Research on the Dynamic Characteristics of High-Speed Elevator System

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Abstract—The present paper studied on the high-speed traction elevator developed by Dongnan Elevator Co., Ltd. And the seven degrees of freedom differential equations of a high-speed traction elevator are established by the Lagrange approach. The natural frequencies of the elevator system are carried out through model analysis. The harmonic analysis of high-speed traction elevator is carried out to obtain the vibration characteristic of elevator car and determine the considerable impact model frequencies on the dynamic performance of elevator car. The influences of elevator car load, rubber stiffness under elevator car and rubber stiffness under tractor on the vibration characteristics of elevator car are investigated in detail. The conclusions of this paper provide theory basis for the elevator’s dynamic design, troubleshooting and structure optimization.

Keywords—high-speed elevator; dynamical model; vibration characteristics; harmonic response analysis

I. INTRODUCTION

With the development of society and the growing population, the high-rise buildings and residential buildings in major cities across the country are constantly emerging, and the demand for elevators is increasing [1-3]. Elevators are used as vehicles for people to go up and down buildings in high-rise buildings. The quality of their operation is directly related to personal safety and comfort of passengers. Vibration is an important factor affecting the comfort and safety of traction elevators. The vibration of elevator is aggravated by the increase of elevator speed, and the damage of elevator vibration in the high-rise and super high-rise buildings will be more serious. The vibration of the elevator will cause additional dynamic loads in the traction system and will also shorten the service life of the elevator and precision instruments. Strong vibration will affect the normal operation of the instrument of elevator, so that the elevator can not be accurately leveled, resulting in a safety accident [1,4]. Domestic and foreign scholars have carried out extensive and in-depth research on the vibration characteristics of elevator systems from the aspects of experimental analysis, numerical simulation and theoretical analysis, and given some effective methods to improve the comfort and safety of elevator systems [5-9].

The eccentric exciting force of the traction motor is the main excitation source that causes the vertical vibration of elevator system. Especially when the excitation frequency of the traction machine is close to the natural frequency of elevator system, it causes vertical vibration in the vertical direction, which seriously affects the comfort and safety of elevator. Therefore, it is very necessary to carry out the analysis of the intrinsic characteristics and the harmonious response analysis of elevator system to make the excitation frequency of tractor far from the natural frequency and avoid resonance. Xabier Arrasate [10] built an elevator model with a traction ratio of 1:1. The natural frequency of the system was obtained by finite element analysis, which solved the practical problem of resonance caused by the vibration of tractor. Nai K et al [1,11] established a 10 degree of freedom model for an elevator with a traction ratio of 1:1, and analyzed the influence of elevator structure on the elevator operation. Kang J K et al [12] proposed a method for actively controlling vibration in the vertical direction of elevator. However, in the previous research, the influence of elevator car’s position on the mode shape was not involved; the vibration characteristics of elevator car under the action of simple harmonic exciting force on tractor was not involved; the influence of the system parameters on the response characteristics of elevator car was not analyzed. The present paper studied on the high-speed traction elevator developed by Dongnan Elevator Co., Ltd. And the vertical vibration dynamics model of high-speed traction elevator system is established. The modal analysis is carried out and the variation law of the mode during the operation of elevator system is given. The vibration characteristics of elevator car under the simple exciting force are analyzed and the influences of system parameters such as running height, elevator car load, rubber stiffness under elevator car and rubber stiffness under tractor on the vibration characteristics of elevator car are given. It provides new methods and ideas for structural optimization, dynamic design and fault diagnosis of high-speed traction elevator systems.

II. DYNAMIC MODEL OF HIGH-SPEED ELEVATOR SYSTEM

The present paper studied on the high-speed traction elevator developed by Dongnan Elevator Co., Ltd, which has 175-meter travel and 1:1 traction ratio. The dynamic model of the high-speed traction elevator is shown in Figure I. The elevator system is mainly composed of the traction machine, the traction rope, the elevator car, the counterweight, and the compensation chain. The mass and moment of inertia of the tractive sheave are \( m_t \) and \( I_t \). Ignoring the specific structure of elevator car frame and elevator car, they can be simplified into rigid mass as \( m_e \) and \( I_e \) respectively. The mass and moment of
inertia of the tensioner pulley are \( m_5 \) and \( I_5 \). The torsional stiffness and torsional damping of the tractor are \( k_t \) and \( c_t \). The suspension stiffness and damping of the tractor are \( k_i \) and \( c_i \). The equivalent connection stiffness and damping of traction rope between the counterweight and the tractive sheave are \( k_i \) and \( c_i \). The equivalent connection stiffness and damping of traction rope between the elevator frame and the tractive sheave are \( k_i \) and \( c_i \). The rubber stiffness and damping under elevator car are \( k_i \) and \( c_i \). In addition, \( k_i \) and \( c_i \) are the connection stiffness and damping between the counterweight and the tensioner pulley. \( k_i \) and \( c_i \) are the connection stiffness and damping between the elevator car and the tensioner pulley.

