Study for elevator cage position during the braking period

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Abstract. An important problem in order to study an elevator cage position for its braking period is to establish a correlation between the studies in the fields of mechanics and electric. The classical approaches to establish the elevator kinematic parameters are position, velocity and acceleration, but the last studies performed in order to determine the positioning performed by introducing supplementary another parameter - the jerk- which is derived with respect to time of acceleration. Thus we get a precise method for cage motion control for third-order trajectory planning.

1. Introduction

The paper presents a part of the theoretical studies carried out in order to find the solution for some problems connected with the operation of the electric elevators and, more precisely, to generate the speed profile so that we should have a positioning of the elevator cage as precise as possible and to analyze the variation of the stiffness of cage suspension cable.

The use of speed modelling in the operation of elevators has been known for a long time. The S curves used for modeling speed at the start and stop can be generated from different arcs of curves: polynomial or trigonometric. In this case one will analyze the situation of an elevator having S curves at start and at stop generated by arcs of sinusoid, modeling which proved to be beneficial because it reduces the space and allows a good positioning of the cage [1], [2]. The parameters that influence the positioning of the cage are both of kinematic (the value of the maximum speed and of the acceleration at start and at stop, the variant of speed modeling) and of dynamic nature (loading the cage, transitory processes, cable rigidity).

If the kinematic parameters can be estimated easily and are the basis for the electric adjustments, it is more difficult to control the dynamic parameters and they differ depending on the type of the elevator. Thus, in case of small capacity, small height and small speed elevators there are different dynamic processes as compared with the big capacity, high speeds and big lengths elevators [3], [4]. In these conditions, it is good to know the dynamic parameters that influence the process and what their effects on operation are [5], [6].

This paper explores the kinematic modeling of the speed profile, taking into consideration the restricted condition and the deformation of the cables over the positioning of the cage.

2. Trajectory planning

The functioning cycle of an elevator has three significant periods, as seen in figure 1: acceleration period (1), constant speed period (2), and the period of braking, which consists of deceleration, (3),
alignment (4) and stop (5). The theoretical diagrams for the variation of kinematic parameters for an elevator with sinusoidal modeling of velocity are presented in Figure 1.

Diagrams will have oriented to motion control for to bring in a short time to wished level at the cage [7]. The paper presents a part of the theoretical studies carried out in order to find the solution for some problems connected

![Velocity, acceleration and jerk Profile](image)

**Figure 1.** Velocity, acceleration and jerk Profile

2.1. **Velocity profile**

The motion equations were written on time intervals (Figure 1). The motion equations written in this way allow the determination of the transitory velocity and durations by imposing limited values for jerk and for acceleration.

The value of the jerk is limited by man’s presence in the system or by the integrity of the transported goods and the value of acceleration by the condition of non-gliding of the cable on the wheel.

First equation is for the acceleration. For the cosinusoidal acceleration profile corresponds sinusoidal jerk variation. The starting period with interval 1 correspondence (Figure 1).

The braking period has three intervals. The first interval for retardation. Second interval with constant velocity. Last interval for retardation, it enables getting a correct levelling regardless of the cage load. Once the levelling process has finished, the motor is electrecally bloked (velocity 0) [8].
Imposing peak value of jerk 1.3 m/s³, peak values of acceleration $a_1 = a_2 = a_3 = 0.8$ m/s², maximum velocity $V_{\text{max}} = 1$ m/s and approach velocity $V_a = 0.2$ m/s, time constant sped 19.53 s,

$$t_i = \frac{2V_{\text{max}}}{a_i},$$

$$t_3 - t_2 = \frac{2(V_{\text{max}} - V_a)}{a_2},$$

using MATLAB, we obtained the acceleration diagram represented in Figure 2 and the velocity diagram in Figure 3. The values of duration of the phases corresponding to the maximum admitted value for jerk were also calculated (Table 1). Good values resulted for braking time with sinusoidal variation acceleration.

