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ANALYSIS OF TRANSVERSE VIBRATION OF HIGH-VELOCITY ELEVATOR WITH VARIABLE-LENGTH HOISTING SYSTEM

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Abstract. *To study the transverse vibration rule of high-velocity elevator hoisting system, Hamilton's principle is applied to establishing the transverse vibration equation for hoisting system. Use the actual running status of a certain elevator as the motion input parameter to obtain the transverse vibration response curves of the lift car and steel ropes. The transverse vibration response of lift car under different parameters is obtained by changing the hoisting mass and linear density of traction steel rope as well as rigidity coefficient of guide shoe. The results show that: during the elevator hoisting, the transverse vibration response of lift car and steel ropes shall increase gradually. Under the same condition, the transverse vibration response is minor if the hoisting mass of single steel rope is reduced, the linear density of steel rope is increased and the guide shoe with lower rigidity and high damping is selected.*
Keywords: Elevator, Hoisting system, Lift car, Steel rope, Transverse vibration

1. **Introduction.** Currently, mainly the traction type elevator hoisting system is used in high-rise buildings [1] and its components are shown in Figure 1. The hoisting system is mainly composed of the tractor, traction steel rope, lift car, guide pulley, counter-weight, balance rope and tension mechanism. As the carrier of hoisting system, the vibration characteristics of traction steel rope have direct influence on the safety and comfort of elevator hoisting. Compared with the common low-velocity elevator, the hoisting speed of high-velocity elevator is faster and the flexibility characteristics of steel ropes are more outstanding, mainly reflected in the increased vibration response of the whole hoisting system [2,3]. This will inevitably cause the fatigue wear and shortened service life of steel rope, and even accidents. One of the important indicators for elevator hoisting performance evaluation in practice is the vibration response of lift car [4]. The on-site test shows that, the vibration responses during actual elevator running are mainly caused by the longitudinal vibration and transverse vibration [5] and the passengers are more sensitive to the transverse vibration response.

During elevator running, lengths of traction steel rope and balance rope change from time to time, causing their parameters such as mass and rigidity also change. For this reason, the vibration rules of steel rope shall be analyzed first of all to study the elevator hoisting performance. Experts and scholars in China and abroad mainly use two kinds of methods to study the steel rope modeling: discrete modeling of lumped parameters and sequential modeling of distribution parameters [6-8]. For the low-velocity hoisting system, the flexibility characteristics of steel rope are not very obvious. The steel rope

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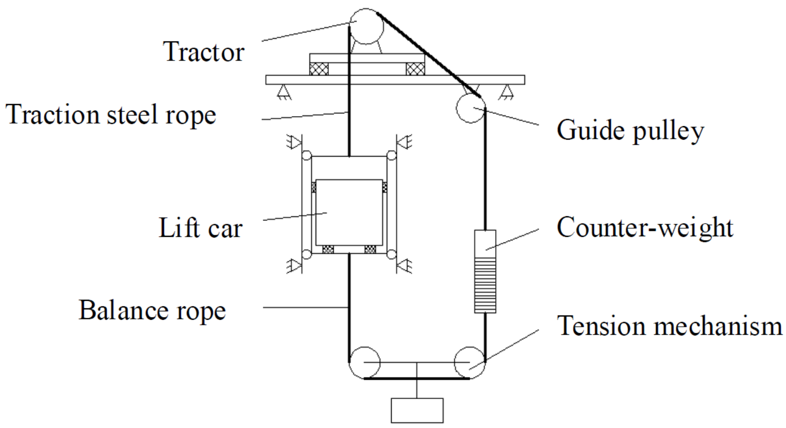


Figure 1. Components of elevator hoisting system

can be dispersed to a spring-damper with multiple variables and parameters and the whole hoisting system could be regarded as a multi-rigid-body vibration system. Using this method, Wang et al. [9] established a vibration model for a certain actual elevator hoisting system. After solving, it was found that the inherent frequency of hoisting system is close to the frequency of tractor. Therefore, there was possibility for the elevator system to have sympathetic vibration. At this point, the sympathetic vibration of elevator system can be avoided effectively by using a compensation device. Zhang and Zhu [10] established coupled vibration equation with multi-degree of freedom for elevator hoisting system and obtained the top five inherent frequency of hoisting system. The further computation showed that the vibration response of elevator was the lowest when the rigidity of steel rope spring was reduced to be 1/2 of the original value.

