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Disturbance-Estimation-Based Robust Control for Ropeless Linear Elevator System

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Abstract : Ropeless linear elevator (RLE) is an attractive solution for skyscrapers in the near future. In this paper, an advanced control method for this elevator system is investigated. The laboratory experimental RLE model of which drive source is a controlled-PM linear synchronous machine (LSM) is first described. The vertical motion control of a RLE is briefly analyzed. The typical difficulties in the control of a RLE, mainly due to unpredictable load and non-linearities, are pointed out and discussed. A robust motion control scheme is then proposed based on a disturbance estimation in order to overcome these difficulties. Finally, the high performance of the proposed advanced controller is shown by dynamic simulation under severe operation conditions.

Keywords : Ropeless linear elevator (RLE), Controlled-PM linear synchronous machine (LSM), Disturbance estimator, Robust control

1. Introduction

Ropeless elevator has become a very hot topic as one of the most important applications of vertical linear motors. It is expected for overcoming the disadvantages of a conventional elevator in very high and large buildings due to the existence of the extremely heavy rope. In our Laboratory, an experimental model of RLE has been designed and manufactured using the theory of a controlled-PM linear synchronous motor (LSM) developed by one of the authors[1)2)]. The long-stator LSM with controlled permanent magnets (PM) mounted on the cage is utilized in this model. By controlling the driving thrust force acting between the armature and the translator of the LSM we can propel the cage vertically. No rope is thus necessary in this system.

One of the major difficulties in the control of RLE resides in quick and unpredictable load change due to people's passage. In this paper, the authors propose a robust controller to overcome this problem. The experimental model of RLE in our Laboratory is first described. The vertical motion control of a RLE is briefly analyzed. A robust control scheme is designed based on a disturbance estimator. Finally, the performance of the proposed robust controller is numerically tested by simulation with a large variation of mass and discussed.

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2. Description of the RLE Model

Figure 1 shows the laboratory experimental model of the RLE system, where the two-armature-long-stator LSM is adopted as driving source. The vertical length of armature iron is about 2m, of which the active part for movement is 1520mm. Other parameters of the RLE model are shown in **Table 1**. The translator of the LSM is the cage itself. Two pairs of controlled PMs are mounted on the left and right sides of the cage of which mass is about 50kg (including the PMs). The guide-rollers are also situated on these sides of the cage. In addition, two shock-absorbers are included in the model as illustrated in **Fig.1** to

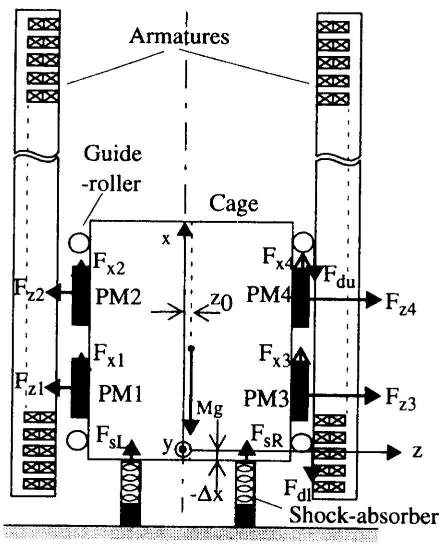


Fig.1 Model of ropeless elevator in our Laboratory.

Table 1 Parameters of the RLE experimental model.

Item	Symbol	Value	Unit
Number of conductors in a slot	N_1	22	
Number of slots per poles/phase	q	2	
Pole pitch	τ	60	mm
Slot width	w_s	5.6	mm
Slot pitch	t_s	10	mm
Length of the PM	l_M	40	mm
Height of the PM	h_M	5	mm
Number of poles per side	p	4	
Air-gap length	δ	(4 - 8)	mm
Number of turns per PM pole	N_2	20	
Width of the control coil	l_C	40	mm
Height of the PM yoke	h_{My}	29	mm
Height of the stator yoke	h_{sy}	40	mm
Mass of the cage	M	50	kg

protect the cage at the bottom position. The vertical position of the cage is measured by an optical pulse encoder, of which the target is mounted on the back side of the cage. And the eight air-gap sensors situated on left and right sides of the cage detect its position in the horizontal direction.

