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Accident Safety Design for High Speed Elevator

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***Abstract*— There have been many elevators exist in buildings for such a long time; however, an accident might happen as a free fall due to lacks of maintenance or some other accident such as firing. Although this situation is rarely occurred, many people are still concerned about it. The question here is how to make passengers to feel safe and confident when they are using an elevator, especially, high speed elevator. This problem is studied here in this paper as a free fall spring-mass-damper system with the stiffness and damping coefficient can be computed as minimum jerk of the system with given constraints on trajectories.**

***Keywords* — Free Fall, Jerk, Elevator.**

I. INTRODUCTION

The most of the dynamic systems such as robots, automation systems and advanced mobile machines nowadays are designed so that they are either optimized on their energy consumption or on their greatest smoothness of motion, [3]. Consequently, the trajectory planning and designs of these dynamic systems are done exclusively through many approaches such as the minimum energy, minimum time and minimum jerk, [4]. Nevertheless, in some applications, the system is needed to work very smoothly in order to avoid damaging the specimen that the system is handling while consuming least amount of energy at the same time. In other words, we may want to minimize the jerk of the movement of the dynamic system as to give it the smoothest motion for safety design as well.

II. PROBLEM STATEMENT

Dynamic systems can be described as the first order derivative function of state as

$$\dot{x}_i = f_i(x_1,\ldots,x_n,u_1,\ldots u_m,t); \quad i=1,\ldots,n\,, \qquad (1)$$

where $x \in R^n$, $u \in R^m$ and t are state, control input, and time respectively, [5]. The problem of interest is to find the states *x*(*t*) and control inputs *u*(*t*) that make our system operates according to the desired objective of minimum energy or minimum jerk. Note that this paper is focusing on the system with fixed end time and fixed end points. Therefore, states and control inputs that serve the necessary condition must also be able to bring the system from initial conditions $x(t_0)$ at initial time t_0 to the end point $x(t_f)$ at time t_f.

The optimization problem of minimum energy will take the form of

$$J = \int_{t_0}^{t_f} \sum_{i=1}^{m} u_i^2\, dt\,, \qquad (2)$$

where u_i is the control input, which can be force or torque applied to the system, and $i=1,\ldots,m$. J is the cost function of the energy consumed by the system from an initial time t_0 to an end time t_f.

The same kind of concept is used to the minimum jerk problem. It is well known that jerk is the change of input force with respect to time. It is, thus, the third derivative with respect to time of *x*, or first order derivative of control input *u*. Therefore,

$$Jerk = \dddot{x} \propto \dot{u}\ . \qquad (3)$$

Defining

$$\dot{u} = \tilde{u}\ , \qquad (4)$$

Called indirect jerk, so that (1) becomes

$$\dot{x}_i = f_i(x_1,\ldots,x_{n+m},\tilde{u}_1,\ldots\tilde{u}_m,t); \quad i=1,\ldots,n+m \qquad (5)$$

From now on, $\tilde{u}$ is treated as a variable and as the control input of our dynamic system. Consequently, (2) can be rewritten for the objective function of the minimum indirect jerk problem as

$$J = \int_{t_0}^{t_f} \sum_{i=1}^{m} \tilde{u}_i^2\, dt\,. \qquad (6)$$

Similarly, (2) also can be rewritten for the objective function of the minimum direct jerk problem as

$$J = \int_{t_0}^{t_f} \sum_{i=1}^{n} \dddot{x}_i^2\, dt\,. \qquad (7)$$

This time, *J* is the cost function of the minimum indirect and direct jerks, respectively.

III. EXAMPLE

Mechanism shown in Fig.1 is used to illustrate an elevator consists of mass, spring and damper. The spring and damper system is attached under the passenger cabin in order to be designed as safety device whenever the accident occurs.

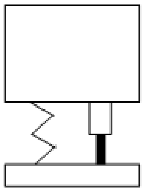

Fig.1. Mechanism of the elevator system

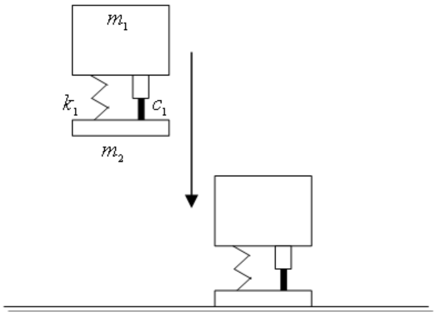

Fig.2. Simple free fall spring mass damper mechanism

When the system falls and reaches the ground, the speed of the system is $v=\sqrt{2gh}$. Once the principal of impulse and momentum is applied, the reaction force that applied to the system is $F=m\sqrt{2gh}/\Delta t$. Let $m=m_1+m_2=1.0$, $\Delta t=1\text{sec}$ and $h=1.0$, then $F=\sqrt{2g}$.

From Fig.2, the equations of motion are

$$m_1 g-k_1(x_1-x_2)-c_1(\dot{x}_1-\dot{x}_2)=m_1\ddot{x}_1 \qquad (8)$$

$$m_2 g-\sqrt{2g}+k_1(x_1-x_2)+c_1(\dot{x}_1-\dot{x}_2)=m_2\ddot{x}_2\,. \qquad (9)$$

The problem statement is to find $c_1(t)$ and $k_1(t)$ in order to minimize jerk of the system which is written as

$$\min J=\int_{t_0}^{t_f}\dddot{x}_1^2+\dddot{x}_2^2\,dt \qquad (10)$$

subject to Eqs. (8) and (9). The boundary conditions are $x_1(t_0)=x_0$, $\dot{x}_1(t_0)=0$, $x_2(t_0)=free$, $\dot{x}_2(t_0)=free$ and all state variables at the final time equal to zeros.

