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HIGH-SPEED ELEVATOR MODEL

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Key words: *modeling, high-speed elevator, natural frequency, vibration isolation, metal-rubber pads, numerical solution, MatLab*

Abstract: *Recently, high-speed elevators have been increasingly installed in high-rise buildings and skyscrapers. In them, the car moves at a set speed of at least three meters per second on extremely straight rails to minimize transverse vibrations, which are extremely small. A high-speed elevator consisting of a cabin, a counterweight, and a machine unit, located at the top of the facility, is investigated. The steel ropes of these elevators are of great length and are usually four numbers. As a first approximation, the steel ropes are assumed to be weightless and inextensible. The elevator is modeled as a mechanical system with two degrees of freedom. One of the disadvantages of this classic construction is that there is a possibility that the vertical vibrations generated by the machine unit, using the ropes, will be transmitted to the cabin and deteriorate the comfort of travel. Therefore, it is placed on reinforced rubber pads on the foundation floor slab. An extremely important task for the designers of such modern high-speed elevators is to center the machine unit in such a way as to minimize inertial disturbances due to the presence of unbalanced masses. The article makes important conclusions and recommendations to designers and technical personnel who maintain such elevators.*

1. INTRODUCTION

Currently, an extraordinary amount of research on high-speed elevators has been published in worldwide literature and the Internet. They relate to the consideration of various technical issues that modern high-speed elevators must meet, to guarantee safety, speed, and environmental requirements.

The work [1] studies a high-speed elevator developed by Dongnan Elevator Co., Ltd. A mathematical model with seven degrees of freedom was constructed. The differential equations are derived using the Lagrange approach. The natural frequencies of the elevator system are determined. A harmonic analysis was performed to obtain the elevator cabin vibrations, [2, 3].

The work [4] has developed methods for testing the main subsystems of ropeways: ropes; propulsion and braking systems; mechanical devices; and vehicles. Modern technology and specialized software are used to obtain more accurate and easy-to-analyze results.

In the work [5], the influence of airflow in the elevator cage in a high-speed elevator is studied. The increase in pressure caused discomfort to the passengers. In this paper, the air pressure in the elevator car is modeled using the compensation method by coupling the internal and external flow fields.

In the work [6], some new trends in high-speed elevators and their impact on the design, construction, and operation of modern buildings are discussed. Additionally, it focuses on technological innovations and how they are applied in high-speed elevators. All these implementations lead to modern, comfortable, safe, and energy-efficient vertical transport.

The paper [7] examines the influence of wind-induced vibration effects on super-tall buildings caused by wind loading, which causes high-speed elevator vibrations. Based on the Bernoulli-Euler Theory, the differential equation of the forced oscillations of the elevator guide rail is established.

In the work [8], a passenger electric elevator for one person is studied. The electric motor drives a hardened steel traction pulley on which the ropes are suspended. The construction has advantages over stairs, ladders, and hydraulic lifts.

A modern way of evaluating the performance of an elevator system and its technical condition is developed in the article [9]. An implemented intelligently multi-sensor module for remote monitoring of the condition of the elevator is designed. The evaluation of the operation of the elevator system and its technical condition is carried out by calculating the basic traffic quality parameters defined by ISO 18738-1 standard. The spectrum of vibrations relative to position, sound pressure, and light levels of the elevator cabin are calculated.

The article [10] presents the design and implementation of an intelligent energy-autonomous plug-and-play sensor unit, which enables a cost-effective way to modernize existing elevator systems in terms of condition monitoring capabilities. The sensor node measures the position of the elevator and its velocity using an inertial measurement unit (IMU) in conjunction with a barometric sensor.

The main goal of the present work, based on the analysis of the latest research in the field of construction and research of high-speed elevators, is to compile a simplified mathematical model of such a system with an upper drive unit. For this model, analytical and numerical solutions should be carried out to obtain the all dynamic characteristics of the system.

2. KINETIC MODEL OF AN ELEVATOR

Fig. 1 shows a kinetic model of a classical elevator. It consists of cabin 1 with useful load, counterweight 2, machine unit 3, guide roller 4, and steel ropes.

The cabin has a mass m_{11}. The mass m_{12} of the useful load adds to it, $m_1 = m_{11} + m_{12}$. The counterweight has a mass m_2 that obeys the formula $m_2 = m_{11} + 0{,}50.m_{12}$. The machine unit creates torque M by turning a disk with a radius r. It has trapezoidal chutes dug into it, where steel ropes are wound. Usually, they are four numbers. Unbalanced masses in the unit, which are a source of disturbances of an inertial nature, are taken into account only with the vertical component F_{in}. The machine unit is mounted on reinforced rubber pads with an elasticity coefficient c. The steel ropes are firmly attached to the elevator cabin and the counterweight. To ensure the necessary distance between the cabin and the counterweight, the ropes pass through a guide roller 4.

