SCHEDULING OF INPUT SHAPING AND TRANSIENT VIBRATION ABSORBERS FOR HIGH-RISE ELEVATORS

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Abstract: This paper presents techniques for the reduction of vibration in high-rise elevator passenger cabs. Reduction in cab vibration improves ride comfort and enables the use of more aggressive motion profiles thereby shortening travel times. Vibration reduction is accomplished by input shaping the elevator commands in a scheduling algorithm based on position. To deal with transient disturbances, a thoughtfully designed vibration absorber is included. This absorber complements the action of input-shaped control scheme. *Copyright ©2005 IFAC*

Keywords: Elevators, Input Shaping, Vibration Absorbers

1. INTRODUCTION

Skyscrapers are a common sight in many metropolitan areas. Such buildings present many engineering challenges, including the creation of elevators that are capable of transporting passengers quickly, safely, and comfortably at a reasonable cost. Due to the drive cable length and flexibility in high-rise elevators, it is difficult to achieve large cab accelerations without inducing significant vibrations into the passenger cab. Adding additional mechanical damping is unappealing, as this would induce wear and power loss. This paper discusses methods for dealing with the elasticity in the cables by implementing input shaping in the control scheme and attaching a vibration absorber to the passenger cab. The input shaper changes with the height of the elevator, while the vibration absorber is chosen to reduce vibration at the height which is the most susceptible to disturbances. These complementary solutions are shown to be effective techniques that can significantly reduce problematic disturbance and motion-induced vibrations in high-rise elevators.

1.1 Elevator Modelling

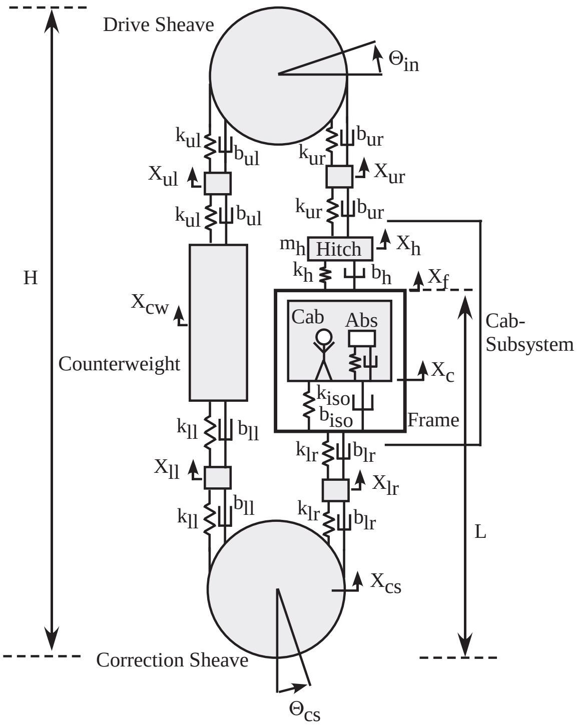

Fig. 1. Model of a High-Rise Elevator

A model of a traditional high-rise elevator system is sketched in Figure 1. The motor, located at the top of the building, rotates the drive sheave, while the counterweight balances the system and the correction sheave prevents slack conditions in the cables. The passenger cab sub-system consists of the cab itself, a structural cage, and a supporting hitch that connects the frame to the drive cable. The hitch allows cable attachment while the cab and frame provide mechanical vibration isolation. Although not included in traditional elevator models, the proposed vibration absorber

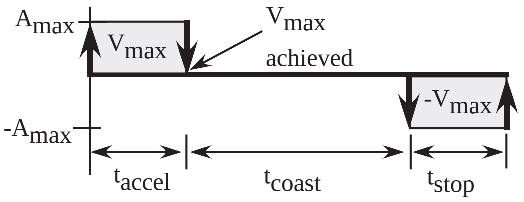

Fig. 2. Bang-Coast-Bang Acceleration Profile of the Drive Sheave

is attached to the cab to further reduce vibration. The cable system of the elevator is modelled as a series of individual cable segments consisting of discrete mass-spring-damper systems. Here one mass per cable segment is used, creating a 22-order model with two modes of vibration within each cable. This model is similar to those developed by the Otis Corporation (Roberts [1998]). The cable's parameters change with length as a nonlinear phenomenon. The primary state of concern is the motion of the passenger cab, X_c. Its motion is described by:

