New Method for Reducing Vertical Vibration in Long-stroke Elevators

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ABSTRACT

Reduction of vertical vibration is essential to maintain good riding comfort in high-speed and long-stroke elevator systems, which are utilized in skyscrapers. We propose a new method to accomplish this purpose in this paper.

A numerical analysis model, in which the main rope of the elevator is divided into five parts, is used in our analysis. The vibration mode analysis indicated that the main vibration sources, which deteriorate riding comfort, are the compensating pulley and the sheave. We proposed a new method, which is extremely effective, to reduce this vibration. The result of the numerical analysis showed that the proposed method, which is the optimization of vibration mode using double compensation pulleys and divided counterweights, is extremely effective for good riding comfort.

INTRODUCTION

Skyscrapers over 300 m tall have been designed to make for efficient use of the expensive land in the metropolitan areas of Japan. The purpose of this study is to reduce vertical vibration in the long-stroke, high-speed elevator which is expected to be used in these new skyscrapers. These buildings require elevators with good riding comfort and high operating speed, but it is difficult to satisfy both of these requirements, because the long-stroke elevators have low natural frequency of the main rope (about 1 Hz), which makes riding quality poor. Conventional studies (1), in which the main rope is considered as a single mass, showed that enough vertical damping for the compensation pulley can reduce the first-order vertical vibration. Unfortunately, the single mass model of conventional study is unsuitable for analyzing the problem caused by the several low-frequency modes of the main rope in long-stroke elevators. We therefore analyzed the cause of the vertical vibration of the long-stroke elevators using numerical models in which the main rope is divided into five parts. The vibration mode showed that the low-frequency vibration of the compensating pulley and the sheave deteriorate riding comfort. To solve this problem, we tried to optimize the vertical vibration mode using double compensation pulleys and divided counterweights. The simulation showed that this method is quite effective for reducing the vertical vibration and maintaining good riding comfort.

1. TECHNICAL PROBLEMS OF LONG-STROKE ELEVATOR

1.1 LONG-STROKE ELEVATOR SYSTEM

Figure 1 shows the conventional long-stroke elevator system and shows disturbances to the elevator system, especially to the speed controller through the elevator mechanisms. In this system, the controller regulates the speed of the motor by monitoring the rotating speed of the sheave directly connected to the motor. There is no gear drive system, then the motor is driven in low frequency. As a result the frequency of the motor torque ripple becomes lower. In general, the speed controller requires a suitable control gain in frequency from DC to 1 Hz to get adequate control response. On the other hand, the mechanical system made up of the main rope coupling the cage, counterweights, and sheave and the compensating rope coupling the cage, counterweight, and compensating pulley operates as a spring-mass system.

