Vibration Analysis and Simulation of Traction Inclined Elevator

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***Abstract*—To provide convenient transportation facilities for long distance buildings and sightseeing landscapes located on the top of the mountain, and residential area set on the hillside due to the insufficient urban area, there have been some demands for the inclined elevator. However, compared with vertical elevator, the inclined elevator will generate a number of new problems in process of design, manufacture, installation and operation, such as horizontal force action on passengers when starting and braking, lower side guide rail bearing heavy load, traction rope and travelling cable overhanging loosely because of gravity etc. Featuring flexible body of suspension lifting device, all the various moving parts in the elevator will inevitably bring multiple degrees of complex nonlinear coupling vibration from internal or external influences, which can directly affect the discomforts of passenger. So the vibration analysis is important, the dynamic model of a traction inclined elevator is built considering wire rope mass, stiffness and damping, the dynamic characteristics are analyzed and the vibration control techniques studied. The transient response comparison to air flow disturbance in elevator is simulated.**

Keywords—traction inclined elevator; vibration analysis; velocity curve; dynamic modeling; simulation

I. INTRODUCTION

The inclined elevator car, which runs along the inclined guide rail in the inclined shaft, is a equipment collection of sightseeing and transportation, from the surface, it seems that there is no essential difference between ordinary vertical elevator. First, the vertical elevator car frame by the upper, lower beam and the vertical beam, can fix and support the car, inclined elevator can complete these functions by the lower trolley installed under the car; secondly, vertical elevator guide rail can direct movement, inclined elevator guide not only plays a role of guidance, but also need to carry the car and counterweight; thirdly, due to gravity the traction rope will produce overhang and looseness, and there must be a lot of wire rope installed on the guide rail to support the roller. Finally, for long stroke inclined elevator, the traveling cable must have special guidance system [1].

Elevator not only must meet the basic requirements for safety and accessibility, but also make the passengers feel relax, quiet and comfortable during the entire ride, without any noise, stress, discomfort, and even hurt. For standing passengers in the car, it can cause the discomfort of the general physical limit level: vertical acceleration/deceleration, 1.0~1.5 m/s^2; jerk acceleration (rate of acceleration change), 2.5 m/s^3, noise, 50dBa; horizontal vibration, 15~20mg (g is the gravitational acceleration), ear pressure, 2000Pa [2]. For inclined elevator the following requirements also involved, horizontal acceleration is not more than 0.01g, horizontal acceleration rate is less than 0.2 g/s, the vertical acceleration is not more than (1 ± 0.1) g [3]. In addition, when the inclination of the inclined elevator over a vertical surface is at an angle greater than 7°, due to bearing larger load by the lower guiding rails and the generated horizontal movement, acceleration and deceleration only 0.5g, and in fact it is only suitable for the elevator below 1m/s, when surpasses 10°, both acceleration and deceleration or rated speed must be further decreased, which limits the application of inclined elevator [4]. Therefore, it is of great significance to study the dynamic characteristics and the influence factors of horizontal acceleration for the inclined elevator to improve the service speed and the ride comfort.

II. VELOCITY CURVE

In elevator running process, its acceleration curve and velocity curve is important because it relates to the operation stability, efficiency and passenger comfort [4]. Currently in practical engineering the speed curve can generally be divided into symmetrical curves and asymmetric curve can also be divided into step curve and sine curve [5]. Trapezoidal velocity curve in Fig.1 is formed by a parabola and a straight line segment, with high efficiency but sudden change of its acceleration, which can cause high shock to elevator mechanism disproportionately and poor ride comfort, yet acceleration curve of sine curve is continuous, the acceleration change rate curve is continuous according to sine function, only when starting and stopping change rate of acceleration has one jump with better ride comfort, but because of the complex calculation of the sine function and not suitable for producing real-time velocity signal, also the analysis is not convenient. So trapezoidal velocity curve is widely used. we take trapezoidal velocity curve as an computation example.