$$m_c\ddot{X}_c + (b_{iso} + b_{cg} + b_{abs})\dot{X}_c + (k_{iso} + k_{abs})X_c = b_{iso}\dot{X}_f + k_{iso}X_f + b_{abs}\dot{X}_{abs} + k_{abs}X_{abs} \qquad (1)$$

where b_{cg} is the damping from the cab to the ground (elevator shaft) and X_{abs} refers to the absorber position, while the rest of the variables are shown in Figure 1. Also important are the equations of motion for the cable masses. Such as the equation for the upper-right cable segment:

$$m_{ur}\ddot{X}_{ur} + 2b_{ur}\dot{X}_{ur} + 2k_{ur}X_{ur} = b_{ur}\left(r_{ds}\dot{\Theta}_{in} + \dot{X}_h\right) + k_{ur}\left(r_{ds}\Theta_{in} + X_h\right) \qquad (2)$$

where r_{ds} is the drive sheave radius, and the cable parameters are defined by:

$$m_{ur} = m_{dr}\frac{H-L}{3}, \qquad b_{ur} = b_{dr}\frac{1}{H-L}, \qquad (3)$$
$$k_{ur} = k_{dr}\frac{1}{H-L}$$

where m_{dr}, b_{dr}, and k_{dr} are structural values per unit length of cable. The equations for the other cables are analogous to (2) and (3).

The specific model used here to investigate the proposed solution is based on a 135 story building with a cab mass of 3400 kg (Roberts [1998]). The length of the upper-right segment of the drive cable varies by 494 meters and its mass changes from 17 kg to 4310 kg, resulting in a 17,000% change in b_{ur} and k_{ur} between the top and bottom floors of the elevator. This change is offset by corresponding changes in the other cables.

The system input is the angular acceleration of the drive sheave, Θ_{in}. Here a baseline command of a bang-coast-bang profile is used with an acceleration limit, A_{max}, and a velocity limit, V_{max} as shown in Figure 2. This command is used since it is the fastest for a given velocity and acceleration constraint. However, this command profile can lead to large cab vibrations as shown in Figure 3. The response shown is for a move of 15 floors lasting 19 seconds. The resulting overshoot at the desired floor is 5 cm for this move. Other move distances generate similar vibration problems.

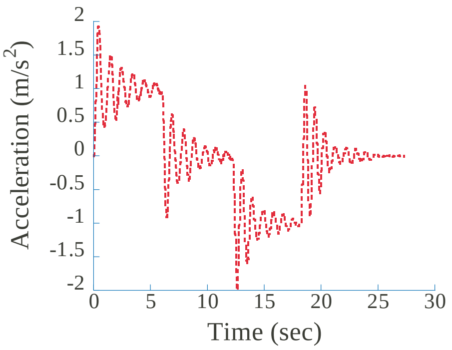

Fig. 3. Acceleration Response of Elevator Cab to Bang-Coast-Bang Input

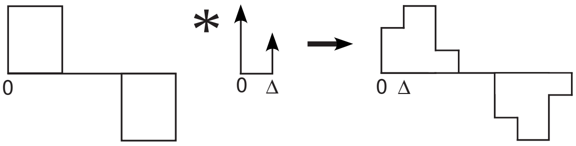

Fig. 4. Convolution Process with an Input Shaper

1.2 Input Shaping

Input shaping is a technique by which the reference commands sent to a system are altered to reduce vibration. For a known set of linear vibratory modes there exists a set of impulses, called an input shaper, that if given as input to a system will excite minimal vibration. This input shaper can be convolved with any baseline input for the system to produce a command that will induce little vibration (Singer and Seering [1990]). Figure 4 shows how this process works with a bang-coast-bang command.