The armatures of LSM are connected in series and fed by high-gain current controllers (not included in **Fig.1**). Single-phase inverters are used for feeding the lower PMs (PM1, PM3) and upper ones (PM2, PM4). If the PM-controlling-current is not applied, the system operates as a PM LSM.

3. Vertical Motion Control of the RLE

3.1 Thrust Force and Attractive Force in RLE

For the reason of convenience, the coordinate system x-y-z is chosen as shown in **Fig.1**, where the origin corresponds to the repose position of the shock-absorbers and the vertical x-axis coincides with the central axis of the armatures. In this RLE system, the thrust force F_X and the attractive force F_Z that act in the x- and z-direction, respectively, can be derived in the following analytical form by using Magnetic Vector Potential (MVP) transfer-matrix method[1)2)].

$$F_x = K_x\left(\delta_e, \sin\frac{\pi}{\tau}x_0, I_2\right)I_1 \quad (1)$$

$$F_z = K_{zS}(\delta_e)I_1^2 + K_{zMS}\left(\delta_e, \cos\frac{\pi}{\tau}x_0, I_2\right)I_1 + K_{zM}(\delta_e, I_2^2) \quad (2)$$

where K_x, K_{zS}, K_{zMS}, K_{zM} are the coefficients of thrust and attractive forces, I_1 effective value of armature current, I_2 PM-controlling-current, τ pole pitch, x_0 mechanical load-angle and $\delta_e = k_C\delta$ effective air-gap length modified by the Carter's coefficient.

3.2 Vertical Motion Equation

The mathematical model of RLE for the vertical control can be directly derived from the equation of motion in the x-axis:

$$M\ddot{x} = F_x - Mg + F_s - F_d = F_x - F_L \quad (3)$$

where $\ddot{x}$ is the differential of second order of the cage position, F_x total thrust force, F_s total mechanical repulsive force produced by the shock-absorbers, F_d total friction force between the guide-rollers and the armature surface, M total mass of the cage and pay-load, g acceleration of the earth and F_L equivalent load force. The total thrust and attractive forces mentioned above can be computed as algebraic sums of individual force components acting on the PMs (F_{x1} to F_{x4} and F_{z1} to F_{z4}, respectively), as illustrated in **Fig.1**. Also, the force F_s is resulting from the repulsive forces produced by the left and right shock-absorbers (F_{sL}, F_{sR}), and the force F_d is the total of the friction forces acting on the upper and lower guide-rollers (F_{du}, F_{dl}). The friction force F_d is due to the attractive force F_z between the cage and the armature.

As the thrust force F_x is a function of the effective value I_1 of armature currents (Eq.(1)), the cage can be vertically propelled by regulating these currents.

4. Robust Control of the RLE

It is seen from Eq. (3) that M is subject to change due to people's passage in the real operation. Moreover, there are non-linearities and system uncertainties in F_x, F_s and F_d. The coefficient K_x in the relation between the thrust force F_x and armature current I_1, as seen in Eq. (1) and latter in Eq. (4), is not generally constant since it is a function of air-gap δ, the mechanical load-angle x_0 and current I_2[2)]. The coefficient of the shock-absorbers' springs has been experimentally found in a hysteresis form. The friction force F_d due to the attractive force F_z is a coulombic function of the cage speed.

The control system of the RLE should be hence insensitive to all of the load variation, non-linearities and uncertainties in order to yield a high performance. We propose a robust controller which is based on the robust control theory widely applied to rotating machines[4)].

4.1 Disturbance Estimator

Since the generalized thrust-force-current I_1 is assumed to be regulated by the high-gain current controllers and the output current I_1 will completely coincide with its reference I_1^*, the following equation can be given.

$$F_x = K_x I_1 = K_x I_1^* \tag{4}$$

Denoting variations by Δ such as $M = M_n + \Delta M$, $K_x = K_{xn} + \Delta K_x$, where the subscript n denotes the rated value and by combining Eq. (4) with Eq. (3), the basic dynamic equation (3) becomes.

