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# MODELING AND PARAMETERS ANALYSIS OF LONGITUDINAL VIBRATION OF HIGH-VELOCITY ELEVATOR HOISTING SYSTEM

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Abstract. *High-velocity elevator hoisting system is used as the study object, continuous flexible body characteristics of traction steel rope is taken into consideration and Hamilton's principle is applied to establishing the longitudinal vibration equation for hoisting system. A hoisting system is taken as an example to obtain the longitudinal vibration response of lift car during elevator hoisting. The longitudinal vibration responses of lift car under different parameters are obtained by changing the hoisting mass and linear density of traction steel rope. The results show that: during the elevator hoisting, the longitudinal vibration response shall increase gradually and become maximum when the hoisting is near to the top. Under the same condition, the greater hoisting mass of a single steel rope is, the less longitudinal vibration response will be; the influence of linear density of traction steel rope on longitudinal vibration is minor.*
**Keywords:** High-velocity elevator, Hoisting system, Steel rope, Longitudinal vibration

1. **Introduction.** The traction type elevator hoisting system is broadly used for conveying passengers and goods in high-rise buildings [1] and its components are shown in Figure 1. The hoisting system is mainly comprised of the tractor, traction steel rope, lift car, guide pulley, counter-weight, balance rope and tension mechanism. As the load bearing part and driving part of hoisting system, the length of traction steel rope changes from time to time during elevator running, which will make the parameters of itself such as its mass and rigidity change correspondingly [2]. Meanwhile, along with the increase of hoisting height and velocity, the flexibility characteristics of steel rope become more outstanding, mainly reflected in the increased vibration response of steel rope and lift car [3]. Therefore, the vibration characteristics of steel rope have direct influence on the safety and comfort of elevator hoisting. One of the important indicators for high-velocity elevator hoisting system in the national standards is the vibration response of lift car [4]. The on-site test shows that, the vibration response of lift car is mainly caused by the longitudinal vibration [5]. For this reason, it is of great importance to study the modeling and response of longitudinal vibration of hoisting system for the vibration absorption design of elevators.

Experts and scholars in China and abroad mainly use two kinds of methods to study the steel rope hoisting system modeling: discrete modeling of lumped parameters and sequential modeling of distribution parameters [6-8]. The study object in early period was mainly low-velocity hoisting system in which the mass of traction steel rope was ignored and its flexibility characteristics were not considered. Thus, the whole hoisting

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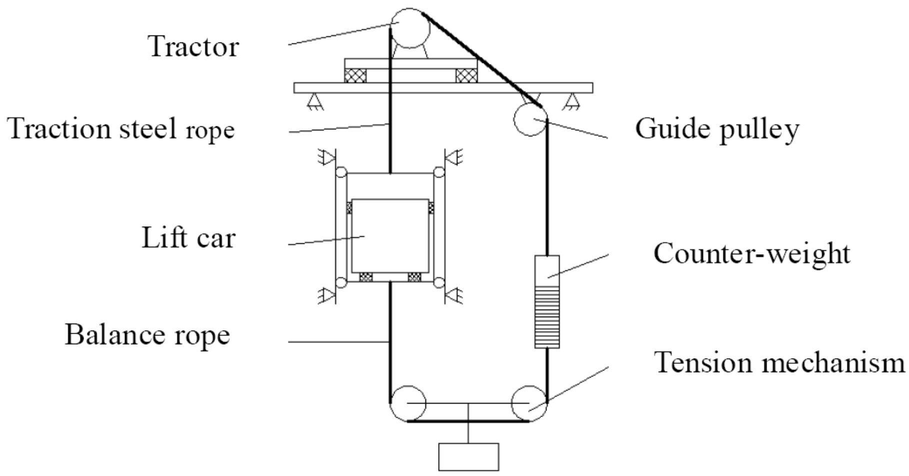



FIGURE 1. Components of elevator hoisting system

system could be regarded as a multi-rigid-body vibration system. Wu et al. [9] established a mathematical model for longitudinal vibration of elevator hoisting system and obtained the vibration response of elevator under up-going conditions with no load. The results showed that the vibration response of lift car was higher in the startup and braking stages of elevator. Lee et al. [10] put forward a new acceleration feedback control strategy to restrain the longitudinal vibration of lift car and validated the validity of control strategy.