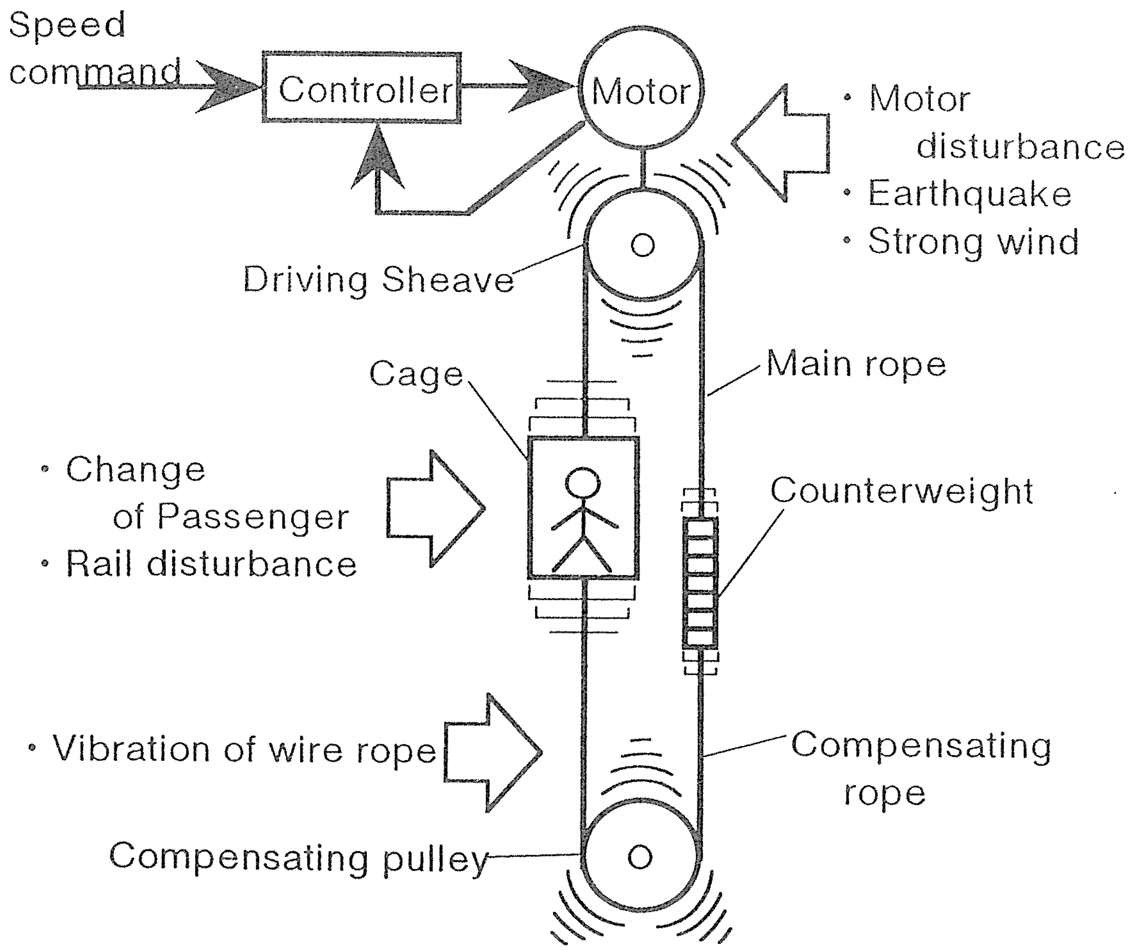

Fig. 1. Elevator vibration.

There are many possible disturbances to the elevator system like motor torque ripple, earthquakes, strong winds and so on. In the case of the long-stroke elevator the most injurious disturbance to the elevator system is the torque ripple of the motor as mentioned before. Therefore we mainly consider the cage vibration caused by the motor torque ripple in this paper.

Generally a numerical analysis model for vertical vibration has four mechanical elements: the cage, the counterweight, the sheave, and the compensating pulley. In the spring-mass system there may be five degrees of freedom. Since the rope becomes very long, the distribution of the mass of the main rope and the compensating rope should be considered. So our simulation model for analyzing vertical vibration uses the rope divided into five parts to consider the distribution of rope mass. In our spring-mass system there are about five degrees of freedom.

1.2 PROBLEMS OF VERTICAL VIBRATION FOR LONG-STROKE ELEVATOR

(1)Frequency response at the top floor

Figure 2 shows the frequency response of open loop characteristics of the controller when the cage is positioned at the top floor of the building. In this figure the vertical axis shows the sheave speed divided by speed command. The first-order natural frequency becomes low from 1.5 Hz to 1 Hz in accordance with an increase of the elevator stroke. Then a 500-m stroke elevator deteriorates riding comfort or time response because the mechanical vibration characteristics interferes the frequency range which the speed controller require.