$$M_n \ddot{x} = K_{xn} I_1^* - F_{dis} \tag{5}$$

where

$$\begin{aligned} F_{dis} &= (M_n g + \Delta M g - F_s + F_d) - \Delta K_x I_1^* + \Delta M \ddot{x} \\ &= F_L - \Delta K_x I_1^* + \Delta M \ddot{x} \end{aligned} \tag{6}$$

Equation (6) means that the new variable called *equivalent disturbance force* F_{dis} is the sum of the load and unknown factors: the unpredictable load variation ΔM, the change ΔK_x due to the air-gap variation, control current I_2 and/or load-angle change. Interestingly, this variable F_{dis} includes also the springs' force F_s and the friction force F_d which are difficult to model. Notice that, for the reason of simplicity, M_n is considered the mass of the cage itself, so ΔM represents the pay-load.

From Eq. (5), we can easily have Eq. (7), which means that the sum of unknown factors F_{dis} can be directly calculated from the current reference I_1^* and measured or estimated cage speed v.

$$F_{dis} = K_{xn} I_1^* - M_n \ddot{x} = K_{xn} I_1^* - M_n \dot{v} \tag{7}$$

This process has however one pure differential (of speed), which is somewhat difficult to implement in practice. For an easier realization, Eq. (7) is modified by using a low-pass-filter, such as:

$$\bar{F}_{dis} = \frac{c}{s+c} F_{dis} \tag{8}$$

where c is the cut-off frequency and $\bar{F}_{dis}$ is the estimated equivalent disturbance force. The shaded part in **Fig.2** represents the implementation of Eqs. (7) and (8). This part is called *disturbance estimator.*

4.2 Robust Control Scheme

The configuration of the proposed robust control is shown in **Fig.2** where the part inside the broken line represents the model of RLE. The position and speed control are realized by PI regulators and feedback loops. The robust controller is obtained by direct feedback of the estimated equivalent disturbance force $\bar{F}_{dis}$ divided by the gain element $1/K_{xn}$. This feedback signal has positive sign, because the equivalent load force F_L has been considered to be of negative sign as shown in Eq. (3) and **Fig.2.** This figure means that the disturbance has little effect on the motion system, since the feedback loop of disturbance is just the same as the feed-forward effect of disturbance to compensate for it.

5. Simulation Results and Discussions

The proposed control scheme has been numerically tested in simulation by using SIMULINK with the timing as follows. From 0 to 1 sec: the cage should be moved from the standstill position where it is completely laid on the shock-absorbers ($x = -\Delta_{xmax} = -32.5$mm), to the so-called "starting-position". The starting-position is defined as the position of $x=0$, where the cage only touches the shock-absorbers without pushing them. This procedure can be defined as "preparing-operation"[3], following which the cage should wait for passengers in the interval (1-2 sec). The "normal operation" which starts at 2 sec consists of three stages: going upstairs to 1.5 m for 6 sec (from 2 to 8 sec), then waiting there for 3 sec, and going downstairs also for 6 sec from 11 to 17 sec. Moving