Although input shaping has not been implemented on elevators, it has proven effective with a variety of feedback control schemes (Drapeau and Wang [1993], Kenison and Singhose [2002], Tzes and Yurkovich [1993]). Input shaping has also been implemented on numerous systems such as long-reach manipulators (Magee and Book [1995]), cranes (Noakes and Jansen [1992], Singer et al. [1997], Singhose et al. [1997]), coordinate measuring machines (Jones and Ulsoy [1999], Singhose et al. [1996]), and micro-mills (Fortgang et al. [2004]).

A wide variety of input shapers have been developed for diverse applications. One common input shaper is the Zero Vibration (ZV) shaper (Singer and Seering [1990], Smith [1957]). This shaper has the shortest duration using only positive impulses. The reason duration is important is that the convolution with the input shaper increases the rise time of the command by the duration of the shaper.

A ZV shaper will cancel all vibration if it is designed with a perfect model. However, if there is modelling error, then some vibration will occur. If robustness to modelling errors is needed, a Zero Vibration Derivative (ZVD) input shaper can be used. This shaper forces the derivative of vibration with respect to modelling error equal to zero at the modelling frequency (Singer and Seering [1990]). The cost of this added robustness is an increased shaper duration.

1.3 Vibration Absorbers

Vibration absorbers are auxiliary mechanical systems that can be affixed to a system to reduce vibration. They modify the base system's dynamics in order to improve the response (Hartog [1985]). The early theoretical work on vibration absorbers only considered the ideal undamped case. With the advent of computational techniques, it has been possible to design an absorber for a variety of situations and criteria, including damping and non-linearity in both the absorber and primary system (Pennestri [1998]). Implementation of multiple absorbers and active absorbers whose parameters are controlled by an external source have also been developed (Chao et al. [1997]).

The use of vibration absorbers has crossed a broad range of applications, including architecture; rotational machinery; and consumer goods (Hunt [1979], Sun et al. [1995]). However, the application to the pre-planned trajectories arising in robotics and large scale machinery, such as elevators, has been limited. Traditionally, absorbers were designed to cope with periodic excitations with few excursions into other areas. However, absorbers have been designed for random excitations (Nigam and Narayanan [1994]), as well as for the "time optimal case" in (Bartel and Krauter [1971]) defined by energy dissipation for an impulse response. The step-like trajectories and disturbances present in elevators have been explored (Fortgang and Singhose [2004], Thomas et al. [2002]), and a properly tuned vibration absorber can be used to improve the settling time of a step disturbed lightly damped system up to 90%.

2. INPUT SHAPING FOR ELEVATORS

In order to implement command shaping on elevator cabs, the input shaper is convolved with the baseline bang-coast-bang acceleration command to create a new command profile. The ideal input shaper for each move is dependent on the frequency characteristics of the elevator during a particular move. Therefore, it is necessary to analyze the elevator for position dependent frequency information.

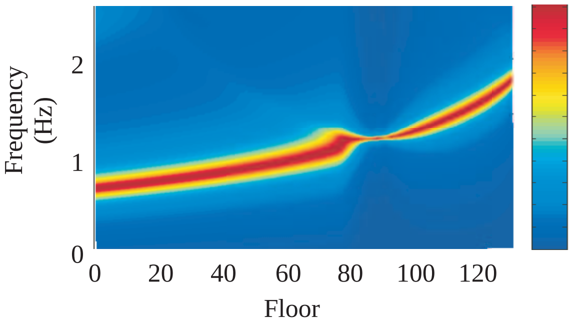

Fig. 5. Frequency Content of Elevator Cab Response

2.1 Frequency Analysis of Elevators

Frequency data of the nonlinear elevator model is obtained by linearizing the cable parameters about possible operating positions. It is important to establish the relationship between the height of the elevator and the associated dominant linearized frequency in order to properly design an input shaper. This frequency data is shown in Figure 5 where the color variation is the magnitude of the frequency response. This surface is used to determine the dominant frequency at each floor. The major trend is that the dominant frequency increases as the elevator rises, because a shorter cable length between the drive sheave and the cab leads to higher frequency oscillations.