Mass of the hoisting steel rope of high-velocity hoisting system was as high as hundreds of kilograms and the mass attribute could not be ignored. The rigid deformation and elastic deformation of steel rope itself would be influenced by each other, which made the vibration response of the whole hoisting system very complex. It was not suitable to treat the hoisting system as a rigid system at this point. Zhu and Ni [11] regarded the traction steel rope as an axially moving string with concentrated load at the end and established the energy expression of string movement based on the Hamilton's principle. Bao et al. [12] established a transverse vibration model for traction steel rope and used the elevator hoisting system as the study object to obtain the vibration response at the end of traction steel rope. The results showed that, without external excitation, the transverse vibration responses under the conditions of up-going and down-going conditions were consistent. Zhang and Agrawal [13] used Newton method and Hamilton method respectively to establish a differential equation for longitudinal vibration of variable-length strings and obtain the numerical solution. The results from both methods were found to be relatively similar. Simpson et al. [14] studied the nonlinear vibration response of elevator hoisting system and pointed out that changes of its structural parameters will result in parameter resonance phenomenon within the hoisting system. In considering the difference between the mine hoisting and elevator hoisting, Wu et al. [15] established a longitudinal transverse vibration equation for steel rope of mine friction lifting system and solved the equation. The results showed that, along with the increased hoisting load, the transverse vibration amplitude of steel rope also increased and the longitudinal vibration amplitude decreased.

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 energy method and Hamilton's principle, the longitudinal vibration equation for high-velocity elevator hoisting system is established to carry out numerical solution and obtain the vibration response of lift car and the rule of influence of hoisting mass and linear density of traction steel rope on vibration is analyzed to provide a strong support for vibration absorption design of elevator hoisting system.

## 2. Study Methods.

2.1. **Establishment of vibration model.** For the high-velocity elevator hoisting system shown in Figure 1, the steel rope at the traction side can be regarded as two variable-length strings in vertical motion. Ignore the specific structure of lift car and simplify it as a rigid body with a mass $m$. Its both ends are connected with a string. Use the separation point of traction steel rope and traction wheel as the origin to establish a mechanical model for elevator 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 steel rope as $\rho$, section area as $S$, elasticity modulus as $E$ and overall hoisting distance as $H$. Since the lift car structure has been ignored, length of the balance rope can be regarded as $H - l(t)$. The vertical down-going of the whole hoisting system is regarded as the forward direction and the longitudinal vibration at the string $x(t)$ position is regarded as $u(x, t)$ during elevator hoisting.

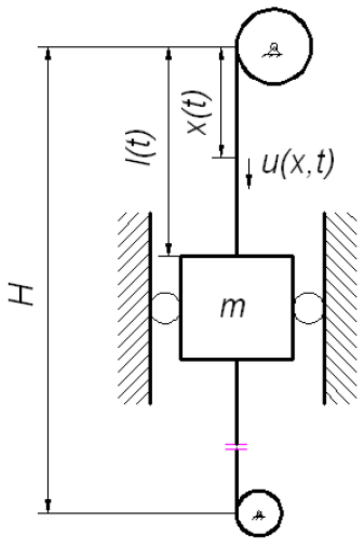



FIGURE 2. Longitudinal vibration model of hoisting system

Based on the finite deformation theory of continuous media, the displacement vector $R$ at $x(t)$ of traction rope is expressed as:

$$R = [x(t) + u(x, t)]i \tag{1}$$

In Formula (1), $i$ is a unit vector along the $x$ axis. The velocity vector $V$ of this point and velocity vector $V_e$ of lift car are:

$$V = \left[v(t) + \frac{Du(x, t)}{Dt}\right] i \tag{2}$$

$$V_e = \left[v(t) + \frac{Du(l, t)}{Dt}\right] i \tag{3}$$

In Formula (3), the differential operator is:

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + v\frac{\partial}{\partial x} \tag{4}$$

The kinetic energy of hoisting system is:

$$E_k(t) = \frac{1}{2}m_e V_e^2 + \frac{1}{2}\rho \int_0^{l(t)} V^2 dx \tag{5}$$

where the first item in the right is the kinetic energy of lift car, the second is the kinetic energy of traction steel rope and $m_e$ is the equivalent mass of lift car, $m_e = m + \rho(H - l(t))$.

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 tension of steel rope at position $x$ at the time of $t$ is $T(x,t) = [m + \rho(H - x(t))](g - a(t)) + F$, where $g$ is the gravitational acceleration.