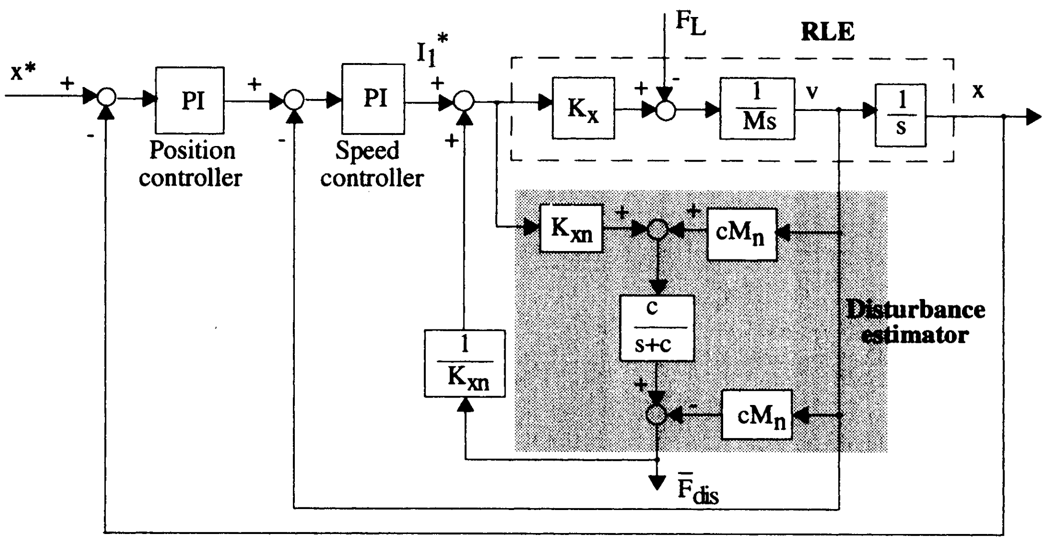
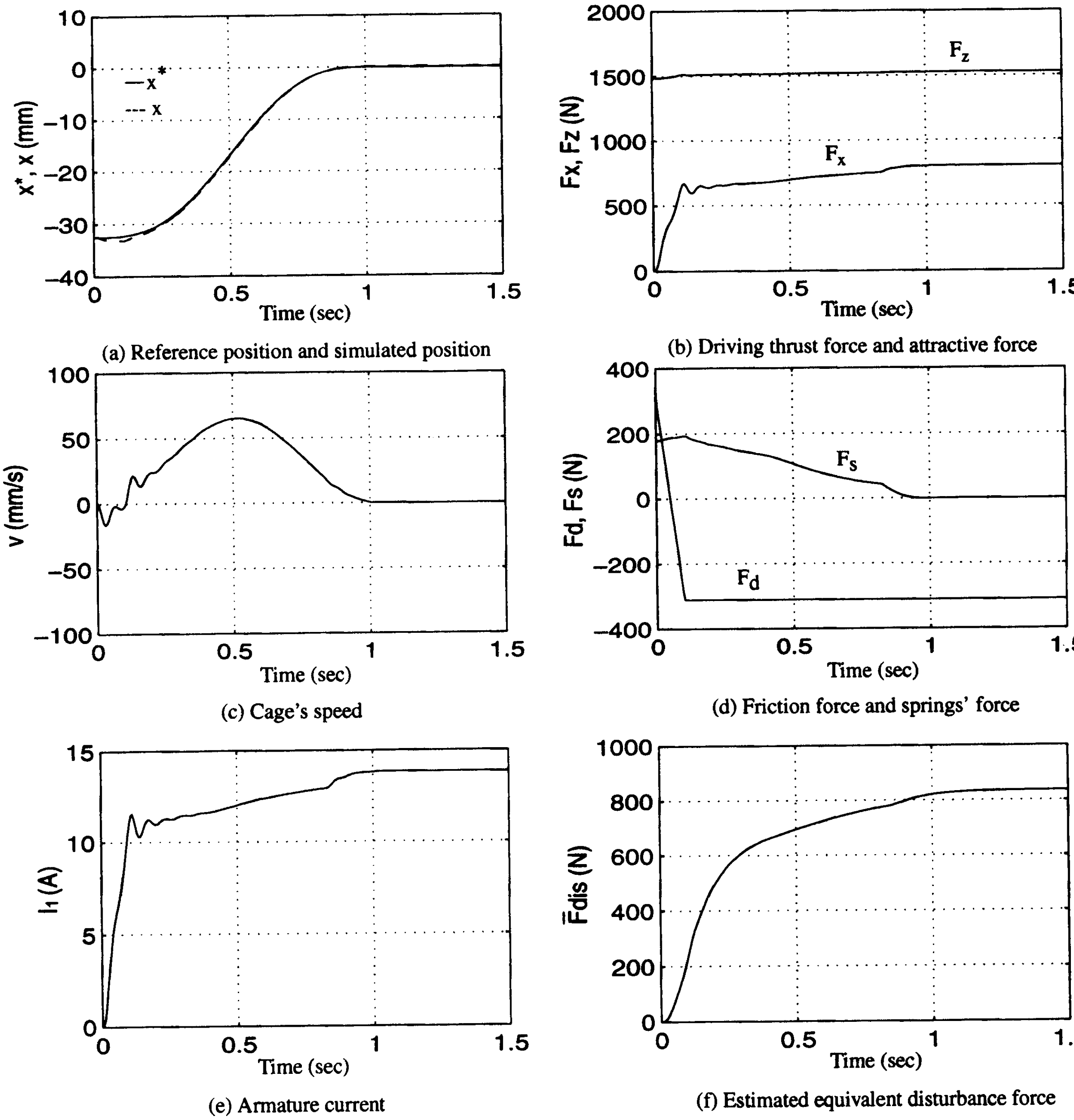