Mass of the hoisting steel rope of a high-velocity hoisting system was as high as hundreds of kilograms and the mass attribute could not be ignored. Zhu and Ni [11] regarded the traction steel rope as an axially moving string with concentrated load at the end and established string kinergety expression based on the Hamilton's principle. Zhang [12] ignored the existence of mass and pre-tension of balance rope, established the coupled vibration equation for elevator hoisting system and provided a detailed solving method. The research results showed that, the coupled vibration during elevator hoisting was dominated by transverse vibration, the energy of which is far greater than that of longitudinal vibration. Bao et al. [2] established transverse vibration model for traction steel rope using the elastic deformation theory of string and used the elevator hoisting system as the study object to obtain the vibration response at the end of steel rope. The research results showed that, without external excitation for the elevator system, the transverse vibration responses of steel rope under up-going and down-going conditions of lift car are consistent. The lower mass of lift car is, the higher speed of elevator operation and the higher vibration response of hoisting system will be. Kimura and Nakagawa [13] designed a damping device to restrain the transverse vibration of steel rope and verified its feasibility by experiment. Wu et al. [14] used a mine friction lifting system as the study object. The research results showed that, under the external disturbance and excitation, the mine friction lifting system was liable to have transverse vibration and the vibration response of steel rope under up-going condition was higher than that under down-going condition.

Based on the above studies, in this paper, the traction steel rope is still regarded as a continuous rigid body and the existence of balance rope mass and pre-tension is considered. Based on the Hamilton's principle, the transverse vibration equation for high-velocity elevator hoisting system is established to carry out numerical solution and obtain the vibration response of lift car and steel rope, and the rule of influence of hoisting mass and linear density of traction steel rope, as well as rigidity coefficient of guide shoe on vibration is analyzed to provide a strong support for vibration absorption design of elevator hoisting system.

2. **Establishment of Vibration Model.** For the hoisting system shown in Figure 1, the steel rope at the lift car side can be regarded as two strings in vertical motion. Ignore the specific structure of lift car and simplify it as a rigid body with a mass m. The lift car is free longitudinally and transverse restraint can be realized by a spring with rigidity coefficient k and a damper with damping coefficient c. Use the separation point of traction steel rope and traction wheel as the origin to establish a mechanical model for hoisting system as shown in Figure 2. Supposing the length of traction string at the time of t is $l(t)$, the velocity $v(t)$ and accelerated velocity $a(t)$ of hoisting system can be obtained by continuous derivation of $l(t)$. Set the linear density of traction steel rope as ρ, section area as S, elasticity modulus as E and overall hoisting distance as H. The vertical down-going of the whole hoisting system is regarded as the forward direction and the transverse vibration at the string $x(t)$ position is regarded as $w(x,t)$ during elevator hoisting.

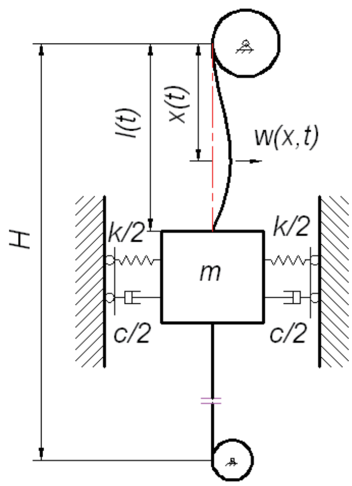


FIGURE 2. Transverse vibration model of hoisting system

The kinetic energy of system is:

$$E_k(t) = \frac{1}{2}\left[m_e + \rho l(t)\right] v^2 + \frac{1}{2}\rho \int_0^{l(t)} \left(\frac{Dw}{Dt}\right)^2 dx + \frac{1}{2} m_e \left[\frac{Dw(l(t),t)}{Dt}\right]^2 \tag{1}$$

where the first item in the right is the kinetic energy of lift car and string in macroscopic motion, the second is the kinetic energy of string in transverse vibration, the third is kinetic energy of lift car in transverse vibration, and m_e is the equivalent mass of lift car and balance rope, $m_e = m + \rho(H - l(t))$. ρ is the linear density of traction steel rope, $l(t)$ is the length of traction string at the time of t, v is the speed of hoisting system and w is transverse vibration of traction string at position $x(t)$.

The differential operator in the formula is:

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + v\frac{\partial}{\partial x} \tag{2}$$

During hoisting, the traction steel rope is under the action of lift car gravity, self gravity and pre-tension. Supposing the pre-tension is F, the static tension of steel rope at position x at the time of t is:

$$T(x,t) = \left[m + \rho(H - x(t))\right](g - a(t)) + F \tag{3}$$

In Formula (3), g is the gravitational acceleration.