2.2 Command Profile Modification

Two methods of input shaping are investigated here. The first approach uses a single input shaper for the entire acceleration profile. The second approach uses four different command shapers to better cancel the vibration utilizing an overall command profile like the one shown in Figure 6. The system is accelerated up to A_{max} using $Shaper_1$. Then the system returns to 0 acceleration using $Shaper_2$. The deceleration profile uses $Shaper_3$ and $Shaper_4$. These shapers are selected by a scheduling algorithm based on the elevator's position.

For the scheduled approach to work, the timing for the modified acceleration profile must be slightly adjusted to account for the system constraints, specifically reaching the desired cruising velocity and stopping at the appropriate floor.

2.3 Single Input Shaper Results

Single input shapers provide a quick and simple solution to neutralize much of the vibration induced by stopping the elevator. By shaping the entire acceleration profile with a single ZV shaper for the dominant frequency at the stopping floor, the vibrations can be greatly reduced, as shown

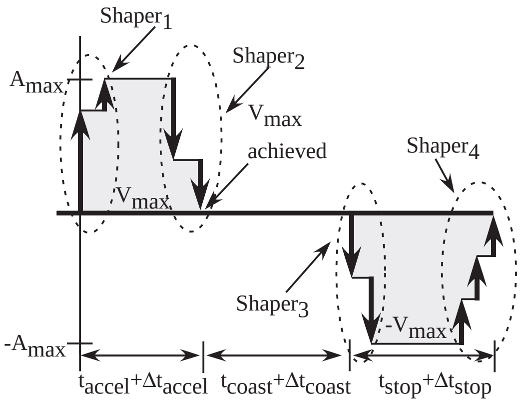

Fig. 6. Input Shaped Bang-Coast-Bang Input

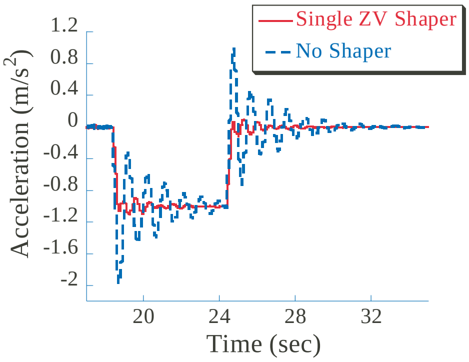

Fig. 7. Shaped and Unshaped Responses from Stopping for a Move from Floor 30 to 50

in Figure 7. Here the maximum acceleration is reduced by 0.9 $\frac{m}{s^2}$, and the maximum overshoot in position is reduced from 3.1 cm to 0.01 cm for this 20 floor move.

Input shaping is not completely effective at cancelling takeoff and coast vibrations because of the change in the dominant frequency of the cab. This is especially true for long moves where the frequency of the elevator at the landing floor can change significantly. This problem can be reduced by using an input shaper that is more robust to frequency variations, like a ZVD shaper. This added robustness comes at the expense of an increase of half a system period in the travel time. Figure 8 shows how the ZVD shaper cancels more cab vibration. Specifically the peak acceleration is reduced by 21% and the displacement magnitude by 56% over the ZV shaped response. One drawback of this single shaper approach is that since the shaping scheme relies on the landing floor, a mid-move change in the desired floor may result in increased vibration.

2.4 Scheduled Input Shaper Results

While single shapers are effective at minimizing landing vibrations of the cab and provide vibration reduction throughout the move, there is a better solution that compensates for the nonlinearity of the system. This is done by using separate input shapers for each acceleration change. Each shaper is designed for the elevator position at the time of the change. The following technique is used to create the adjusted acceleration profile:

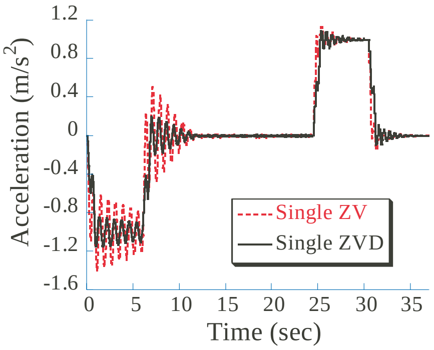

Fig. 8. ZV and ZVD Responses for a 35 Floor Move Down

(1) The instantaneous dominant natural frequency of the elevator at each acceleration change of the bang-coast-bang acceleration profile of Figure 2 is found using Figure 5.
(2) These frequencies are used to design input shapers for each acceleration change.
(3) Δt_{accel} and Δt_{stop} are computed to satisfy the velocity constraints.
(4) Δt_{coast} is used to adjust the cruise time so the elevator will stop at the desired floor.