The elastic potential energy of elevator hoisting system is:

$$E_e(t) = \int_0^{l(t)} \left( T u_x + \frac{1}{2} E S u_x^2 \right) dx \tag{6}$$

The gravitational potential energy of elevator hoisting system is:

$$E_g(t) = -\int_0^{l(t)} \rho g u(x,t) dx - m_e g u(l,t) \tag{7}$$

Two items at the right of equation are the gravitational potential energy of traction string and that of lift car respectively.

Based on the Hamilton's principle, the system motion at the two moments of $t = t_1$ and $t = t_2$ shall inevitably meet:

$$\int_{t_1}^{t_2} [\delta E_k(t) - \delta E_e(t) - \delta E_g(t)] dt = 0 \tag{8}$$

Substitute the kinetic energy, elastic potential energy and gravitational potential energy of hoisting system into Equation (8) and obtain the longitudinal vibration equation:

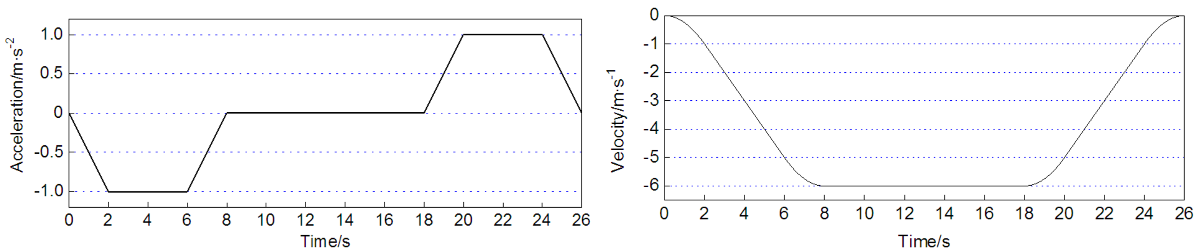
$$\rho \left( u_{tt} + 2 v u_{xt} + a u_x + v^2 u_{xx} + a \right) - T_x - E S u_{xx} - \rho_g = 0 \tag{9}$$

Equation (9) is a system of partial differential equations with infinite degree of freedom. In practice, Galerkin method may be used for discretization to turn it to an ordinary differential equation with finite dimension and solve it by a numerical method. The specific solution procedure will be not described in this paper. It is finally turned into a system of ordinary differential equations of motion:

$$\boldsymbol{M}(t)\ddot{\boldsymbol{q}}(t) + \boldsymbol{C}(t)\dot{\boldsymbol{q}}(t) + \boldsymbol{K}(t)\boldsymbol{q}(t) = \boldsymbol{F}(t) \tag{10}$$

where $q(t)$ is a generalized coordinate vector and $M(t)$, $C(t)$, $K(t)$ and $F(t)$ are generalized mass, damping, rigidity and force matrix of hoisting system respectively.

2.2. **Simulation of elevator running status.** To better reflect the motion status of elevator during the whole hoisting process, use the common T-type accelerated motion. Set the maximum acceleration of hoisting process to be $1\text{m/s}^2$ and maximum velocity 6m/s, hoisting distance 108m and hoisting time 26s. By defining the duration of every running phase, obtain the running status curve of elevation hoisting system during up-going phase as shown in Figure 3.



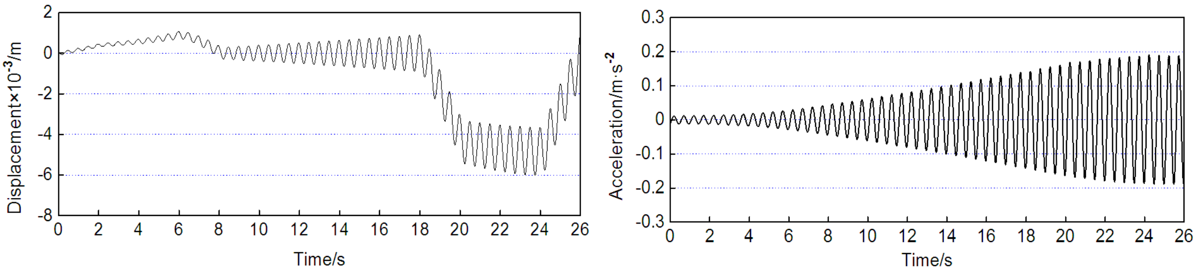

(a) Time-acceleration curve

(b) Time-velocity curve

FIGURE 3. Running status curve of hoisting system

## 3. Results and Discussion.

**3.1. Longitudinal vibration response curve of lift car.** Substitute the relevant parameters to the vibration equation to obtain the longitudinal vibration response curve of lift car as shown in Figure 4.