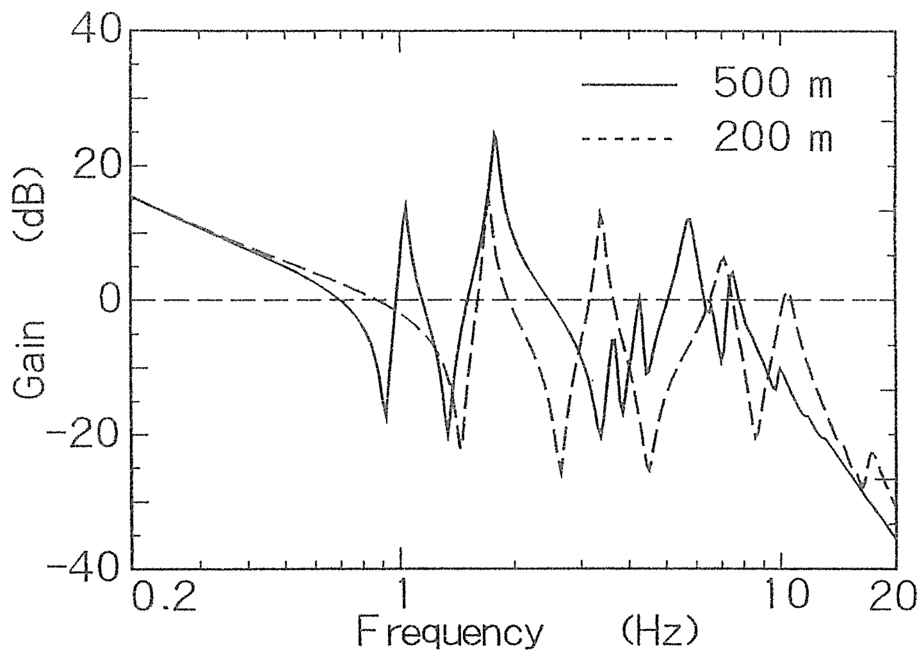

Fig. 2. Frequency response (top floor).

Figure 3 shows calculation results of modal analysis. In this figure the vertical axis shows the elements of the elevator, the horizontal axis shows normalized modal displacement of the first-order vibration mode. We can understand that the vertical vibration of the compensating pulley shows maximum modal displacement. Figure 4 shows the conventional damper where the pulley is supported flexibly in the vertical direction and slightly tied by friction force which reduces only the vertical vibration of the compensating pulley. The conventional compensating damper is useful for suppressing first-order vertical vibration.

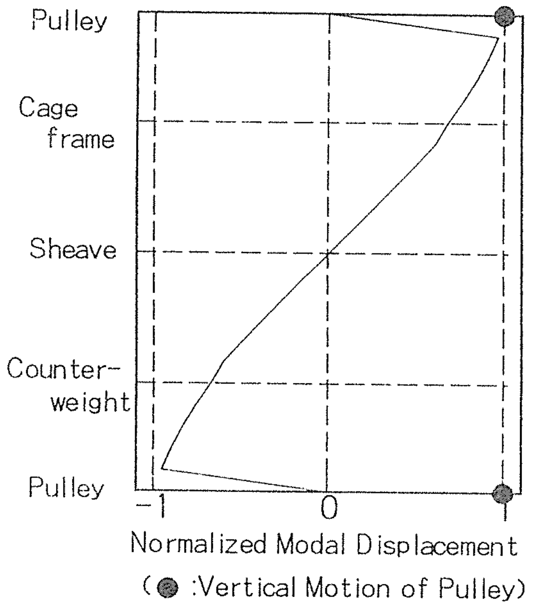

Fig. 3. First-order vibration mode of elevator system.