Planning cosinusoidal acceleration offered the advantages of better stability in relation to changes to the system parameters (the acceleration, time limits, jerk).

| Parameter      | Value  |
|----------------|--------|
| $\Delta t_s$ - starting [s] | 2.19845 |
| $\Delta t_b$ – breaking [s] | 1.98318 |
| $\Delta t_l$ - levelling [s] | 0.69521 |

**Table 1.** The values of duration

Figure 2. Acceleration Profile

Taking into consideration the periods defined in the previous paragraph, the variation equations versus time have been written for the velocity and for the travel of the cage for the intervals. The velocity equations for intervals (Figure 1) are:
\[
\begin{align*}
    r \cdot \dot{\phi}_h(t) &= \frac{a_1}{2} \left( t - \frac{a_1}{2j_1} \sin \frac{2j_1}{a_1} t \right) \\
    r \cdot \dot{\phi}_v(t) &= v_{\text{max}} \\
    r \cdot \dot{\phi}_s(t) &= v_{\text{max}} - \frac{a_2}{2} \left( t - t_2 \right) \sin \frac{2j_2}{a_2} \left( t - t_2 \right) \\
    r \cdot \dot{\phi}_a(t) &= v_a \\
    r \cdot \dot{\phi}_b(t) &= v_a - \frac{a_3}{2} \left( t - t_4 \right) \sin \frac{2j_4}{a_4} \left( t - t_4 \right)
\end{align*}
\] (3)

Notations used: \( r \)- radius of the driving pulley, \( a_1, a_2, a_3 \) - peak values of the accelerations in the transitory periods, \( \dot{\phi}(t) \) - angular speed of the driving pulley for each time interval.

![Velocity Profile](image)

**Figure 3.** Velocity Profile

### 2.2. Space Profile

The space equations for intervals (Figure 1) are:
\[
\begin{align*}
\mathbf{r} \cdot \phi_{i1}(t) &= \frac{a_i}{2} \left( \frac{r^2}{2} + \frac{a_i^2}{4j_i^2} \cos \frac{2j_i t}{a_i} - \frac{a_i^2}{4j_i^2} \right) \\
\mathbf{r} \cdot \phi_{i2}(t) &= y_{i2}(t_i) + v_{\text{max}}(t - t_i) \\
\mathbf{r} \cdot \phi_{i3}(t) &= y_{i3}(t_2) + v_{\text{max}}(t - t_2) - \frac{a_2}{2} \left( \frac{(t - t_2)^2}{2} + \frac{a_2^2}{4j_2^2} \cos \frac{2j_2}{a_2} (t - t_2) - \frac{a_2^2}{4j_2^2} \right) \\
\mathbf{r} \cdot \phi_{i4}(t) &= y_{i4}(t_3) + v_a(t - t_3) \\
\mathbf{r} \cdot \phi_{i5}(t) &= y_{i5}(t_4) + v_a(t - t_4) - \frac{a_3}{2} \left( \frac{(t - t_4)^2}{2} + \frac{a_3^2}{4j_3^2} \cos \frac{2j_3}{a_3} (t - t_4) - \frac{a_3^2}{4j_3^2} \right)
\end{align*}
\]

Figure 4. Space Profile

3. Study for the cage position
The study for the cage position was realized considering the cable elasticity.

Figure 4 shows the space variation diagram at the ascension of the cage, in the hypothesis that the suspensions cables are inextensible. In fact, the cage’s position depends on the cable’s stiffness and on the cabin’s load. We write motion throughout for the all interval with analyzed braking period.

3.1. Differential equation of motion
The motion equation of the cage (5) for elevator represented in Figure 5 was determined starting from the following hypotheses:

- only the movement of the of the elevator cage is studied;
- only the movement designed for the direction of the theoretical travel has been studied, which is defined in figure 5 as Oy axis;
- the mass of the pull cable represents a very small part of the moving masses and it is neglected;
- the suspension cables are considered elastic elements with a variable elasticity strain. The influence of the elasticity of pulley can be neglected in comparison with the steel wire-rope elasticity;
For $r \cdot \phi$ - displacement of the pulley, we have $y$ - real motion (absolute) corresponding of the cage.

$$M \cdot \ddot{y} = -M \cdot g + \frac{E \cdot A}{L - r \cdot \phi} \Delta y - 1,2 \frac{v_{\text{max}}^3}{27} B \cdot C - F_{fr} \left( \text{sgn} \ y \right)$$  \hspace{1cm} (5)

Notations used:

- $y$ [m] - real position of the cage, considering the cable elastic elements;
- $M$ [kg] represents the mass of the loaded cage;
- $\Delta y = r \cdot \phi - y$ - cable deformation;
- $r \cdot \phi$ - represents the cage kinematic travel, governed by the equations of modelling the speed for each interval (equations 1);
- $F_{fr} = \mu \cdot N$ [N] Coulomb friction force, caused by the contact with the guides. Its value is considered constant.
- $F_{frv} = 1,2 \frac{v_{\text{max}}^3}{27} B \cdot C [N]$ - air friction force, where B and C are the cage’s dimensions [9].