ZV shapers are used for the first three changes in the acceleration command, while a ZVD shaper is used to bring the elevator to a stop. The inherent robustness of the ZVD shaper better cancels the nonlinear effects of the system, thus leading to lower residual vibration. However, since the transient vibrations are not as important, and a fast move is critical, ZV shapers were chosen for the other acceleration changes. For the scheduled case, the results are good even when the desired floor changes during the motion as would occur if a passenger pushes a button in mid-move.

This scheduled input shaping process improves performance over the single shaper scheme as shown in Figure 9, where the accelerations of the first portions of the move have been greatly reduced. To determine the overall effectiveness of the proposed input shaping scheme, one-hundred random moves, in both the up and the down directions, were simulated with and without the gain-scheduled shaper. The maximum overshoot of the cab position was computed for each case, and the resulting percent improvement in peak overshoot is shown in the histogram of Figure 10. On average, a 97.4 percent reduction in peak overshoot is achieved. The cost of this improvement is an average increase in the move time of 0.674 seconds. Real elevator systems utilize less aggressive smooth acceleration profiles that take longer than the bang-coast-bang profile used as

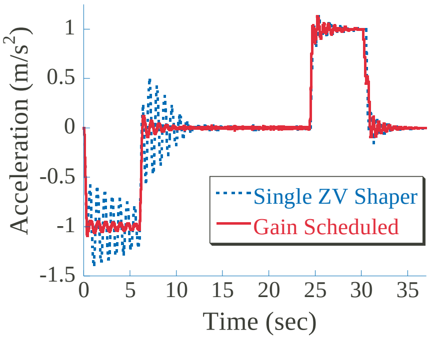

Fig. 9. Single Shaper and Gain Scheduled Shaper Response for a 35 Floor Move Down

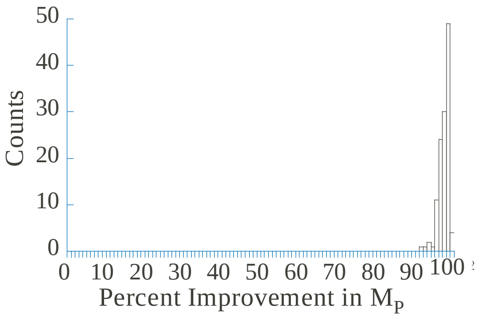

Fig. 10. Histogram of Peak Overshoot Percent Improvement of Scheduled Shaper

a baseline case here. With the implementation of input shaping this smooth baseline profile can be made significantly more aggressive.

3. VIBRATION ABSORBERS FOR ELEVATORS

Input shaping is an effective way to reduce predictable elevator vibrations; however, it cannot account for vibrations caused by disturbance forces, such as someone jumping inside the elevator. To deal with this problem without using feedback control on the cab position, a vibration absorber can be added. A properly selected vibration absorber can significantly reduce the duration of the transient vibrations induced by step disturbance forces, as shown in Figure 11. One absorber shown is the classic formulation developed by Den Hartog using a 10% absorber mass. The response with a thoughtfully "optimal" designed absorber is also shown. This absorber outperforms the Hartog absorber because it is design specifically for a step disturbance using the techniques in (Brogan et al. [2003], Fortgang and Singhose [2004]). On the other hand, Hartog's absorber is designed for sinusoidal disturbances.