The elastic potential energy of elevator hoisting system is:

$$E_e(t) = \frac{1}{2}kw^2(l(t),t) + \frac{1}{2}\int_0^{l(t)} T(x,t)w_x^2 dx \tag{4}$$

The first item at the right of equation is the deformation energy of spring and the second is that of string.

Virtual work of transverse damping force of hoisting system is:

$$\delta W(t) = -c\frac{Dw(l(t),t)}{Dt}\delta w(l(t),t) \tag{5}$$

δ in Equation (5) is a variation symbol.

The study object is a flexible body and it is quite difficult to use the Newtonian Mechanics System to model. Therefore, the Hamilton's principle is used for kinetics modeling. That is, the system motion at the two moments of $t = t_1$ and $t = t_2$ shall inevitably meet:

$$\int_{t_1}^{t_2} \left[\delta E_k(t) - \delta E_e(t) + \delta W(t)\right] dt = 0 \tag{6}$$

Substitute the kinetic energy, elastic potential energy and virtual work of hoisting system into Equation (6), use the corresponding boundary conditions and obtain the transverse vibration equation:

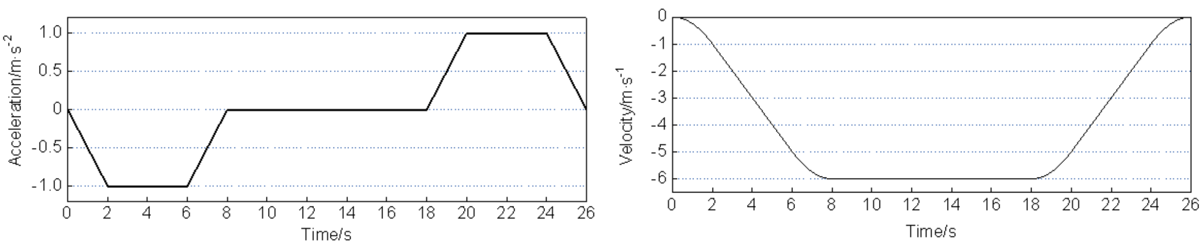
$$\rho\left(w_{tt} + 2vw_{xt} + aw_x + v^2w_{xx}\right) - T_xw_x - Tw_{xx} = 0 \tag{7}$$

The subscripts "t" and "x" in Equation (7) are the partial derivatives of t and x respectively.

3. Results and Discussion.

3.1. Simulation of elevator running status.

To truly reflect the motion status of elevator, divide the hoisting process into seven phases, with a total hoisting duration of 26s. Set the maximum acceleration of hoisting process to be 1m/s^2, maximum velocity 6m/s and hoisting distance 108m. By defining the duration of every running phase, obtain the running status curve of elevation hoisting process as shown in Figure 3.



(a) Time-acceleration curve (b) Time-velocity curve

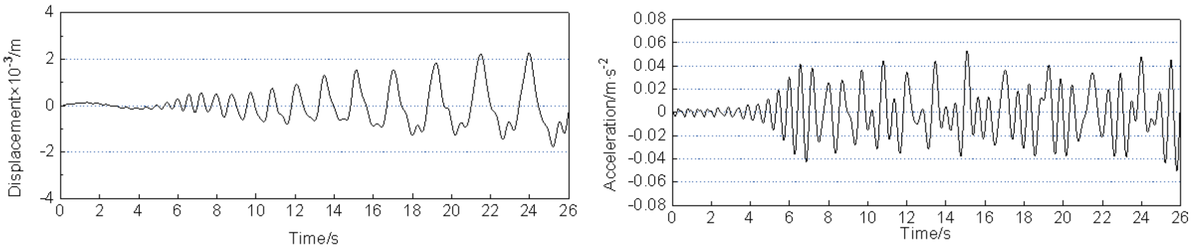
FIGURE 3. Running status curve of hoisting system

3.2. Vibration response analysis.

The rated load of this high-velocity elevator is 1,600kg which is hoisted by 8 steel ropes with a diameter of 0.013m, linear density of 0.58kg/m, elasticity modulus of 9×10^{10}N/m^2, rigidity coefficient of guide shoe of 1×10^5N/m and damping coefficient of 200N·s/m.