The following simplifying assumptions are assumed:

- The studied model is planar;
- The elevator cabin with the useful load and the counterweight are moving strictly vertically on perfectly smooth rails, ignoring any lateral deviation;
- Steel ropes are weightless and inextensible;
- The guide roller is also weightless.

3. EQUATION OF MOTION

The elevator facility is modeled as a two-degree-of-freedom system. The machine unit's vertical displacement z_3 and the disk's rotation angle φ_3 are taken as generalized coordinates. They are combined into the following vector:

$$\mathbf{q} = \left\langle\, z_3 \quad \varphi_3 \,\right\rangle^T . \tag{1}$$

The vertical coordinates that determine the position of the cabin with the payload and the counterweight are respectively x_2, and x_3, (Fig.1).

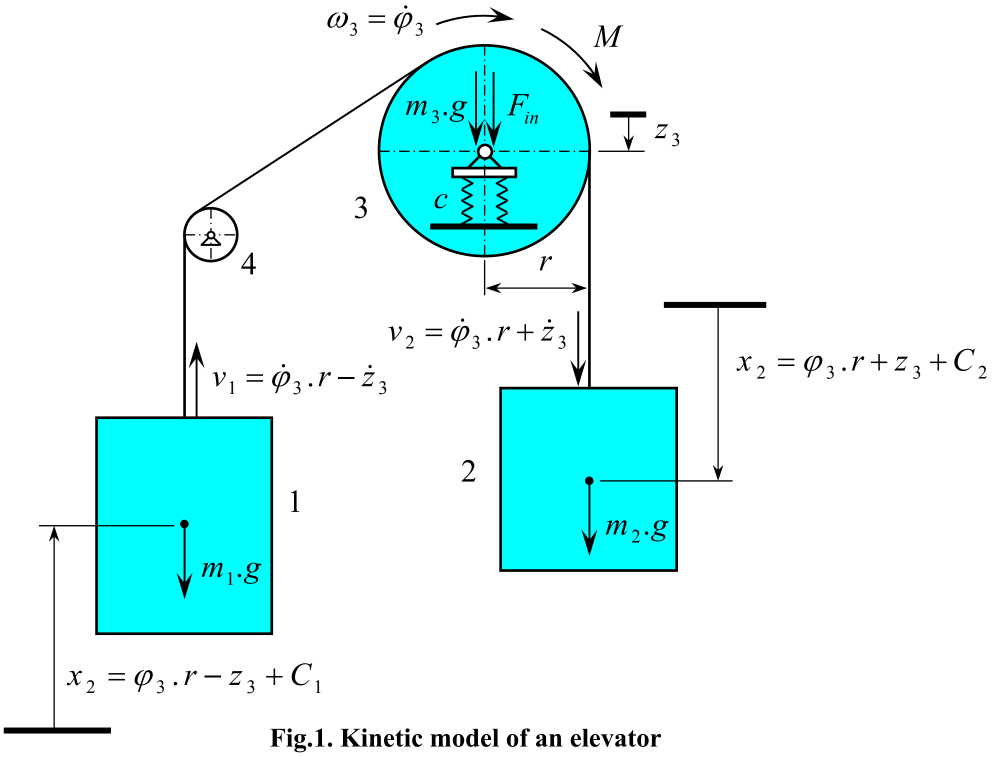

Fig.1. Kinetic model of an elevator

Lagrange's equations of the second kind are used to obtain the system of differential equations that describes the movement of the elevator cabin, the counterweight, and the disk:

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{z}_3}\right) - \left(\frac{\partial E_k}{\partial z_3}\right) = Q_{z_3} - \frac{\partial E_p}{\partial z_3} , \tag{2}$$

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{\varphi}_3}\right) - \left(\frac{\partial E_k}{\partial \varphi_3}\right) = Q_{\varphi_3} - \frac{\partial E_p}{\partial \varphi_3} , \tag{3}$$

where E_k and E_p are respectively the kinetic [11, 12] and potential energy of the system:

$$E_k = \frac{1}{2}.\dot{\mathbf{q}}^T.\mathbf{M}.\dot{\mathbf{q}} , \tag{4}$$

$$\mathbf{M} = \begin{bmatrix} m & S \\ S & J \end{bmatrix} . \tag{5}$$

The matrix $\mathbf{M}$ of mass and inertial properties has the form:

$$m = m_1 + m_2 + m_3 , \tag{6}$$

$$S = \left(m_2 - m_1\right).r , \tag{7}$$

(8) $$J = \left(m_1 + m_2\right).r^2 + J_3 \ .$$

The total potential energy in compact form is written as follows:

(9) $$E_p = \frac{1}{2}.c.\left(z_3 + \delta_{st}\right)^2 - m.g.\left(z_3 + \delta_{st}\right) - S.g.\varphi_3 \ ,$$ where

(10) $$c.\delta_{st} - m.g = 0 \ .$$

where δ_{st} is static deformation of the rubber spring pads.

The generalized forces have the form:

(11) $$\mathbf{f} = \begin{bmatrix} Q_{z_3} \\ Q_{\varphi_3} \end{bmatrix} \equiv \begin{bmatrix} F_{in} \\ \widetilde{M} \end{bmatrix} = \begin{bmatrix} m_{in}.L.p^2.\sin p.t \\ M + S.g \end{bmatrix},$$

where m_{in} is the unbalanced mass, L is the eccentricity of the unbalanced mass, p is the angular velocity of the shaft that creates the inertial disturbance, and M is the reduced torque relative to the axis of the disk.

The system of differential equations, which describes the movement of moving bodies, written in vector-matrix form, has the form:

(12) $$\mathbf{M}.\ddot{\mathbf{q}} + \mathbf{C}.\mathbf{q} = \mathbf{f} \ ,$$

(13) $$\mathbf{C} = \begin{bmatrix} c & 0 \\ 0 & 0 \end{bmatrix} .$$

4. NUMERICAL CALCULATIONS

The numerical calculations were carried out assuming the following average values of the individual parameters: mass of the elevator car $m_{11} = 400\ kg$, the maximum mass of the useful load $m_{12} = 320\ kg$, the mass of the elevator car and the maximum useful load $m_1 = m_{11} + m_{12} = 720\ kg$, the mass of the counterweight $m_2 = m_{11} + 0.5 \times m_{12} = 560\ kg$, mass of the motor $m_3 = 400\ kg$, radius of the disc $r = 0.325\ m$, mass moment of inertia of disk $J_3 = 0.33\ kg.m^2$, unbalanced mass $m_{in} = 0.25\ kg$, the eccentricity of the unbalanced mass $L = 0.005\ m$, the angular velocity of the shaft that creates the inertial disturbance $p = 20\ s^{-1}$, elasticity coefficient $c = 5.5 \times 10^6\ \ N/m$.

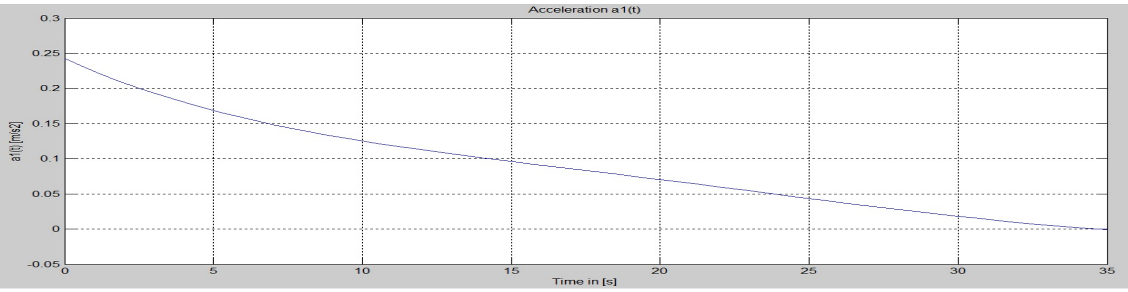

Fig.2. Acceleration $a_1\ [m/s^2]$ of the elevator cabin on departure

Modern high-speed elevators have sensors that detect the change in the payload in the elevator car and send a signal to the motor, which adjusts the torque to obtain a smooth vertical acceleration.

In this case, the numerical calculations were carried out at the maximum value of the payload and torque of the form:

(14) $$\widetilde{M} = \hat{M}.e^{-0.008.t} = 200.e^{-0.008.t} \ \ [N.m]$$

A program was prepared in the MatLab environment. The most important kinematic characteristics during the start of the elevator cabin in Fig. 2, 3, and 4 are shown.

From the graphs (Figs. 2, 3, and 4) it can be seen that the vertical acceleration at the initial moment of 0.25 m/s2 gradually decreases and after 35 seconds the elevator car moves at a constant velocity of about 3 m/s. Just at this moment, the elevator cabin has traveled a vertical distance of about 25 m.