3.1 Absorber Design

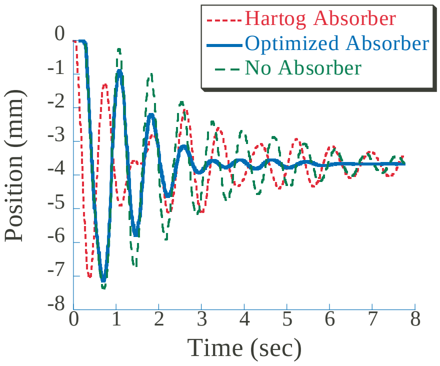

Fig. 11. Step Disturbance Response of Elevator with Various Absorbers

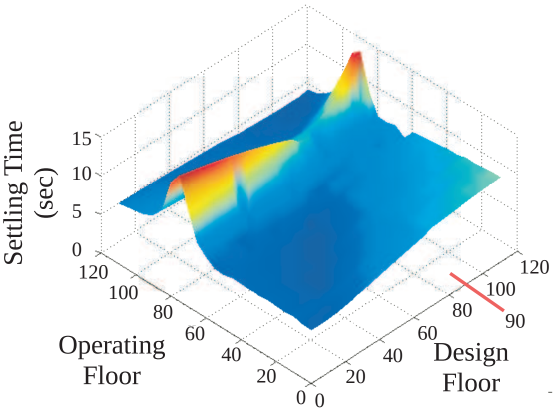

Fig. 12. Settling Time for a Variety of Absorber and Elevator Locations

Vibration absorbers, like input shapers, can reduce vibrations occurring at specific frequencies. However, unlike input shapers, they cannot be easily altered. The challenge is selecting the frequency to minimize through mechanical design. Here the goal of finding an effective absorber for an elevator was simplified by only considering step-disturbance-designed absorbers (Fortgang and Singhose [2004]). For each floor a separate absorber was designed to cancel that floors dominant frequency. Then, each absorber's performance was evaluated by the settling time while at different locations in the workspace (operating floors). Figure 12 shows this settling time for each absorber (Design Floor) when tested over the workspace. In Figure 12, the line of maximum settling times occurring at operating floor 90 show it is the most problematic no matter which absorber is added. Therefore, the absorber that performed best at the 90th floor was selected. This absorber also reduced the settling time of the cab while operating at other floors as can be seen in Figure 13. The solid line on Figure 13 represents a cross section of Figure 12, while the dashed line is the response of the cab without any absorber.

4. COMBINED INPUT SHAPING AND VIBRATION ABSORBERS

Position-dependent input shaping control and thoughtfully designed vibration absorbers are

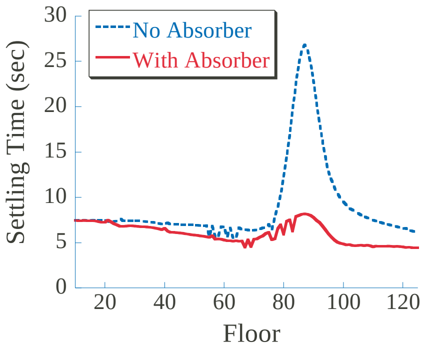

Fig. 13. Settling Time Comparison With and Without Chosen Absorber

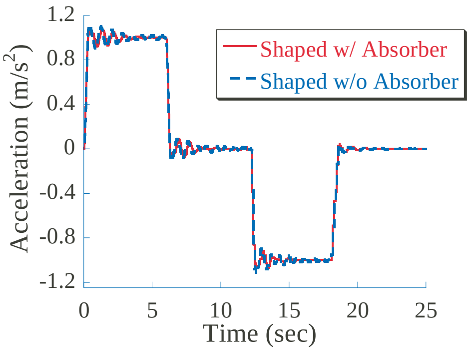

Fig. 14. Shaper Comparison Between Elevators With and Without Vibration Absorbers

complementary solutions. Input shaping is able to deal with predictable motion-induced vibrations, but it does not address disturbance forces. If a vibration absorber is added to deal with disturbances, there are no significant differences in the input shaped commanded motion response as shown in Figure 14. Note, the elevator equipped with the absorber actually experiences slightly less vibration throughout the shaped move than the elevator without an absorber.

5. CONCLUSION

This study suggests that high-rise elevators could be made significantly faster and more comfortable by implementing aggressive commands that are properly input shaped. The most effective method utilizes a scheduling algorithm based on elevator position. Furthermore, thoughtfully designed vibration absorbers complement the input shaping techniques by reducing disturbance vibrations. Here an absorber was chosen that worked best at a problematic floor. These two solutions work well together to decrease both command and disturbance-induced vibrations.

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