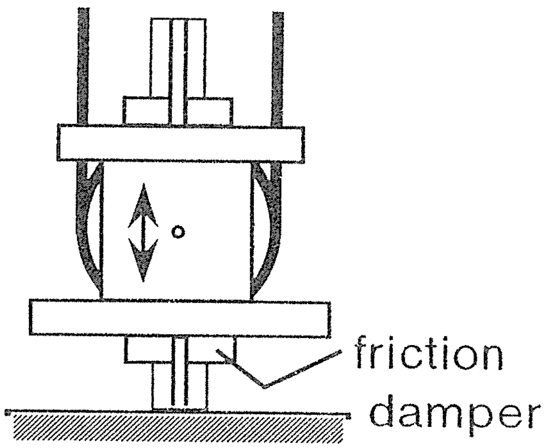

Fig. 4. Previous mechanism of compensating pulley

(2)Frequency response at the middle floor

Figure 5 shows the frequency response of open loop characteristics of the controller when the cage is positioned at the middle floor of the building. The first-order natural frequency disappears and the second-order natural frequency changes from 2 Hz to 5 Hz in accordance with an increase of the elevator stroke. The 500-m stroke elevator also deteriorates riding comfort or time response at the middle floor.

Figure 6 shows calculation results of modal analysis. In this figure, the vertical axis shows the elements of the elevator, the horizontal axis shows normalized modal displacement of the second-order vibration mode. We can understand that the rotative vibration of the sheave and compensating pulley show maximum modal displacement and they are in an opposite phase relationship. The previously mentioned conventional compensating pulley damper is not useful for suppressing the second-order vibration at the middle floor because the vertical motion of the compensating pulley is very small. To reduce this vibration, new vibration-suppressing mechanisms will be needed.

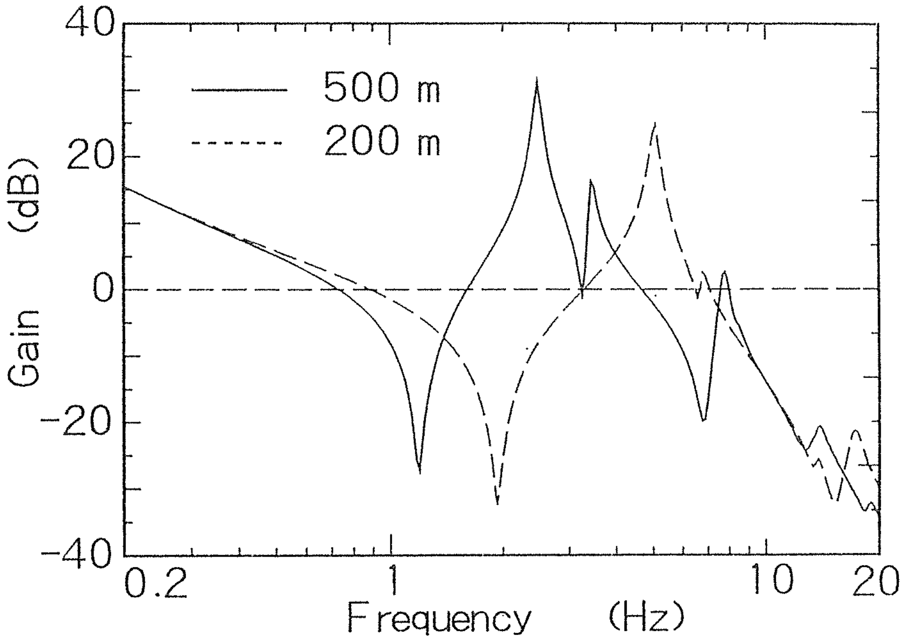

Fig. 5. Frequency response (middle floor).

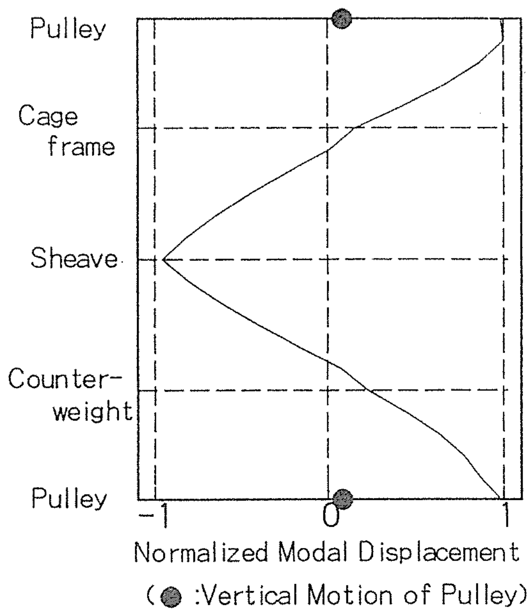

Fig. 6. Second-order vibration mode of elevator system.