The present section studied on the high-speed traction elevator system will change with time, then the natural frequency of each stage of elevator car frame and the tensioner pulley continuously changes with time. Then, the natural frequency of each stage of the high-speed traction elevator system will change with time, the operation curve of elevator system is shown in Figure II. The elevator displacement gradually increases with time. The speed of the elevator is gradually increased in the beginning stage, and then it undergoes a period of uniform motion. At last, the speed gradually decreases to zero. During the operation of elevator, the acceleration first goes through the process of increasing from zero and then remaining unchanged, and finally decreasing to zero. After running for a long distance without acceleration, the acceleration of running elevator undergoes a process of decreasing from zero and then remaining unchanged, and finally increasing to zero.

### Table I. System Parameters of High-Speed Traction Elevator

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Symbol</th>
<th>Numerical value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of tractor</td>
<td>( m_1 )</td>
<td>2000</td>
<td>kg</td>
</tr>
<tr>
<td>Mass of counterweight</td>
<td>( m_2 )</td>
<td>1800</td>
<td>kg</td>
</tr>
<tr>
<td>Mass of the car frame</td>
<td>( m_3 )</td>
<td>500</td>
<td>kg</td>
</tr>
<tr>
<td>Mass of elevator car</td>
<td>( m_4 )</td>
<td>1000</td>
<td>kg</td>
</tr>
<tr>
<td>Mass of Tensioner pulley</td>
<td>( m_5 )</td>
<td>800</td>
<td>kg</td>
</tr>
<tr>
<td>Radius of traction wheel</td>
<td>( r_t )</td>
<td>0.5</td>
<td>m</td>
</tr>
<tr>
<td>Radius of tensioner pulley</td>
<td>( r_p )</td>
<td>0.4</td>
<td>m</td>
</tr>
<tr>
<td>Traction wheel moment of inertia</td>
<td>( I_1 )</td>
<td>50</td>
<td>kgm²</td>
</tr>
<tr>
<td>Tensioner pulley moment of inertia</td>
<td>( I_5 )</td>
<td>19</td>
<td>kgm²</td>
</tr>
<tr>
<td>Torsional stiffness of tractor</td>
<td>( k_t )</td>
<td>( 1.4 \times 10^6 )</td>
<td>N/rad</td>
</tr>
<tr>
<td>Rubber stiffness under tractor</td>
<td>( k_i )</td>
<td>( 1.5 \times 10^6 )</td>
<td>N/m</td>
</tr>
<tr>
<td>Traction rope Young's modulus</td>
<td>( E )</td>
<td>( 8 \times 10^{10} )</td>
<td>Pa</td>
</tr>
<tr>
<td>Traction rope cross-sectional area</td>
<td>( A )</td>
<td>( 1.4 \times 10^{-4} )</td>
<td>m²</td>
</tr>
</tbody>
</table>

### Table II. Operational Parameters of the High-Speed Elevator

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Symbol</th>
<th>Numerical value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated speed</td>
<td>( v_a )</td>
<td>7</td>
<td>m/s</td>
</tr>
<tr>
<td>Maximum acceleration</td>
<td>( a_a )</td>
<td>1</td>
<td>m/s²</td>
</tr>
<tr>
<td>Maximum acceleration jerk</td>
<td>( j_a )</td>
<td>0.5</td>
<td>m/s³</td>
</tr>
<tr>
<td>Largest lifting height</td>
<td>( S )</td>
<td>170</td>
<td>m</td>
</tr>
</tbody>
</table>