Because the acceleration changes over time, so the running time is divided into 7 time interval to calculate parameter of

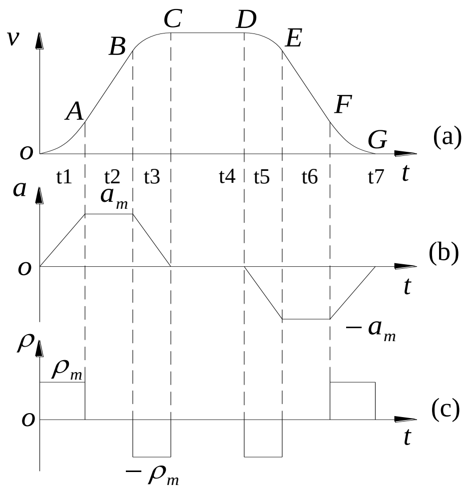

Fig .1. Trapezoidal velocity curve

each section, where a_m is the maximum acceleration, ρ_m as the acceleration change rate, v_m velocity peak, the optimum value for a_m and ρ_m can both satisfy the ride comfort demand, and also make the starting and stopping time be shortest, realize the effective motion. $0 < t < t_1$ is variable accelerating parabolic section, $t_1 < t < t_2$ is uniform accelerating linear section, $t_2 < t < t_3$ is variable accelerating parabolic section, $t_3 < t < t_4$ is uniform speed straight line, $t_4 < t < t_5$ is variable accelerating parabolic section, $t_5 < t < t_6$ is uniform deceleration parabolic section, $t_6 < t < t_7$ is accelerating parabolic section, if assuming $t_3 = t_1 / \gamma$, γ is the time scale factor, when deciding the elevator travel distance S , through the deduction of each curve motion parameters, the maximum and minimum travel can be obtained by the following formula:

$$S_{\min} = 2v_m \frac{a_m}{\rho_m} = 2\frac{a_m^3}{\rho_m^2} \tag{1}$$

$$S_{\max} = \frac{a_m^2 v_m + \rho_m v_m^2}{a_m \rho_m} + v_m (t_4 - t_3) \tag{2}$$

When the actual travel distance surpasses this scope, we need to adjust the correlation parameters or the corresponding performance curve to guarantee the elevator normal operation. Because there are certain data communication time among the speed control module, the elevator master controller and the inverter, simultaneously the speed control module also needs certain time for speed computation according to the travel distance, this causes a time lag in the speed control, meanwhile the reverse slip in starting phase and the load change will possibly result in the speed control deviation through distance. In order to guarantee the accuracy in elevator real-time speed control, after calculating the real-time running velocity on the surplus distance basis, we also must regulate the running rate according to the elevator time variation. The classic PID control expression is [6]:

$$p(t) = k_n \left[e(t) + \left(\frac{1}{T_l} + T_D \right) \int e(t)dt \right] \tag{3}$$

The increment PID control mathematical formula (4) can make the integral and the differential in control, be easy to obtain the good adjustment effect.

$$\begin{aligned} &\Delta p(k) = p(k) - p(k-1) = \\ &k_n [e(k) - e(k-1)] + \left(\frac{1}{T_l} + T_D \right) * k_n * T * e(k) \end{aligned} \tag{4}$$

III. VIBRATION DYNAMICS MODELING

Elevator is characterized by frequent starting and braking. During the process of acceleration/deceleration traction rope is subjected to static load and also inertia load. As the steel wire rope and the rope end spring are elastic body and thus certain frequency vibration load are superimposed on the above two loads, vibration and inertia loads form the dynamic load of the elevator. Due to dynamic load effect, jitter will appear in a wire rope making the car vibrate, affect the ride comfort [4]. Elevator is a variable parameter system, in running process the length of wire rope and elevator load change, so to establish a time-varying continuous model of elevator is very difficult, but can take the elevator operation process discretization in time domain, assuming every time interval the elevator parameters are the same, and in every interval elevator system can be regarded as a multiple degree of freedom vibration system, its dynamic equation can be expressed as common form of multiple DOF centralized mass system dynamics equation [7,8]:

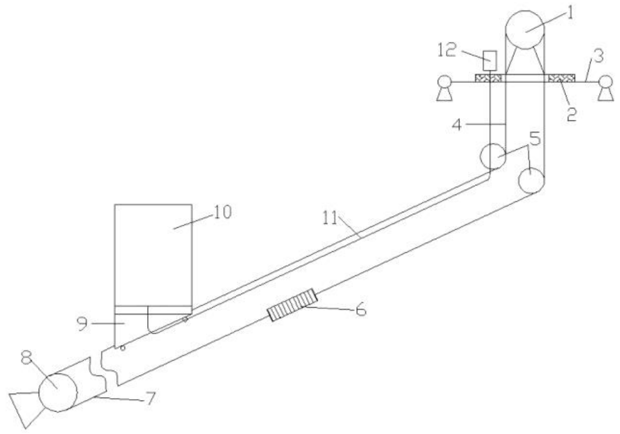

Fig. 2. Physical model of traction inclined elevator. 1-traction motor, 2-motor base rubber, 3-bearing beam, 4-traction rope, 5-deflector sheave, 6-counterweight, 7- compensation rope, 8 -tensioning system, 9- lower trolley, 10-car ,11- travelling cable, 12- control cabinet.

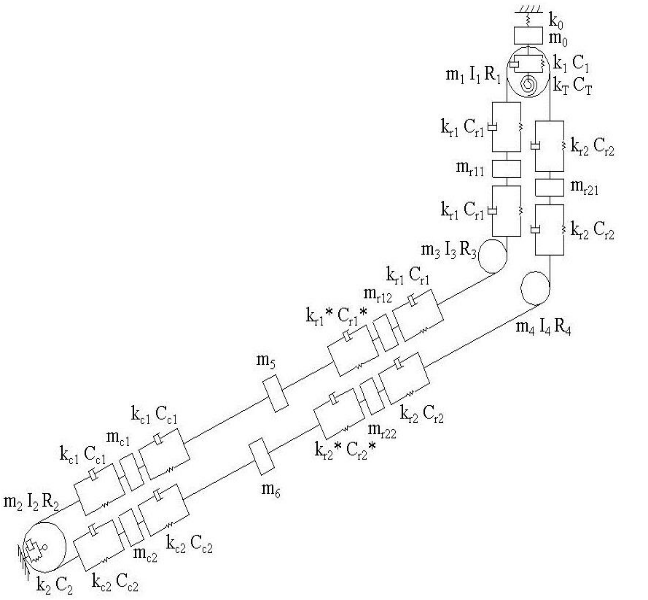

Fig. 3. vibration dynamics system

$$M \cdot \ddot{x}(t) + C \cdot \dot{x}(t) + K \cdot x(t) = q(t) \tag{5}$$

M , C and K respectively is the system quality matrix, the damping matrix and the stiffness matrix;

x , q respectively is movement displacement vector of each DOF and force load vector.

Taking gearless traction inclined elevator with tilt angle 25°as an example, car dragged by the lower trolley, driven by permanent magnet synchronous motor, the motor speed consistent with the traction sheave speed. According to physical structural characteristics and vibration mechanism of inclined elevator, the physical model is established shown in Fig.2, the vibration dynamics system shown in Fig .3.

m_0, k_0- equivalent mass, stiffness of bearing beam

m_1,I_1,R_1-equivalent mass, rotary inertia and groove radius of traction sheave

m_2,I_2,R_2- equivalent mass, rotary inertia and groove radius of tension sheave

m_3,I_3,R_3- equivalent mass, rotary inertia and groove radius of car stationary sheave

m_4,I_4 你那边,R_4- equivalent mass, rotary inertia and groove radius of counterweight sheave

m_5,m_6- mass of car plus load and counterweight

m_{r11},m_{r12},k_{r1},C_{r1},k_{r1}*,C_{r1}*- section rope equivalent mass, stiffness and damping between trolley and sheave, * is equivalent value including the rope end spring stiffness

m_{r21},m_{r22},k_{r2},C_{r2},k_{r2}*,C_{r2}*- section rope equivalent mass, stiffness and damping between counterweight and sheave, * is equivalent value including the rope end spring stiffness

m_{c1},k_{c1},C_{c1}- section rope equivalent mass, stiffness and damping between trolley and tension sheave

m_{c2},k_{c2},C_{c2}- section rope equivalent mass, stiffness and damping between counterweight and tension sheave

k_1,C_1- equivalent stiffness and damping of motor base rubber

k_2,C_2- stiffness and damping of damper below tension sheave

k_T,C_T - rotary stiffness and damping of traction sheave

x - Vibration displacement corresponding to quality m respectively

φ_1 , φ_2 , φ_3 , φ_4 - vibration angular displacement corresponding to I_1, I_2, I_3, I_4