Fig.2 Block diagram of the proposed robust control for RLE.

the cage back into the initial position from 18 to 19 sec completes the simulation. For simulating people's passage, the total mass of the cage and pay-load is supposed to be changed from 100 to 200% at 1.5 sec, and then back to 100% at 9.5 sec. The friction force F_d is assumed to have a sign form in function of speed. In this simulation, this force has been supposed to be changed from F_{dmax} to $-F_{dmax}$ during 0.1 sec, and vice versa, when the cage changes the movement direction. The springs' repulsive force F_s produced by the shock-absorbers has been determined by experimentation and implemented by a look-up table in our case.

As in the "preparing-operation" all the forces have to be taken into account and because this operation lasts for a quite short time, its simulation results are presented on the expanded time base as shown in **Fig. 3**. In this figure, we have reported the most representative signals, namely, (a) reference position x^* and actual position x; (b) driving thrust force F_x and attractive force F_z; (c) actual speed v; (d) friction force F_d and springs' force F_s; (e) armature current I_1; and (f) estimated equivalent disturbance force $\bar{F}_{dis}$.

The simulation results of the complete operation according to the mentioned timing are presented in **Fig.4**, where we have from left to right and from top to bottom: (a) reference position x^* and actual position x; (b) total mass of the cage and pay-load; (c) speed v; (d) friction force F_d and springs' force F_s; (e)