**Figure 5.** Elevator model

3.2. Numerical simulation for deviation of the cage position

For study, an elevator having the characteristics below has been taken into account:

- Nominal power $P_m = 5,5$ kW,
- Maximal speed $V_{\text{max}} = 1$ m/s,
- Levelling speed $V_a = 0,2$ m/s,
- Cabin weight $G_C = 6280$ N,
- Counterweight weight $G_{CG} = 7780$ N,
- Load $G_u = 3000$ N,
- Reactions on the car guides: $S_y = 223$ N
Reactions on the counterweight guides: $S_y = 158$ N

Friction coefficient: $\mu = 0.12$

The cage suspension cables 6x19 +1, having the characteristics below:

- $d = 10$ mm – nominal diameter of a cable,
- $E = 89$ GPa – elasticity module of the cable;
- $L = 27.3$ m – length of the cables with the cage at station 0 (ground floor).

The most unfavourable situation from the point of view of adjusting the cage position is when the cage goes up from the zero level to the last but one level, due to the fact that in case of frequency control (a method currently used for elevators) it is important that the engine should reach the rotative speed corresponding to the approaching frequency before receiving the levelling signal [10].

In the initial moment of movement cabin at level 0, the initial conditions of motion are:

$$t = 0; \quad y_0 = -\frac{m \cdot g \cdot L}{E \cdot A}; \quad \dot{y} = 0$$ (6)

Numerical solution of the equation (3) was determined by algorithms type predictor – corrector multipass, using the function code 113 in the program MATLAB. After solving equation, the following diagrams for the variation of the cable deviation resulted: for the situation of going up with the empty cage (Figure 6) and for the situation of going up with the fully loaded cage (Figure 7).

By analysing the diagrams (Figure 6 and Figure 7) one can notice that elongation at the start is influenced by the cabin’s load. The deviation is smaller at the stop also due to the levelling stage.

![Figure 6. Deviation of the motion the empty cage](image)

One can notice an increase of the maximal cable deformation of about 35% between the situation of the empty case and that of the fully loaded cabin. In the transitory period of start at the static loading, the dynamic loading is added. In the period of constant travel the deformation varies approximately linearly and is determined by the modification of the cable rigidity. Two jumps corresponding to the intervals $(21.98 - 26.5)$ s in Figure 6 and in Figure 7 are noticed in the period that corresponds to braking.

In these conditions the cage have a complex motion, considered through cinematic motion and oscillatory motion.
For a better appreciation of the dynamic process many authors detailed the oscillations cable. For example in the dynamic analysis of mine elevators used with underground high lifting, the high velocity and using the steel ropes is necessary forming a another model for the dynamic analysis [11].

![Figure 7. Deviation of the motion fully loaded cage](image)

4. Conclusions
From a kinematic point of view versus the classical control, where the restrictions are the position, the maximum speed and the acceleration, additionally enforcing the limit on the acceleration derivative brings important advantages such as a better adjustment of the trajectory variation to the restrictions and the behavior of the electro mechanic system. Another advantage consists in the possibility of imposing by design the amplitude of the mechanic places at start and at braking. The cable rigidity is not constant during an operation cycle. The transitory regime of decelerating with levelling step is beneficial from the point of view of the positioning; in this case the dynamic regime modifies the elongation less, as compared with the transitory period at start. The taking over of the load modifies the cable rigidity.

The cable lengths variation (shortening or extension) directly affects its rigidity and also affects directly the dynamic behavior and therefore, the cable dynamic behavior. The studies carried out, both those referring to the kinematic regime and those referring to the dynamic regime are beneficial in order to generate the Velocity Profile and to decide the Control Strategy of the elevator.

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