2. NEW VIBRATION-SUPPRESSING MECHANISMS

2.1 DOUBLE COMPENSATING PULLEYS

Figure 7 shows the proposed damper which has double compensating pulleys. Each compensating pulley is supported at the end of an arm and each arm has a viscosity damper and a spring. Two arms are supported by the pulley frame.

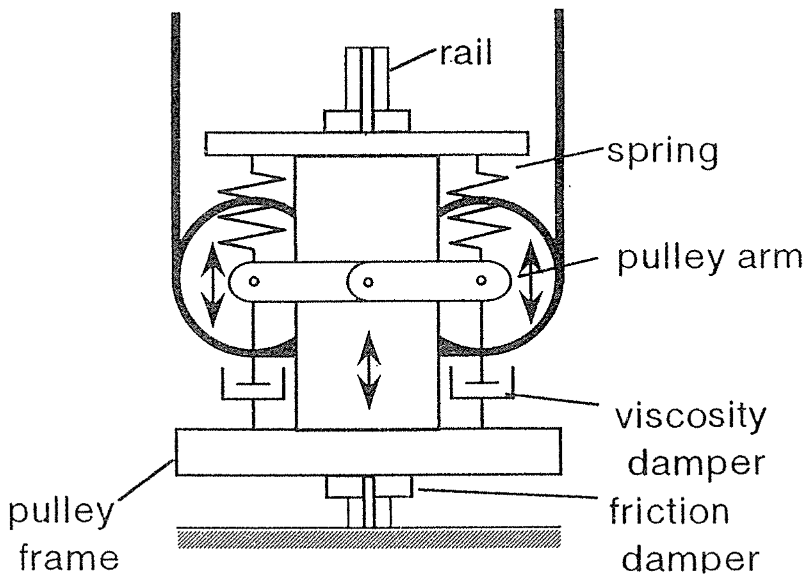

Fig. 7. Double compensating pulleys.

Figure 8 shows calculation results of modal analysis of the first-order vibration mode at the top floor. This figure shows how the vibration mode changes and how it is improved. As a comparison with Figure 3, the vertical modal displacement of the compensating pulley is reduced. On the other hand, the vertical vibration of the two arms shows maximum modal displacement. Since pulley arms have viscosity dampers, they are able to reduce the first-order vertical vibration. The new compensating damper can also suppress the first-order vertical vibration.

Then new double compensating damper operation at the middle floor is considered by modal analysis in the same way. Figure 9 shows modal analysis of the second-order vibration mode at the middle floor of the building. The rotative vibration of the compensating pulley becomes less than that in Figure 6, but the two pulley arms show maximum modal displacement. We can reduce the rotative vibration of the compensating pulley because it is substituted for the vertical vibration of the pulley arms and viscosity damper makes the vibration of the arms small. The double compensating pulleys damper can suppress the second-order vibration caused by the compensating pulley, but the rotative vibration of the sheave remains almost the same as in the conventional way. Therefore another vibration-suppressing mechanism is required.

