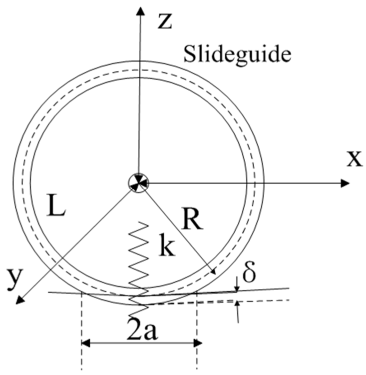


***Figure 4.*** *Normal contact model of guide wheel and guide wheel with 8 DOF.*

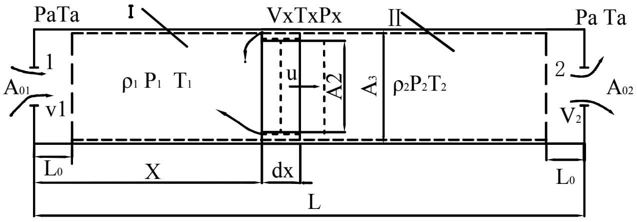


***Figure 5.*** *Gas state parameter model of elevator moving process.*

## 3. Research on Elevator Noise

Elevator noise has been generated in the operation, and the size of noise on human safety and comfort has varying degrees of impact. There are many reasons for the noise generated by elevator movement. At present, the mainly research progress is: Ding Zijia et al., by analyzing the causes of noise and combining with noise testing, have put forward the corresponding measures to deal with noise, such as elevator car noise sound insulation and sound absorption processing [26]. Lu Zhihua et al., through the study of noise transmission path from air and solid sound aspects, have proposed noise reduction method of sound insulation. The influence of sound insulation cover parameters on noise transmission in the field of air has been analyzed, and sound insulation cover's structure has been further improved. The elevator system has been equivalent to rigidity-mass-damping system in solid sound field as shown in Figure 6. Among them, $k$ and $c$ are respectively rigidity and damping coefficient of load - bearing rubber, rope head spring, steel wire rope, and car bottom rubber. $M$ is the quality of traction machine, rope head taper sleeve, car frame and car. According to dynamic model, vibration characteristics have been analyzed and local rigidity of car wall has been modified to achieve noise reduction [27]. Li Qi has simulated aerodynamic noise in high speed elevators through fluid and acoustic analysis software. The sound field distribution of elevator car outside and inside has been analyzed to provide reference for future elevator acoustics optimization design [28]. Du Xiaoqiang has established SEA model and analysed main influencing factors of car interior noise. By changing the interaction between rolling guide and guide rail, the sound pressure level in the car has been predicted. It has been concluded that the car can be effectively improved if operation speed is stable and rail condition is good [29]. Dong-mei et al., through describing and modeling noise problems on the conductor, have used linear elevator system to control air gap height to improve elevator performance to reduce noise [30]. Landaluze has reduced noise level by applying active noise control technology to elevator compartment [31]. At present, the main research is mechanical noise and aerodynamic noise. The effect of noise suppression and control on parameters of human body structure and the influence on the comfort of passengers are the research emphasis.

