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Dynamic modelling and input-energy comparison for the elevator system

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ABSTRACT

The elevator system driven by a permanent magnet synchronous motor (PMSM) is studied in this paper. The mathematical model of the elevator system includes the electrical and mechanical equations, and the dimensionless forms are derived for the purpose of practicable upward and downward movement. In this paper, the trapezoidal, cycloidal, five-degree (5-D) and seven-degree (7-D) polynomial and industry trajectories are designed and compared numerically in various motion and the absolute input energies. From numerical simulations, it is found that the trapezoidal trajectory consumes the minimum energy; the 7-D polynomial trajectory consumes the maximum one. The less end-point constraints are required, the less energy is consumed. Finally, the proposed sliding mode controller (SMC) is employed to demonstrate the robustness and well tracking control performance numerically.

1. Introduction

Nowadays, the elevator system has been a significant vertical transportation device for tall buildings, and has brought human convenience and efficiency in the recently decade years. However, the energy (electrical power, crude oil for example) has been consumed and exploited greatly for many years. The energy consumption of the elevator system is the most part in the power consumption of tall buildings. Therefore, the energy saving of the elevator system is an interesting study and meaningful topic. In the previous studies, the authors only emphasized that the string vibration suppression control [1,2], but the topic in energy consumption was not discussed. The robust control algorithms [3–6] also were employed for the elevator system, where the car trajectory was tracked by the robust controller, and the numerical simulations and experimental results demonstrated that the proposed controller was superior. In the previous papers [1–6], what kind of trajectories can save energy was seldom discussed. Furthermore, the end-point constraints of trajectories were not studied for the comparisons in the input electrical energies.

Schlemmer and Agrawal [7] proposed the elevator to transport passengers in a near minimum time while satisfying elevator's intrinsic dynamic constraints, such as allowable hoist torque/power, and extrinsic comfort constraints, such as allowable acceleration and deceleration. Mutoh et al. [8] proposed a induction motor driving controller for the drive system of elevators on the basis of simulations and experiments to improve performance of elevators. These papers [7,8] neither define the energy nor to propose energy-saving controllers for the minimum energy/time trajectories. Moreover, the previous

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researches [9–11] even proposed the minimum-energy control method to the energy-saving problems, but the energy definition is not the physical one.

The most definition of cost function in an optimal control problem is the sum of square control effort of the system, but not the physical energy. Fortunately, Kokotovic and Singh [12] presented the minimum-energy control for a nonlinear second-order model of a ground transportation vehicle with dc traction motor. They proposed the electrical energy as the cost function for the dc motor drive system. Huang et al. [13] proposed a minimum-energy point-to-point (PTP) trajectory planning method for a motor-toggle servomechanism, and defined the electrical energy as the fitness function for the real-coded genetic algorithm method. In [13], a nine-degree polynomial trajectory and the initial- and final-state constraints were discussed. Zhua and Teppo [14] proposed a novel scaled model to simulate the linear lateral dynamics of a hoist cable with variable length in a high-rise, high-speed elevator, where the position function is given by a fifth order polynomial and is divided into seven regions, and the prototype movement profile was described clearly and compared with other trajectories.

The trajectory planning topics also were discussed in the previous studies [15–19]. The authors emphasized the optimal time-jerk trajectory planning to the robot manipulators. In order to obtain the optimal trajectory, two objective functions composed of two terms are minimized. The high degree polynomial trajectory was planned and implemented in the manipulator [20]. The linear acceleration profiles of end-effector were planned for the polynomials of degree 9, 7 and 5. In these studies [15–20], the energy consumptions of the trajectories for the robot manipulator were not considered, and the initial- and final-time constraints were also not discussed and compared.

In this paper, we propose the complete mechatronic model with the electrical equation of a PMSM and the mechanical equation of an elevator system. The car's displacement and travel time of the elevator system is transferred to the dimensionless form for the upward and downward movement. The energy definition of the elevator system is proposed and the total input energies are compared among various trajectories, which include the trapezoidal, cycloidal, 5-D, 7-D polynomial and industry trajectories. The end-point constraints are not the same for various trajectories, and then their input energies are different. This paper is going to find the relationship between the initial- and final-time constraints and the total absolute input energies from numerical simulations. Finally, the proposed SMC demonstrates that the controller has the robustness and well tracking control performance numerically.

2. Modeling of the elevator system

Firstly, the electrical equation of the PMSM is given, and then the mechatronic elevator system driven by the PMSM is formulated. The string mass of the elevator system is also considered as the variable external force acting on the PMSM. The dimensionless process is applied and the elevator model becomes a normalized form. The energy definition of the PMSM is also defined.

2.1. Model of the PMSM

The stator flux-linkage equation of a PMSM [21] can be described as follows:

$$v_q = R_s i_q + L_q di_q/dt + \lambda_d \omega_r, \tag{1a}$$

$$v_d = R_s i_d + L_d di_d/dt - \lambda_q \omega_r, \tag{1b}$$

where v_d and v_q are the stator voltages, i_d and i_q are the stator currents, L_d and L_q are the inductances, λ_d and λ_q are the stator flux linkages of the d and q axis, respectively. R_s is the stator resistance, d/dt is total differentiation with respect to time, and ω_r is the rotor angular speed.

The electromagnetic torque τ_e can be described as:

$$\tau_e = T_r + B_m \omega_r + J_m \dot{\omega}_r. \tag{2}$$

The applied torque can be obtained as follows:

$$T_r = K_t\ i_q - J_m\ \dot{\omega}_r - B_m\ \omega_r. \tag{3}$$

Fig. 1 shows the PMSM including a gear speed-reducer. n is the gear ratio number and can be described as follows:

$$n = n_a/n_b = \omega_r/\omega = T_l/T_r, \tag{4}$$

where n_a and n_b are the gear number, T_l is the torque applied on the sheave, and ω is the angular speed of the sheave. Then, the electrical torque and the applied torque are given respectively as:

$$T_r = K_t i_q - J_m \dot{\omega}_r - B_m \omega_r = K_t i_q - J_m n \dot{\omega} - B_m n \omega, \tag{5}$$

$$T_l = n T_r = n K_t i_q - J_m n^2 \dot{\omega} - B_m n^2 \omega. \tag{6}$$

2.2. Elevator system driven by a PMSM

In Fig. 2, the elevator system is shown and the sheave rotation is driven by a PMSM. The main string passes over the drive sheave and is attached to a counterweight. The purpose of the counterweight is to compensate the elevator's weight and it