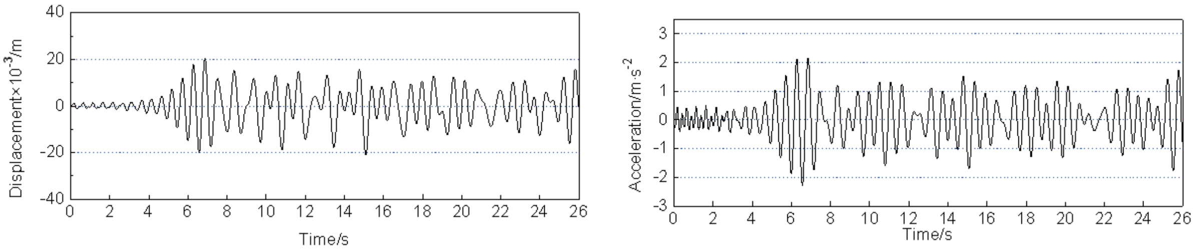
Substitute the relevant parameters to the vibration equation to obtain the transverse vibration simulation curve of lift car and steel ropes as shown in Figures 4 and 5. The calculated distance of steel rope is 5m from the top of lift car.

As shown in Figure 4(a), the transverse vibration displacement of lift car shows a tendency of gradual increase. At its beginning, the transverse vibration displacement is



(a) Vibration displacement of lift car (b) Vibration acceleration of lift car

Figure 4. Transverse vibration response of lift car



(a) Vibration displacement of steel rope (b) Vibration acceleration of steel rope

Figure 5. Transverse vibration response of steel rope

small and almost negligible. It becomes larger and larger gradually and the maximum value is about 2.2mm. As shown in Figure 4(b), the transverse vibration acceleration of lift car is very small at the beginning, increases rapidly and then keeps at a relatively stable vibration scope. The maximum vibration acceleration is about 0.05m/s^2.

As shown in Figure 5, the transverse vibration displacement and acceleration of steel rope are quite small at the beginning of hoisting, increase rapidly and then keep at a relatively stable vibration scope. Its maximum vibration displacement is about 20mm and maximum vibration acceleration is about 2m/s^2.

Comparing Figure 4 with Figure 5, the transverse vibration displacement and acceleration of steel ropes are much greater than the vibration displacement and acceleration of lift car, which is because that, compared to the lift car, the steel ropes have more obvious flexibility characteristics reflected in stronger vibration amplitude and frequency.

3.3. **Parameter influence analysis.** Select the single steel rope hoisting mass, linear density of steel rope and guide shoe coefficient to solve the corresponding transverse vibration displacement of lift car during elevator hoisting.

As shown in Figure 6, the change rules of transverse vibration displacement of lift car under the three groups of hoisting mass parameters are almost the same and all show the tendency of consistent increase. The transverse vibration displacement is the highest when the single steel rope hoisting mass is 460kg, followed by 390kg and 320kg. This is because that, the change of hoisting mass will result in the change of generalized rigidity in the above vibration equation and also the transverse vibration displacement of lift car.

As shown in Figure 7, under the three groups of linear density parameters of traction steel rope, the transverse vibration displacement of lift car is the highest when the linear density is 0.45kg/m, followed by 0.58kg/m and 0.75kg/m. This is because, the higher linear density of traction steel rope is, the bigger section area and tensile rigidity will be. The change of tensile rigidity will result in the change of generalized rigidity in the vibration equation and also the transverse vibration displacement of lift car.

As shown in Figure 8, under the three groups of parameters, the transverse vibration displacement of lift car is the highest when the rigidity coefficient of guide shoe is 2 ×

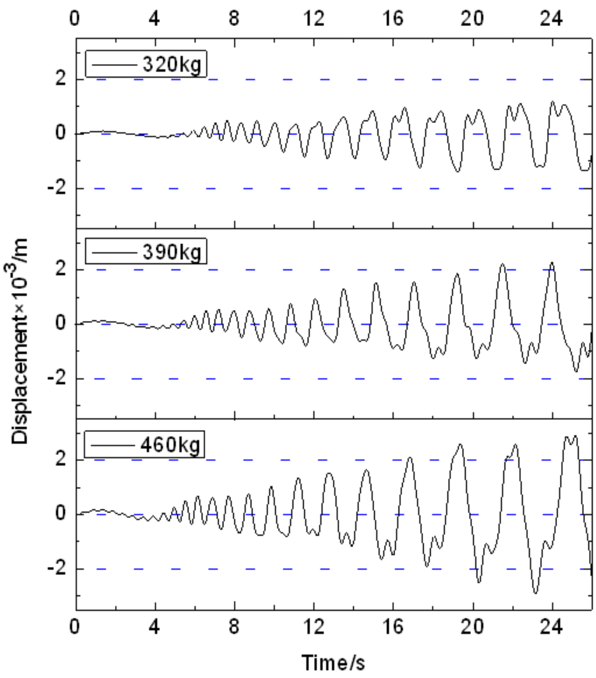


FIGURE 6. Influence of single steel rope hoisting mass on transverse vibration of lift car