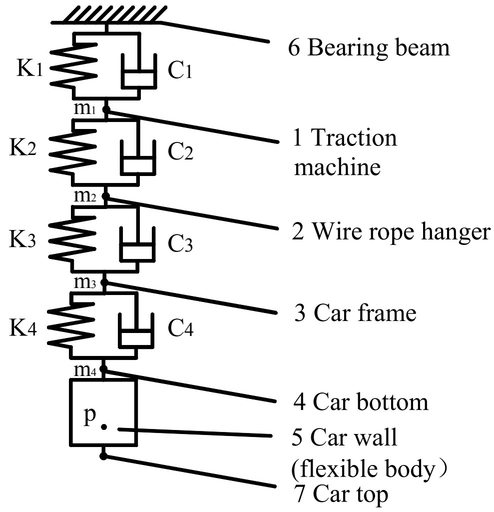


***Figure 6.*** *Considering solid transmission dynamics model of elevator.*

## 4. Comfort of Elevator Riding

With the development of economic society, when people take the elevator, the comfort requirement is getting higher and higher under the premise of safety guarantee. At present, the research is mainly reflected in: Chang Da et al. have taken straight top hydraulic elevator to analyze dynamic performance by means of the lateral restraint system. Different effects of PID and PDF control methods have been compared to find out the reasons that affect their comfort [32]. Mutoh N et al. have studied the main factors influencing the comfort of the elevator. The design of the guiding system, the defects of the installation of the guide rail itself, and the periodic variation of the rails in the horizontal stiffness are the main factors affecting the comfort [33]. Okada K. et al. have studied the incentive for the elevator in the airflow and the building. High-speed elevator in the operation has produced "piston effect" due to damping. The rapid flow of airflow has an effect on the vibration of car and traction wire [34]. J. Fernandez et al. have proposed a latency-optimized fuzzy logic elevator controller, which for the first time uses fully dynamic scheduling and possesses many excellent performances [35]. Zhang Peng has carried out experiments on elevator safety and comfort. The suspension system transverse-longitudinal coupling vibration model has been established as shown in Figure 7. The traction wire rope was passed as axial movement of the string and the elevator car is passed as the quality hanging in the bottom of the rope. When the longitudinal was free, the horizontal was constraint by the spring and damping. From the whole perspective, the horizontal vibration state has been analyzed by the distributed method, and the dynamic characteristics of suspension system has been studied. The dynamic response of different rails under excitation of the roughness was taken as the research object, and the method of reducing vibration was proposed to improve the ride comfort [36]. Liu Wen et al. have used Solidworks and ADAMS to establish virtual prototype model. High - speed elevator vibration was dynamically simulated and analyzed. The parameters were optimized to improve ride comfort [37]. Ying lean in the elevator plus (subtraction) speed experiment has proposed to evaluate the comfort through the subjective feelings of human body and combined with the anatomical and physiological functions of vestibular organs, which combined psychology and physiology. On the other hand, the "dynamic state diagram" and "EEG" method were used to express the impact on ECG and EEG and autonomic nerve during the elevator's acceleration change in order to study the impact of acceleration change on the comfort. Through the experimental, a new method was proposed to study the dynamic comfort of elevator: medical, physiological and psychological comprehensive evaluation [38]. Hamdi Taplak et al. have proposed an adaptive neural network predictor to analyze the vibration on elevator system [39]. The direction of future research of comfort should be combined with main feelings and physical function, such as the impact of different accelerations on the effects of different people and the impact of the environment inside the elevator car on physical performance of the staff.

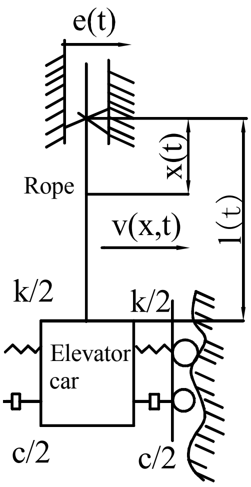


***Figure 7.*** *Equivalent model of elevator suspension system.*

## 5. Conclusion

This review describes the impact of the elevator system structure on elevator movement. The main contents are as follows: The research direction of influencing factors of elevator vibration: The present stage is mainly to establish and analyze elevator system model. To analyze the causes of noise, the relevant model has been used for research and the noise has been suppressed by optimizing relevant experimental parameters; The main research directions of ride comfort: the design of elevator mechanical system, the installation of vibration, noise and the impact of external conditions on people's subjective feeling. The conclusions are as follows:

1) At present, the influence of elevator vibration on elevator performance has attracted more and more attention, and the measures to reduce vibration are also increasing. However, most studies only focus on single aspect of vertical vibration or horizontal vibration, and the further research need to combine vertical vibration and horizontal vibration.
2) While the elevator running speed is gradually improved, the noise has more and more influence on elevator comfort. The existing research mainly focuses on aerodynamic noise of elevator car's exterior structure and mechanical noise of the elevator itself. Further research can be set about noise suppression and vibration reduction on the basis of human psychology and physiology.
3) The existing research focuses more on vibration reduction and noise control of the elevator itself, and there is a lack of research on man machine model. And there is no research on the comfort evaluation through the subjective feelings of the staff. The future development direction should pay more attention to the close integration of engineering and medicine. Therefore, under the premise of elevator safety, the future elevator should be developed in the direction of high-speed, humanization and comfortable.

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