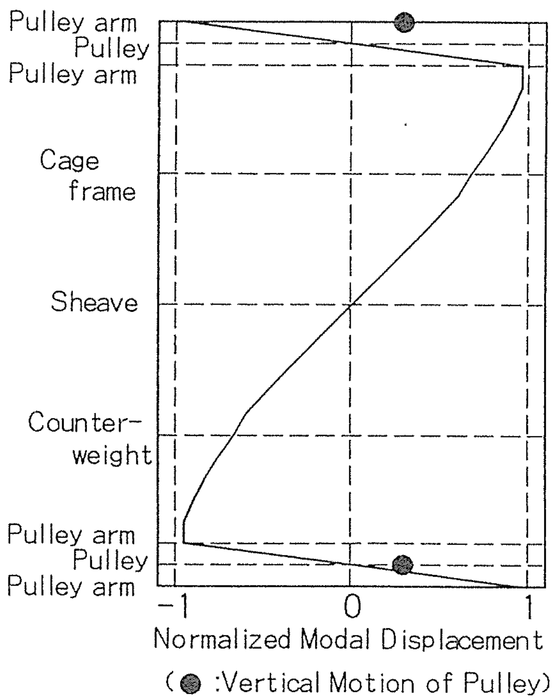

Fig. 8. First-order vibration mode (with double compensating pulleys).)

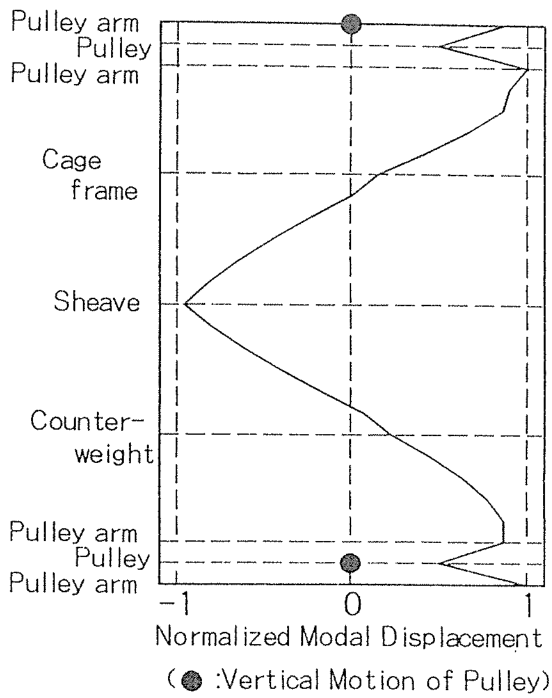

Fig. 9. Second-order vibration mode (with double compensating pulleys).

2.2 DIVIDED COUNTERWEIGHTS

Figure 10 shows the proposed damper which has divided counterweights, connected by springs and viscosity dampers. The spring constant is determined so that the natural frequency of the counterweights coincides with the second-order natural frequency of the elevator system.

Figure 11 shows modal analysis of the second-order vibration mode using only divided counterweights at the middle floor of the building. The sheave's displacement of rotative vibration is almost equal to the displacement of the upper counterweight. Therefore it may be possible to reduce the vibration of the sheave if the upper counterweight vibration could disappear. As mentioned each counterweight is connected by viscosity dampers, so counterweight vibration is easy to remove. Then new divided counterweights can suppress the second-order vibration of the sheave.