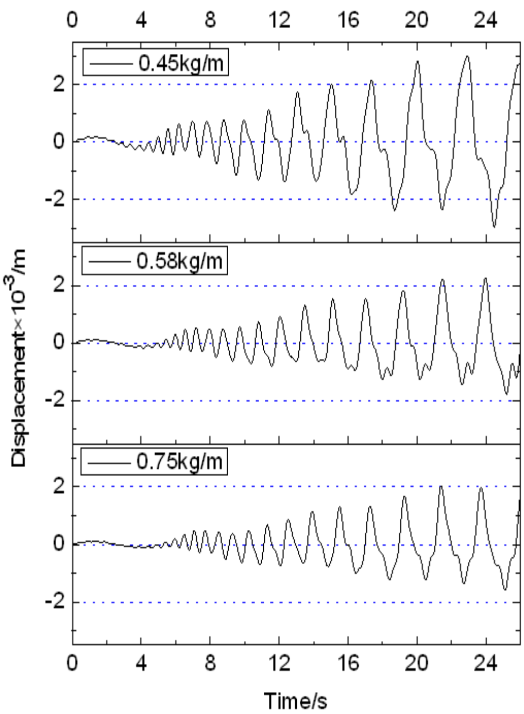


FIGURE 7. Influence of linear density on transverse vibration of lift car

10^5N/m and damping coefficient is 200N·s/m, followed by the rigidity coefficient of 1.5×10^5N/m, damping coefficient of 250N·s/m and rigidity coefficient of 1×10^5N/m and damping coefficient of 300N·s/m.

To sum up Figures 6, 7 and 8, under the same conditions, the transverse vibration response of elevator hoisting system can be restrained efficiently by reducing the single steel rope hoisting mass, increasing the linear density of steel rope and selecting the guide shoe with lower rigidity and higher damping.

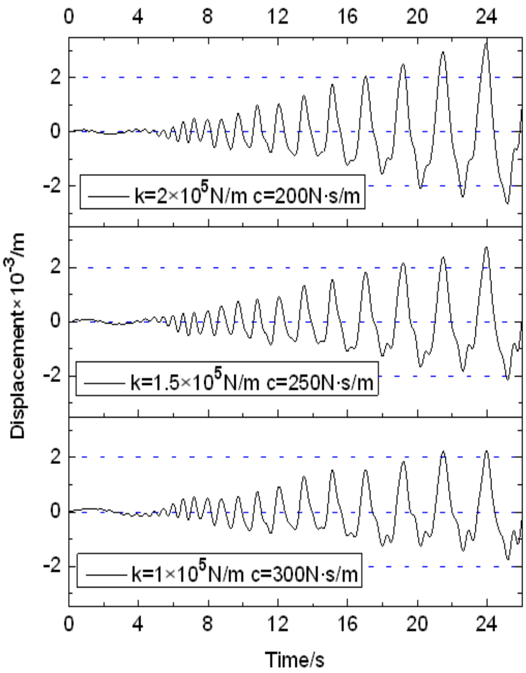


FIGURE 8. Influence of guide shoe coefficient on transverse vibration of lift car

4. **Conclusions.** The traction steel rope and balance rope of the high-velocity elevator hoisting system have the variable-length characteristics. The flexibility characteristics of steel rope shall be taken into consideration to establish a vibration equation.

Enter the actual parameters of a certain high-velocity elevator hoisting system to the vibration equation to obtain the transverse vibration response curves of lift car and steel rope. The results show that, during elevator hoisting, the transverse vibration of lift car and steel rope increases gradually. Change the hoisting mass and linear density of traction steel rope as well as the rigidity coefficient and damping coefficient of guide shoe to obtain the transverse vibration response of lift car under different parameters. The results show that, under the same conditions, the transverse vibration response of elevator hoisting system can be restrained efficiently by reducing the single steel rope hoisting mass, increasing the linear density of steel rope and selecting the guide shoe with lower rigidity and higher damping.

During studying the transverse vibration characteristics of elevator hoisting system, to simplify the modeling, the longitudinal vibration of traction steel rope is ignored. However, during the elevator hoisting, its transverse vibration comes along with the longitudinal vibration and they have influence on each other. Therefore, the influence of coupled vibration of steel ropes on the vibration performance of elevator hoisting system shall be discussed further in the future.

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