In this model, take all of the vibration linear displacement along the traction rope upward and rightward as positive, angular displacement counterclockwise as positive. According to the Lagrange equation, establishes the system dynamics equation [9]:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_i}\right) - \frac{\partial T}{\partial x_i} + \frac{\partial D}{\partial \dot{x}_i} + \frac{\partial U}{\partial x_i} = q_i \tag{6}$$

Total kinetic energy T is:

$$\begin{aligned} T = {} & \frac{1}{2}m_0\dot{x}_0^2 + \frac{1}{2}m_1\dot{x}_1^2 + \frac{1}{2}m_2 x\dot{x}_2^2 + \frac{1}{2}m_3\dot{x}_3^2 + \frac{1}{2}m_4\dot{x}_4^2 + \\ & \frac{1}{2}m_5\dot{x}_5^2 + \frac{1}{2}m_6\dot{x}_6^2 + \frac{1}{2}m_7\dot{x}_7^2 + \frac{1}{2}m_{r11}\dot{x}_{r11}^2 + \frac{1}{2}m_{r12}\dot{x}_{r12}^2 + \\ & \frac{1}{2}m_{r21}\dot{x}_{r21}^2 + \frac{1}{2}m_{r22}\dot{x}_{r22}^2 + \frac{1}{2}m_{c1}\dot{x}_{c1}^2 + \frac{1}{2}m_{c2}\dot{x}_{c2}^2 + \frac{1}{2}I_1\dot{\varphi}_1 + \\ & \frac{1}{2}I_2\dot{\varphi}_2 + \frac{1}{2}I_3\dot{\varphi}_3 + \frac{1}{2}I_4\dot{\varphi}_4 \end{aligned} \tag{7}$$

Total potential energy V is:

$$U = \frac{1}{2}k_T\varphi_1^2 + \frac{1}{2}k_1x_1^2 + \frac{1}{2}k_1(x_1 - x_0)^2 + \frac{1}{2}k_2x_2^2 + \frac{1}{2}k_0x_0^2$$

$$+\frac{1}{2}k_{r1}[(x_1 - R_1\varphi_1) - x_{r11}]^2 + \frac{1}{2}k_{r1}[x_{r11} - (x_3 + R_3\varphi_3)]^2$$

$$\frac{1}{2}k_{r1}[(x_3 + R_3\varphi_3) - x_{r12}]^2 + \frac{1}{2}k_{r1}^*(x_{r12} - x_5)^2 +$$

$$\frac{1}{2}k_{c1}(x_5 - x_{c1})^2 + \frac{1}{2}k_{c1}[x_{c1} - (x_2 - R_2\varphi_2)]^2 +$$

$$\frac{1}{2}k_{r2}[(x_1 + R_1\varphi_1) - x_{r21}]^2 + \frac{1}{2}k_{r2}[x_{r21} - (x_4 + R_4\varphi_4)]^2$$

$$+\frac{1}{2}k_{r2}[(x_4 + R_4\varphi_4) - x_{r22}]^2 + \frac{1}{2}k_{r2}^*(x_{r22} - x_6)^2 +$$

$$\frac{1}{2}k_{c2}\left(x_6 - x_{c2}\right)^2 + \frac{1}{2}k_{c2}\left[x_{c2} - \left(x_2 + R_2\varphi_2\right)\right]^2 \qquad (8)$$

Total dissipation energy D is:

$$D = \frac{1}{2}c_T\dot{\varphi}_1^2 + \frac{1}{2}c_1\dot{x}_1^2 + \frac{1}{2}c_1\left(\dot{x}_1 - \dot{x}_0\right)^2 + \frac{1}{2}c_2\dot{x}_2^2 +$$

$$\frac{1}{2}c_{r1}\left[\left(\dot{x}_1 - R_1\dot{\varphi}_1\right) - \dot{x}_{r11}\right]^2 + \frac{1}{2}c_{r1}\left[\dot{x}_{r11} - \left(\dot{x}_3 + R_3\dot{\varphi}_3\right)\right]^2 +$$

$$\frac{1}{2}c_{r1}\left[\left(\dot{x}_3 + R_3\dot{\varphi}_3\right) - \dot{x}_{r12}\right]^2 + \frac{1}{2}c_{r1}^*\left(\dot{x}_{r12} - \dot{x}_5\right)^2 +$$