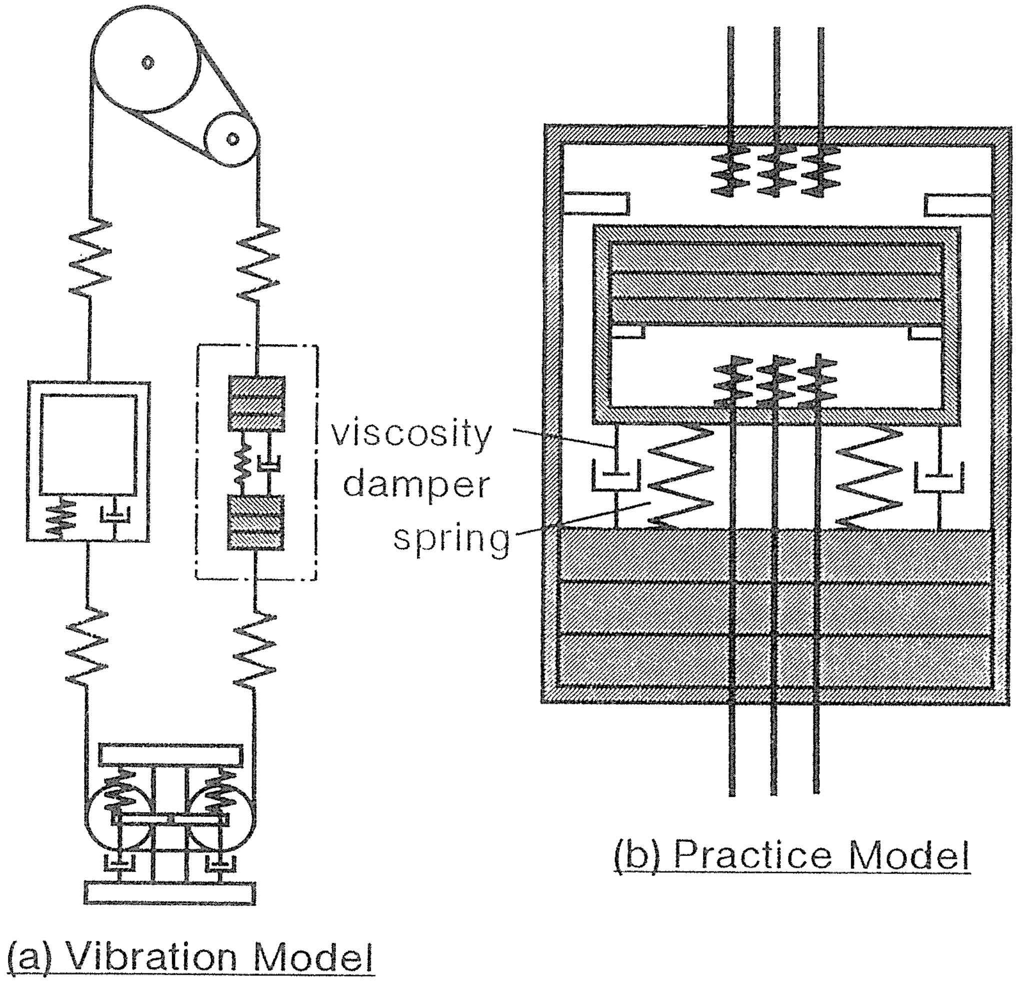

Fig. 10. Divided counterweights

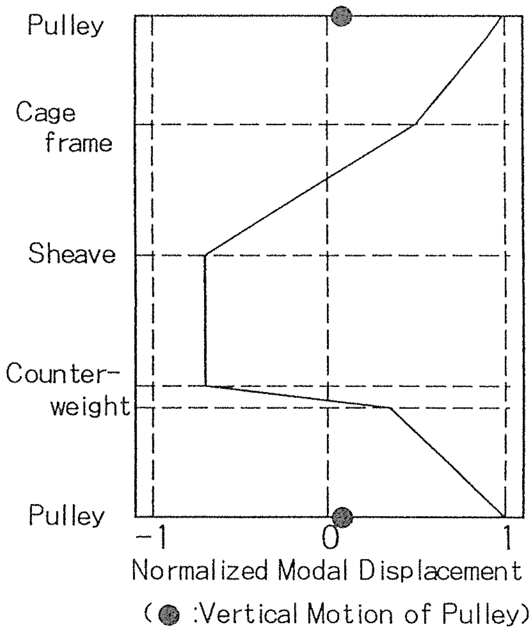

Fig. 11. Second-order vibration mode (with double compensating pulleys).

2.3 EFFECTS OF NEWLY DEVELOPED DAMPERS

The characteristics of two kinds of damper mechanisms were mentioned above. The effects of newly developed dampers are described as follows. Figure 12 and Figure 13 show the frequency response of the cage acceleration which is regarded as riding comfort. The input is the torque ripple of the motor. The solid line shows the effect of using newly developed damper mechanisms in comparison to the broken line which shows the response without a damper mechanism. Figure 12 shows that the newly developed damper mechanisms suppress the first-order and second-order vibrations. Figure 13 also shows that the second-order vibration caused by the rotation of the sheave can be removed. The results of the numerical analysis show that the method developed, which is the vibration mode optimization using a compensating pulley and divided counterweights, is extremely effective for good riding comfort.