During the operation of the high-speed traction elevator system, the length of traction rope between the elevator counterweight and the tractive sheave, between the elevator car frame and the tractive sheave, between the elevator counterweight and the tensioner pulley, and between the elevator car frame and the tensioner pulley continuously changes with time. Then, the natural frequency of each stage of the high-speed traction elevator system will change with time, and its operating parameters are shown in Table II. The ascending operation process of running elevator system is: increased-acceleration motion - uniformly accelerated motion - decreased-acceleration motion - uniform motion - increased-deceleration motion - uniformly decelerated motion - decreased-deceleration motion until stopping. The operation curve of elevator system is shown in Figure II. The elevator displacement gradually increases with time. The speed of the elevator is gradually increased in the beginning stage, and then it undergoes a period of uniform motion. At last, the speed gradually decreases to zero. During the operation of elevator, the acceleration first goes through the process of increasing from zero and then remaining unchanged, and finally decreasing to zero. After running for a long distance without acceleration, the acceleration of running elevator undergoes a process of decreasing from zero and then remaining unchanged, and finally increasing to zero.
and its changing law is shown in Figure III. It can be seen from the figure that the first-order, the third-order, and the fifth-order natural frequencies of the high-speed traction elevator system continue to decrease with time during ascending operation. It also can be seen from the figure that the second-order, the fourth-order, the sixth-order, and the seventh-order natural frequencies gradually decrease and then gradually increase with time. In general, the front six natural frequencies of the high-speed traction elevator system are all less than 22Hz, and the seventh-order natural frequency is near 27Hz. It can be seen that the natural frequency of each order of elevator deviates from the rotational frequency 25Hz of the traction motor at any time during ascending operation. Therefore, the high-speed traction elevator system developed by Southeast Elevator Co., Ltd. can effectively avoid the resonance phenomenon caused by the eccentric force of traction motor rotor.

The relationship between the vibration response characteristics of elevator car and the frequency of the exciting force is shown in Figure VI. It can be seen from the figure that the change process of the vibration amplitude of elevator car is first increased and then decreased, then increased and finally decreased. In the vicinity of the first-order, second-order, and fourth-order natural frequencies, there occurs the large amplitude due to resonance. However, other natural frequencies do not cause an increase in the vibration amplitude of elevator car. Therefore, in the future design, the vibration amplitude of elevator car should be reduced by keeping the excitation frequency away from these three natural frequencies.

The Rayleigh damping coefficient of the metal material in elevator system is $\alpha = 0.01$, and the Rayleigh damping coefficient of the non-metallic material such as rubber in the elevator system is $\alpha = 0.1$. When the elevator car is in the ground floor, a 1.3Hz exciting force close to the first-order natural frequency is applied to the traction machine, and the time series and the spectrum plot of vibration response of elevator car are shown in Figure IV. If the frequency of the exciting force is increased to 15 Hz, the time series and the spectrum plot of vibration response of elevator car are shown in Figure V. By comparing Figure IV and Figure V, it can be found that when the excitation frequency is close to the first-order natural frequency, the resonance phenomenon occurs and the vibration amplitude of elevator car is large, and when the excitation frequency is far from the natural frequency, the vibration amplitude of elevator car is small.

The Rayleigh damping coefficient of the metal material in elevator system is $\alpha = 0.01$, and the Rayleigh damping coefficient of the non-metallic material such as rubber in the elevator system is $\alpha = 0.1$.
When the elevator car is lifted to the middle floor, the relationship between the vibration response characteristics of elevator car and the frequency of the exciting force is shown in Figure VII. It can be seen from the figure that elevator car has the large amplitude in the vicinity of the first-order, second-order and third-order natural frequencies due to resonance, while the other natural frequencies do not cause an increase in the vibration amplitude of elevator car. When the elevator car is lifted to the top floor, the relationship between the vibration characteristics of elevator car and the frequency of the exciting force is given in Figure VIII. The figure shows that elevator car has the large amplitude only near the first-order and second-order natural frequencies. Especially at the second-order natural frequency, the amplitude of the vibration is very large. And excessive vibration amplitude seriously affects elevator car comfort. Therefore, the elevator design should avoid the excitation frequency close to the natural frequency of the order.