$$\frac{1}{2}c_{c1}\left(\dot{x}_5 - \dot{x}_{c1}\right)^2 + \frac{1}{2}c_{c1}\left[\dot{x}_{c1} - \left(\dot{x}_2 - R_2\dot{\varphi}_2\right)\right]^2 +$$

$$\frac{1}{2}c_{r2}\left[\left(\dot{x}_1 + R_1\dot{\varphi}_1\right) - \dot{x}_{r21}\right]^2 + \frac{1}{2}c_{r2}\left[\dot{x}_{r21} - \left(\dot{x}_4 + R_4\dot{\varphi}_4\right)\right]^2$$

$$+\frac{1}{2}c_{r2}\left[\left(\dot{x}_4 + R_4\dot{\varphi}_4\right) - \dot{x}_{r22}\right]^2 + \frac{1}{2}c_{r2}^*\left(\dot{x}_{r22} - \dot{x}_6\right)^2$$

$$+\frac{1}{2}c_{c2}\left(\dot{x}_6 - \dot{x}_{c2}\right)^2 + \frac{1}{2}c_{c2}\left[\dot{x}_{c2} - \left(\dot{x}_2 + R_2\dot{\varphi}_2\right)\right]^2 \qquad (9)$$

According to the Lagrange equation, the matrix and vector of the motion equation can be determined.

IV. DYNAMIC ANALYSIS RESULT

Transient response is to calculate the response of elevator system under the stimulus of arbitrary change over time, can be represented as (1), harmonic response can be seen as a special case of the transient response.

For computation of elevator running velocity curve, the elevator various movement parameters are generally calculated in assigning the reasonable movement maximum speed, simultaneously establishing the maximum acceleration and the acceleration rate of change,

The elevator speed curve generally consists of the acceleration phase, the steady phase and the deceleration phase. The steady phase speed is determined according to the transportation capacity request and in principle of small motor power consumption. The acceleration in acceleration/ deceleration phase is generally decided according to the elevator system vibration, the impact effect, riding comfortableness as well as the slip resistant condition resulting from the motion inertia force and the impulse.

Disturbance of the air flow in the well also have a force above the car, affect the vibration of the elevator. This exciting force is not the same as pulse excitation from the traction machine; it changes with the car's vibration state. This air exciting force also affects the dynamics performance of the elevator. The elevator movement speed control uses PID control and the simulation of air flow disturbance uses MATLAB software [10]. Apply the air flow disturbance in elevator vertical direction to do transient response analysis, the resulting acceleration transient response as shown in fig. 4, the acceleration transient response without air flow perturbation as shown in fig. 5, the vibration amplitude of adding the air flow perturbation decreased slightly than the amplitude without adding air flow perturbation.

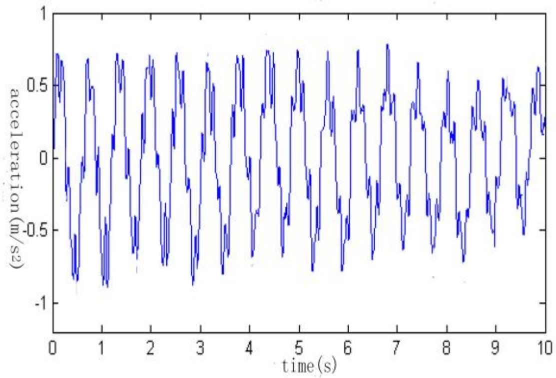

Fig. 4. acceleration transient response adding air perturbation

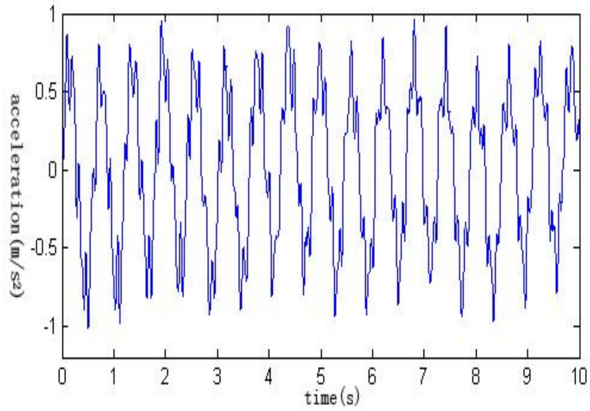

Fig. 5. acceleration transient response without air perturbation

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