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

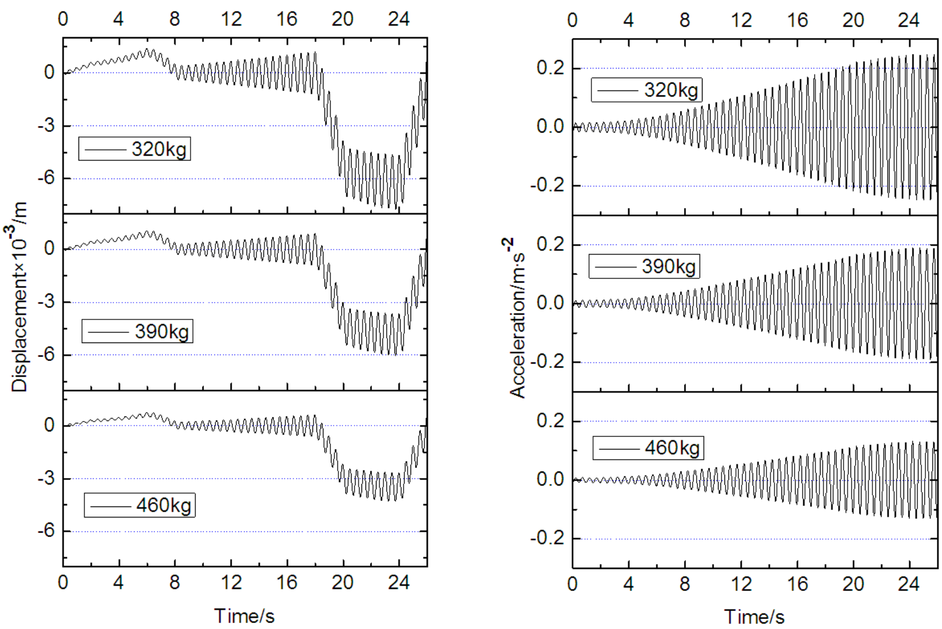
FIGURE 4. Longitudinal vibration response of lift car

As shown in Figure 4(a), at the beginning of elevator hoisting, the longitudinal vibration displacement is small and becomes larger slowly. The longitudinal vibration response of lift car is very violent when the lift stroke is about to finish and the maximum vibration displacement is about 6mm. As shown in Figure 4(b), the longitudinal vibration acceleration of lift car shows a tendency of gradual increase and the maximum vibration acceleration is about 0.2m/s$^2$, which is less than the standard value of 0.35m/s$^2$ in national standards. When the hoisting system goes upwards, the traction steel rope becomes shorter and shorter and the hoisting system will generate negative running damping, which increases the hoisting system energy in multiple and also increases the longitudinal vibration response of lift car. This is the main reason why the steel ropes are liable to encounter dynamic instability when the hoisting approaches to the top.

**3.2. Influence of hoisting system parameters on vibration characteristics.** The elevator hoisting system parameters are mainly the hoisting mass and linear density of single steel rope. Select the hoisting masses of single steel ropes as 320kg, 390kg and 460kg and the linear densities of traction steel ropes as 0.45kg/m, 0.58kg/m and 0.75kg/m respectively, and substitute them into the vibration equations to determine the longitudinal vibration displacement of lift car.

