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Dynamic modeling and experiments on the coupled vibrations of building and elevator ropes

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A B S T R A C T

This study is concerned with the theoretical modelling and experimental verification of the coupled vibrations of building and elevator ropes. The elevator ropes consist of a main rope which supports the cage and the compensation rope which is connected to the compensation sheave. The elevator rope is a flexible wire with a low damping, so it is prone to vibrations. In the case of a high-rise building, the rope length also increases significantly, so that the fundamental frequency of the elevator rope approaches the fundamental frequency of the building thus increasing the possibility of resonance. In this study, the dynamic model for the analysis of coupled vibrations of building and elevator ropes was derived by using Hamilton's principle, where the cage motion was also considered. An experimental testbed was built to validate the proposed dynamic model. It was found that the experimental results are in good agreement with the theoretical predictions thus validating the proposed dynamic model. The proposed model was then used to predict the vibrations of real building and elevator ropes.

1. Introduction

The market for ultra-high-speed elevators continues to grow due to the expanding demand for skyscrapers worldwide. As the market grows, the development of new technologies is required to satisfy higher standards for safety, lifting height and comfort of the elevator system. The technology of efficient elevator operation is also important since in skyscrapers, a limited number of elevators must transport a large number of people. An optimized operation strategy can maximize customers' satisfaction by maximizing the elevator capacity and minimizing the waiting time. Examples of highly efficient elevators are twin elevators and double deck elevators.

One of the problems with ultra-high-speed-elevators is rope sway. As the length of the elevator ropes increases, the fundamental natural frequency becomes low. This potentially leads to the resonance of the ropes when the building is excited by wind or earthquakes. The excessive vibrations of the rope can cause severe damage to the elevator's machines and parts through collision. The vibrations of the elevator rope cannot be easily reduced after they occur because the damping of the rope is small and no method has yet been developed for suppressing vibrations. Many studies have been conducted to analyze rope sway problems, particularly in Japan where earthquakes occur frequently. The effect of earthquakes is typically considered more significant than the wind effect since the effect of wind is usually controlled in advance

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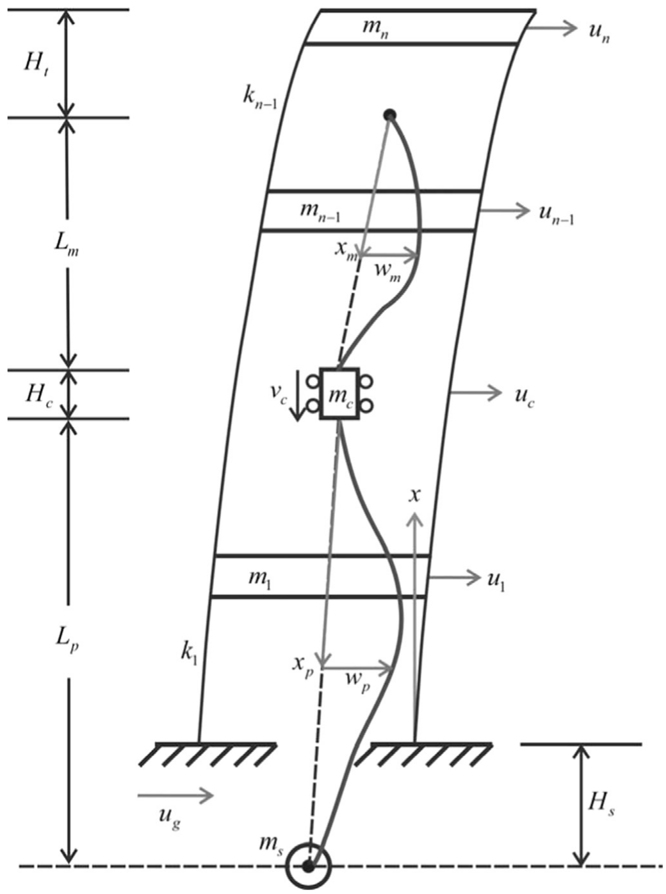

Fig. 1. Dynamic model for building and elevator rope vibrations.

by using wind tests. The most dangerous earthquake for an ultra-tall-skyscraper is that with a long-periodic wave, which is slow but has a large amplitude.

Kimura [1] reported that the resonance between the elevator rope and the building, which is caused by an earthquake, can cause significant damage to the structures inside the elevator passage. For example, during the Chuetsu earthquakes that occurred in the Niigata Prefecture, an elevator cage which is 200 km away from the earthquake source became stuck inside the elevator shaft due to the enlarged vibration of the elevator rope [1]. According to a survey conducted on the damage to the Tohoku area caused by the earthquake, of which for the magnitude was greater than 5, about 24% of the damage was due to ropes colliding with the machinery or the elevator becoming stuck, trapping people inside the elevator [1].

Theoretically, the sway of the elevator rope is difficult to predict because the length of the rope changes with time. Many efforts have been devoted to developing a theoretical model that deals with this sway issue. The simplest model is a string where the top is fixed and a mass is hung at the bottom. However, since the roller guides that contain springs are attached to the cage, it is more accurate to include a spring between the string and the mass. The elevator rope can be regarded as a string, cable or chain due to its similar structural characteristics.

For the vibration of an end-free rope, the equation of motion and the solution are well known as a classical dynamics problem [2]. Huang [3] studied a chain with a constrained end. Andrew and Kaczmarczyk [4] reported comprehensive studies on the motion of the rope. Kimura et al. [5–8] performed numerical analysis for the time-dependent length and tension of the rope using the finite difference method. Kimura et al. [5–8] carried out a numerical analysis with a dynamic model of an elevator rope and building, and conducted an experiment. The numerical results showed that the maximum displacement of the rope can be reduced by the introduction of the dampers, but optimal design is necessary to find the best locations of the dampers. They considered wind as an excitation source for the skyscraper and the elevator rope. Masuda et al. [9] developed a dynamic model by regarding an elevator cable as a collection of rigid bodies connected by springs and rotational joints. They showed that the vibration of the rope is affected by the speed of the cage and the length of the cable, but rarely affected by the acceleration of the cage. Kamada et al. [10] proposed a dynamic model for a traveling cable. The dynamic model for the traveling cable was validated by the finite element method (FEM). However, since the FEM analysis is time consuming, they suggested a viscos-elastic modeling method with temperature-dependent parameters based on multi-body dynamics. They performed an experiment for validation and concluded that the experimental result follows the