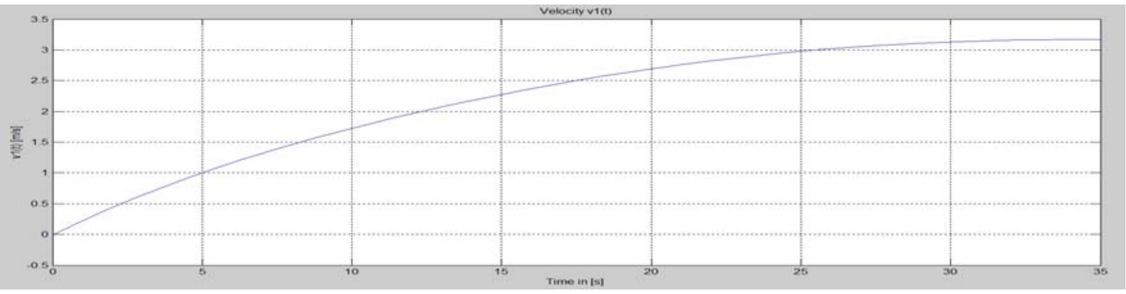

Fig.3. Velocity $v_1\ [m/s]$ of the elevator cabin on departure

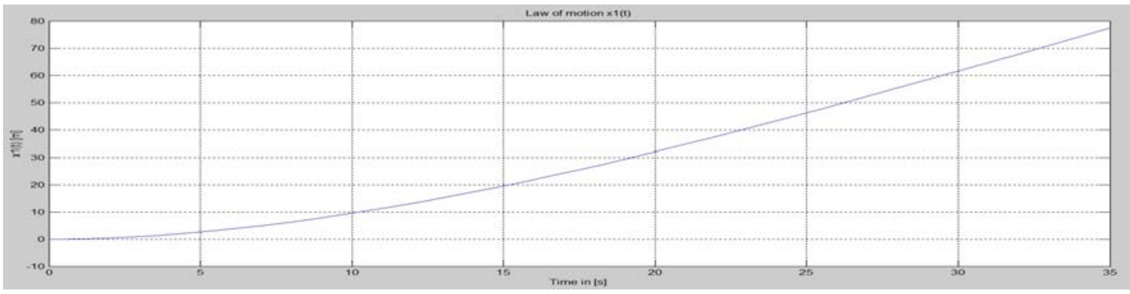

Fig.4. Vertical distance $z_1\ [m]$ of the elevator cabin on departure

5. CONCLUSIONS

A kinetic model of a classic high-speed elevator with an overhead machine room has been compiled. Although maximum simplified, all kinetic characteristics can be obtained with this model. It can be complicated in order to reduce the number of assumptions and to take into account other influences, such as the elasticity of the steel ropes, the not perfectly smooth rail track, the damping in the system, etc. It is necessary to carry out the study under different load regimes within the entire path - from starting, where there is a positive acceleration, uniform movement, where the acceleration is zero, and a stop phase, where the acceleration is negative. In all cases, however, the comfort and safety of passengers must be ensured.

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МОДЕЛ НА ВИСОКОСКОРОСТЕН АСАНСЬОР

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Ключови думи: *моделиране. високоскоростен асансьор, собствена честота, виброизолиране, метало-гумени подлоцки, числено решение, MatLab*

Резюме: *В последните години високоскоростните асансьори все по-често се монтират във високите сгради и небостъргачите. При тях кабината се движи с установена скорост най-малко три метра в секунда по изключително прави релси с цел да се минимизират напречните вибрации, които са изключително малки. Изследвана е високоскоростен асансьор, състоящ се от кабина, противотежест и машинен агрегат, който е разположен в горната част на съоръжението. Стоманените въжета на тези асансьори са с голяма дължина и обикновено са четири. Като първо приближение, те са приети безтегловни и неразтегливи. Асансьорът е моделиран като механична система с две степени на свобода. Един от недостатъците на тази класическа конструкция е, че се открива възможност вертикалните вибрации, породени от машинния агрегат, посредством въжетата, да се предадат на кабината и да се влоши комфорта на пътуване. Ето защо, той поставен на армирани гумени подложки върху фундаментната етажна плоча. Изключително важна задача на конструкторите на такива модерни високоскоростни асансьори е така да центрира машинния агрегат, че да се сведат до минимум инерционните смущения, вследствие наличието на дебалансни маси. В статията са направени важни изводи и препоръки към конструкторите и техническия персонал, който подържа такива асансьори.*