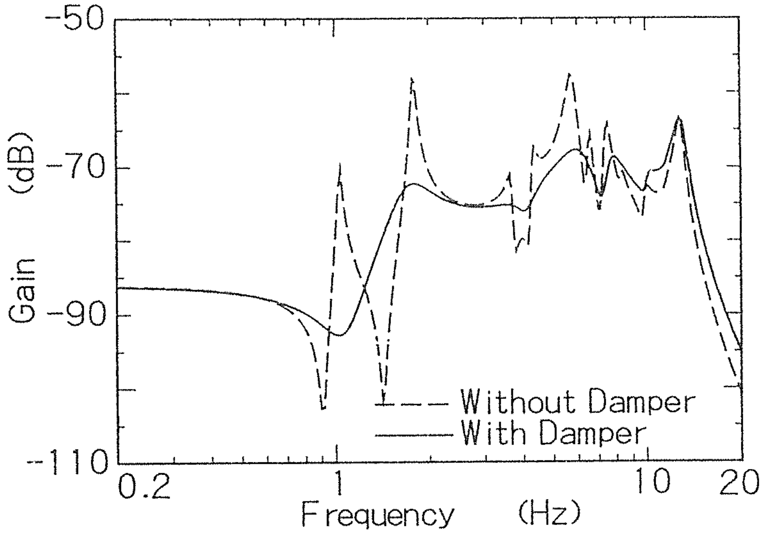

Fig. 12. Frequency response (top floor with damper).

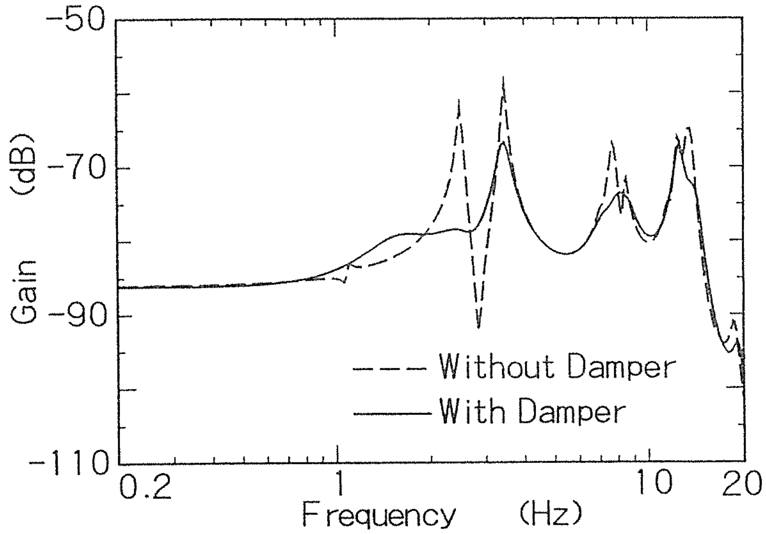

Fig. 13. Frequency response (middle floor with damper).

3. SUMMARY

The authors aimed to suppress the vertical vibration of the long-stroke elevator by mechanical means. Numerical modal analysis suggested that the compensating pulley and the sheave, which are the main vibration sources, should be improved.
Changing and controlling the vibration mode, we developed double compensating pulleys and divided counterweights which are able to suppress first-order and second-order vibrations of long-stroke elevator systems.

REFERENCES

(1)M. Shigeta et al.,"Analysis of vertical vibration for high-speed elevators," *Hitachi Highborn* **50**,pp.842-845(1968)in Japanese.

ABOUT THE AUTHOR

The author was born in Japan in 1964, graduated from Keio University in mechanical engineering in 1990, and is now working at Hitachi Ltd's Mechanical Engineering Research Laboratory.