![FIGURE VI. EFFECT OF EXCITING FREQUENCY ON THE VIBRATION AMPLITUDE OF ELEVATOR CAR AT GROUND FLOOR](image)

![FIGURE VII. EFFECT OF EXCITING FREQUENCY ON THE VIBRATION AMPLITUDE OF ELEVATOR CAR AT MIDDLE FLOOR](image)

![FIGURE VIII. EFFECT OF EXCITING FREQUENCY ON THE VIBRATION AMPLITUDE OF ELEVATOR CAR AT TOP FLOOR](image)

From Figure VI to Figure VIII, it is found that the lifting height of elevator car affects its vibration characteristic. The relationship between the vibration characteristic of elevator car and the lifting height of elevator system is shown in Figure IX. In this figure, the abscissa indicates the lifting height of elevator car, and the ordinate represents the excitation frequency value and the natural frequency value. The color represents the magnitude of vibration amplitude of elevator car under different working conditions. The black line represents the each order natural frequency of elevator at different lifting height. It can be seen that the vibration amplitude of elevator car at the ground floor is significantly smaller than that at the middle and top levels. Moreover, when the excitation frequency is near the first-order, second-order, third-order and fourth-order natural frequencies, the response of elevator car generates large amplitude due to resonance. The vibration amplitude of elevator car is always large when the excitation frequency is near the second-order natural frequency. This frequency is the main frequency that affects the performance of elevator system, and is also the main frequency component that needs to be suppressed in the future.

![FIGURE IX. INFLUENCE OF ELEVATOR RUNNING HEIGHT ON RESPONSE CHARACTERISTICS OF ELEVATOR CAR](image)

V. INFLUENCE OF SYSTEM PARAMETERS

During the operation of elevator system, the number of passengers and the mass of goods often change. The vibration characteristic should be affected by the varying elevator car load. In order to reduce the vibration amplitude of elevator car, it is often used to change the rubber stiffness under elevator car or to reduce the rubber stiffness under tractor. However, the influence of stiffness on the vibration amplitude of elevator car has not been systematically studied. Therefore, the present paper will use harmonic response analysis to study the influence of elevator car load, rubber stiffness under elevator car and rubber stiffness under tractor on the vibration characteristics of elevator car when the elevator car at the middle floor.

A. Influence of Elevator Car Load

The influence of elevator car load on the vibration characteristic of elevator car is shown in Figure X. The figure shows that the vibration amplitude of elevator car is relatively large when the exciting force frequency is near the first-order, second-order, and third-order natural frequencies. When the exciting force frequency is near the first-order natural frequency, the vibration amplitude of elevator car does not change with elevator car load. But it will gradually decrease with the increase of elevator car load when the exciting force frequency is near the second-order and third-order natural frequencies. It means that the more passengers or the greater the mass of goods, the smaller the vibration amplitude. Therefore, it is possible to increase the comfort of elevator car by increasing the weight of elevator car.
rubber stiffness under tractor. In the dynamic design of elevator system or can be effectively reduced by increasing the rubber stiffness frequencies. Therefore, the vibration amplitude of elevator car near the first-order, second-order and third-order natural frequencies is significantly reduced when the excitation frequency is near the first-order and third-order natural frequency, the rubber stiffness under elevator car has little influence on the vibration amplitude. However, the elevator vibration amplitude can be effectively reduced by increasing the mass or load of elevator car and increasing the rubber stiffness under tractor.

C. Influence of Rubber Stiffness under Tractor

The effect of the rubber stiffness under the tractor on the vibration characteristic of elevator car is shown in Figure XII. It can be seen from the figure that as the rubber stiffness under the tractor increases, the amplitude of vibration decreases. The vibration amplitude of elevator car can be effectively reduced by increasing the rubber stiffness under the tractor. In the dynamic design of elevator system or the design of vibration and noise reduction, the comfort and safety of elevator system can be improved by increasing the rubber stiffness under tractor.

VI. CONCLUSIONS

The present paper studied on the vibration characteristic of high-speed traction elevator developed by Dongnan Elevator Co., Ltd. The dynamic model was established and harmonic response analysis was performed. Through numerical analysis, the vibration characteristics of elevator car were obtained. The influence of lifting height elevator car load, rubber stiffness under elevator car and rubber stiffness under tractor on the vibration characteristics of elevator car are analyzed in detail. The analysis results show that the vibration amplitude of elevator car is small when the elevator car is at ground floor, and the vibration amplitude of elevator car increases with lifting height. The rubber stiffness under elevator car has little influence on the vibration amplitude. However, the elevator vibration amplitude can be effectively reduced by increasing the mass or load of elevator car and increasing the rubber stiffness under tractor.

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