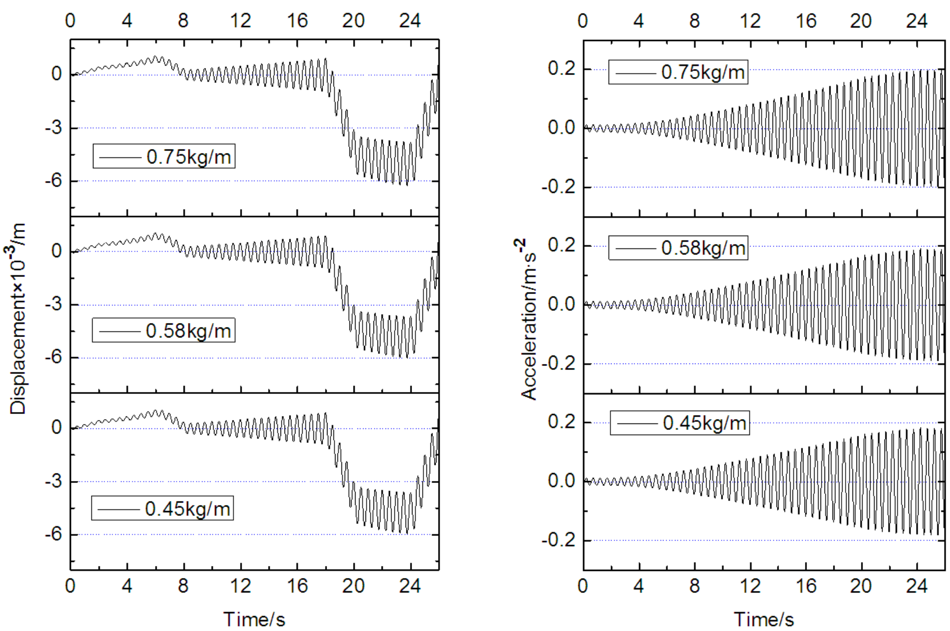
Figure 5(a) shows the longitudinal vibration displacement curve of lift car with three sets of hoisting mass parameters of single steel rope and Figure 5(b) shows its longitudinal vibration acceleration curve. As shown in Figure 5, comparing the longitudinal vibration response of lift car with three sets of hoisting masses, the response is the highest when the hoisting mass of single steel rope is 320kg, followed by 390kg and 460kg. This is because the numerical value differences of the three sets of steel rope hoisting masses will result in greater change of generalized rigidity in the longitudinal vibration equation of hoisting system and also greater change of longitudinal vibration response of lift car.

Figure 6(a) shows the longitudinal vibration displacement curve of lift car with three sets of linear density parameters of steel rope and Figure 6(b) shows its longitudinal vibration acceleration curve. As shown in Figure 6, when the linear density of traction steel rope is 0.75kg/m, the longitudinal vibration response of lift car is slightly higher than those under the other two conditions. However, when it is seen as a whole, longitudinal vibration response differences under the three sets of linear density parameters of traction steel rope are not obvious. This is because the numerical value differences of the three sets of steel rope linear density has less influence on generalized rigidity in the longitudinal vibration equation of hoisting system and results in a similar longitudinal vibration response of lift car.




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

FIGURE 5. Influence of hoisting mass on longitudinal vibration response of lift car




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

FIGURE 6. Influence of linear density on longitudinal vibration response of lift car

4. **Conclusions.** For the high-velocity elevator hoisting system, the steel rope has the variable-length characteristics and the mass of steel rope cannot be ignored any more. Due to these factors, the high-velocity elevator hoisting system cannot be regarded as a multi-rigid-body vibration system in analyzing the vibration characteristics.

Enter the actual parameters of a certain high-velocity elevator hoisting system to the vibration equation to obtain longitudinal vibration response of lift car. The results show that, during elevator hoisting, the vibration response of lift car shows a tendency of gradual increase. Change the hoisting mass and linear density of traction steel rope to obtain the longitudinal vibration response of lift car under different parameters. The results show that, under the same conditions, the greater hoisting mass of single steel rope is, the less longitudinal vibration response is; the influence of linear density of traction steel rope on longitudinal vibration is minor.

The rated load of elevator has been determined during design. To increase the hoisting mass of single traction steel rope, reduce the number of traction steel ropes or increase the mass of car frame. Reducing the number of traction steel ropes may have influence on the hoisting safety. Therefore, the longitudinal vibration response of lift car is improved by increasing the mass of car frame appropriately in practice. Under the same conditions, the linear density of traction steel rope has less influence on the longitudinal vibration characteristics of lift car. The selection scope of linear densities is relatively broad. However, the traction steel rope with larger linear density is good for the safety of hoisting system. The one with larger linear density shall be selected and used in practice.

During actual operation of elevator, factors such as motor rotor displacement and liftway airflow will have a certain influence on longitudinal vibration of hoisting system. However, during the actual modeling, these interference factors are ignored. For this reason, the influence of these factors on hoisting system will be further studied in the future.

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