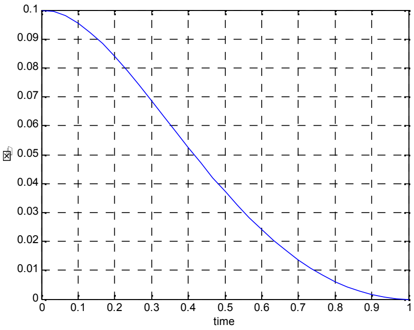

Fig.3. Trajectory of $x_1(t)$

This system is solved for the solutions by separated the dynamic optimization problem into two phases. First, the problem is stated as free fall motion from a specific height and the second is when the system falls on the ground. The second phase is set as a dynamic optimization problem for finding stiffness and damping coefficient of the spring and damper, respectively in order to minimize jerk of the system by applying theorem in the problem statement section. Extra constraints must be added to the necessary conditions are the derivative of the equations (8) and (9) which can be written as

$$-k_1(\dot{x}_1-\dot{x}_2)-c_1(\ddot{x}_1-\ddot{x}_2)=m_1\dddot{x}_1 \qquad (11)$$

$$k_1(\dot{x}_1-\dot{x}_2)+c_1(\ddot{x}_1-\ddot{x}_2)=m_2\dddot{x}_2\,. \qquad (12)$$

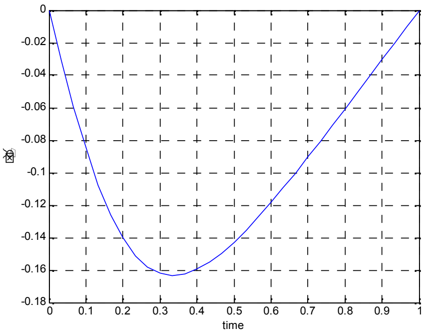

Fig.4. Trajectory of $\dot{x}_1(t)$

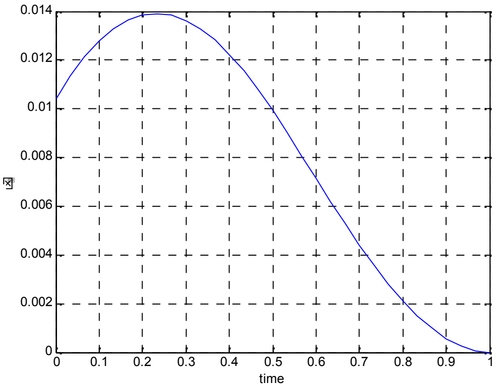

Fig.5. Trajectory of $x_2(t)$

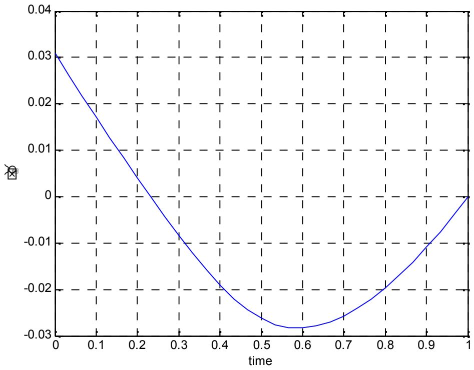

Fig.6. Trajectory of $\dot{x}_2(t)$

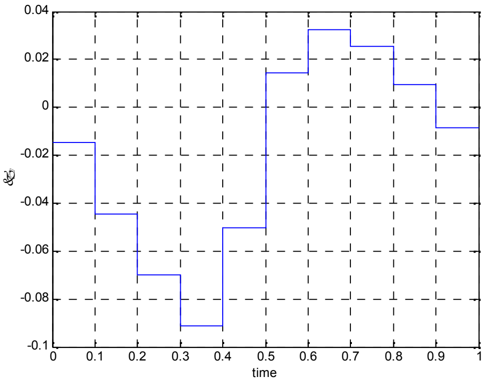

Fig. 7 Trajectory of $k_1(t)$

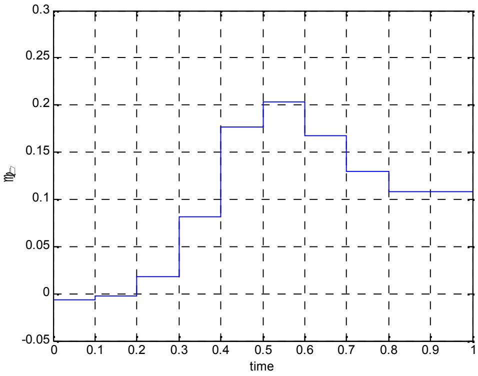

Fig.8. Trajectory of $c_1(t)$

Let $t_0 = 0$, $t_f = 1$, $x_0 = 0.1$, $m_1 = 0.9$, $m_2 = 0.1$ and $g = 9.81$ in MKS units, the solutions of all state variables are obtained in Fig. 3-6 and the solutions of $k_1(t)$ and $c_1(t)$ are shown in Fig. 7 and 8, respectively. The stiffness of a spring and the coefficient of a damper as functions of time are not quite vary. This may possible to use constant spring stiffness and damping coefficient for the real mechanism. However, the experiment must be performed to ensure that the goal as stated earlier will be achieved.

IV. CONCLUSION

The problem is well defined as the solutions obtain by applying dynamic optimization, especially for the minimum jerk problem. Solutions found here are suitable and can be applied to a real elevator system. For the future work, this idea can be used in many applications such as an automobile suspension and personal accessories in a military training. For the real application, there is one future work must be done is to make the stiffness of a spring and the coefficient of a damper become functions of time.

V. ACKNOWLEDGEMENT

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