Chapter 5

Summary and Conclusions

5.1 Summary

A realistic analytical model of rail-counterweight system of elevator that includes the detail of the supporting system, code restricted clearances, and acceleration inputs from the floors of the building, has been developed and studied in this work. The counterweight is modeled as a rigid mass and the supporting system, consists of a pair of continuous rail on bracket supports and roller guide assemblies at each corner of the counterweight frame, provides the flexibility to the system. The code requires the clearance between the restraining plate at each roller guide assembly and the rail to be 3/16 inches or less and the gap between the counterweight frame and the rail to be no more than ½ inches. These limited clearances introduce nonlinearity to the system during seismic-induced vibration. When the gap at a restraining plate is closed, that particular roller guide assembly essentially becomes ineffective and the equivalent stiffness at that point increases significantly. Similarly, when the clearance between the frame and the rail is closed, the bracket support where contact happens provides more stiffness to the system and further increases its stiffness and natural frequency.

Numerical analyses for different set of parameters such as gap sizes, ground acceleration types and intensities, rail sizes, and the use of optional intermediate tie-bracket, were performed to study their effects on the dynamic responses of rail-counterweight system. Based on the numerical results, the need for using protective systems on elevators became quite apparent if the elevators are desired to remain operational during and after a significant earthquake occurrence event.

Several types of protective devices for the rail-counterweight system are proposed. The effectiveness of the proposed protective systems in reducing the maximum stress in the rail and also in reducing the fragility of the system is examined. From the passive control category, (1) the installation of additional viscous damping devices and (2) converting a part of the weights to a tuned mass damper were examined as the possible options. The supplemental damping devices were placed parallel to the spring in the roller guide assemblies. However, this arrangement renders the devices ineffective when a contact between the restraining plate on the roller guide assembly and the rail occurs. The option of a tuned mass damper could be realized by letting the top part of the weights in the frame to move in the in-plane direction but restraining its motion by using a spring and a damper between the mass and the frame. As there is no identifiable system frequency to which the mass damper could be tuned, several sets of analyses were performed over a broad range of the frequencies to decide about the tuning frequency for the mass damper.

To further improve the effectiveness of a passive tuned mass damper, this study also investigated the use of active mass driver with an actuator placed between the mass damper and the frame. The control force was determined by linear control algorithms using the original non-contact condition of the system. Two types of feedback were considered: the ideal full state-feedback and the more practical acceleration-feedback. Finally, a semi-active control approach that combines the benefit of passive damper and low power control ability was applied by using a magnetorheological device to regulate the motion of the mass damper.

5.2 Conclusions

Several conclusions can be drawn from the numerical results of this work:

- The maximum stress in the rails and force in the bracket supports vary with the position of the counterweight along the rail. As expected, the stress in the rails is higher when the counterweight is located in the middle span of the rail and the force in the brackets is higher when one of the roller guides is on or near the bracket supports. Although this is the trend for each span of the rail, the absolute maximum of stress or force, however, does not necessarily occur when counterweight is located at the top story of the building where the floor acceleration is usually the highest.
- The limits on the clearances required by the code help to reduce the displacement and also stress in the rail. More reduction in the maximum stress can be achieved with smaller clearances but the side effects are frequent impacts during vibration and higher force in the bracket supports.
- Installing additional viscous damping devices parallel to the spring in the roller guide assemblies is not very effective in reducing the maximum stress in the rail due to the ineffectiveness of the roller guide assemblies when a contact happens.
- Passive control using the top part of the weights as a tuned mass damper can moderately reduce the maximum stress in the rail if designed properly. The best performance is obtained with a small mass damper (10% or 20% mass ratio) with mass damper frequency

tuned to 0.8-1.0 times the frequency of the rail-counterweight system for the case when the contacts happen at all roller guide assemblies.

- The performance of the rail-counterweight system with mass damper can be further improved by providing actuator with active control scheme. The results using ideal full state-feedback control scheme show that the maximum stress can be reduced by about 50%. Although not as good as the full state-feedback results, the acceleration-feedback using LQG method can also improve the seismic response of the rail-counterweight system with much less complicated sensing needs to estimate the system state.
- Semi-active control approach using magnetorheological damper device provides a low power option to improve the performance of the rail-counterweight system with mass damper. The reductions of the maximum stress in the rail are comparable, and even better in some cases, to those of the active control.

5.3 Suggested Future Works

The analytical model for the seismic response of rail-counterweight system has been developed and several protective schemes have been proposed and their effectiveness has been examined. However, there are several interesting topics related to the seismic response of rail-counterweight system of elevator that need further investigation. Some of these issues are as follows

- Search of other methods of increasing damping of the system that are not sensitive to the change of stiffness or frequency of the system during vibration. Increasing the damping of the rail using viscoelastic material under the rail is, perhaps, one of the options.

- Search of control algorithm that is more adaptive to the nature of the rail-counterweight system. As suggested by the results of ideal active control schemes, there is still much room for improvement in reducing the maximum stress in the rail using active or semi-active control methods.
- Verification of the analytical model with experimental works to clear the way for implementation in real structures.