(a) Reference position and simulated position

(b) Driving thrust force and attractive force

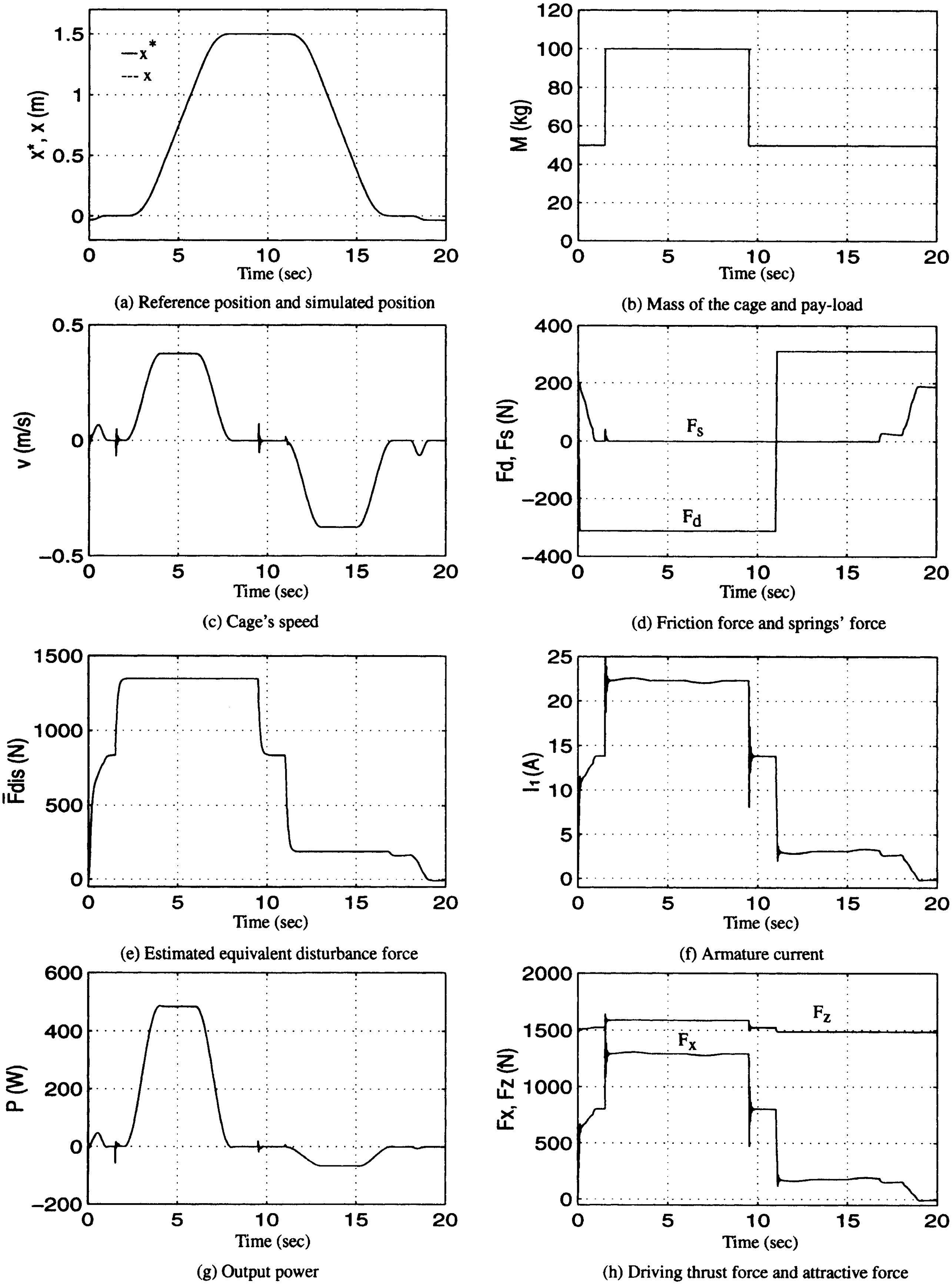
(c) Cage's speed

(d) Friction force and springs' force

(e) Armature current

(f) Estimated equivalent disturbance force

Fig.3 Simulation results in the preparing-operation.



(a) Reference position and simulated position

(b) Mass of the cage and pay-load

(c) Cage's speed

(d) Friction force and springs' force

(e) Estimated equivalent disturbance force

(f) Armature current

(g) Output power

(h) Driving thrust force and attractive force

Fig.4 Simulation of RLE in the preparing-operation and normal operation with a load variation at 1.5 sec and 9.5 sec.

estimated equivalent disturbance force $\bar{F}_{dis}$; (f) armature current I_1; (g) output power P; and (h) driving thrust force F_x and attractive force F_z.

From these figures, we can conclude that very good control performance has been achieved, both in the "preparing-operation" and the "normal operation". We can observe that the cage has followed very closely the reference position trajectory as two curves x^* and x are quite identical and that the position tracking is insensitive to the load variation. The speed v has been developed very smoothly. The stator current I_1 has the same form as the driving thrust F_x since the current $I_2=0$ in this simulation. The role of the shock-absorbers in the preparing-operation and in the final stage is shown. The friction force F_d changes its sign at 11 sec as the cage changes its movement direction. The image of the load variation at 1.5 sec and 9.5 sec can be clearly detected by observing the forces F_x, F_z and current I_1. The form of $\bar{F}_{dis}$ shows that the disturbance estimator can scope all the variations in the system parameters and external load. It is interesting to notice that the thrust force F_x is never negative in the normal operation of the RLE system. When the cage is going up, a big F_x has to be produced to propel the load and the mass of cage itself. while going down, a positive force F_x plays the role of braking force. As shown in **Fig.4 (g)**, a part of power generated by LSM can be recuperated to increase the overall effectiveness of the system.

6. Conclusion

The experimental model of RLE in our Laboratory has been designed and manufactured using the theory of a controlled-PM linear synchronous motor (LSM). This paper has presented an advanced control method in order to deal with the quick load variation, the non-linearities and uncertainties in the RLE system. The design of the proposed robust scheme has been based on the disturbance estimation. The simulation results with a large variation of pay-load have confirmed the excellent command position tracking and load regulating responses of the system. The main advantage of this proposed robust control is that we can compensate directly for the system disturbance, and its implementation is relatively simple. The implementation of the proposed control system is in progress in our Laboratory using a Digital Signal Processor (DSP) TMS320-C32 system.

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