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LATERAL VIBRATION ANALYSIS FOR ELEVATOR COMPENSATION ROPE

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Abstract. *The weight of the compensation sheave affects not only the lateral vibrations of the compensation rope, but also the rope winding shape around the sheave. Therefore, it is important to clarify the relationship between the rope behavior and the sheave weight. In this paper, an analytical model to calculate the static and dynamic behavior of the compensation rope is established. The model is derived as a lumped mass-spring model by using multi-body dynamics theory. Throughout experiments at the elevator test tower, the rope bending stiffness and the contact force against the sheave are validated by several sheave weight conditions. By identified simulation parameters, the static suspended shape and lateral vibrations of the compensation rope are calculated under several elevator conditions. All the simulation results match the experimental ones precisely. Using the proposed simulation model, influence of the sheave weight on rope vibrations is also investigated.*

1 INTRODUCTION

In recent years, the number of skyscrapers has been increasing globally. For example, more than 100 skyscrapers are under construction or planning to be built. Such growing demand for high-rise building lead to expansion of the number of high-rise elevators. Elevators installed in high-rise buildings need long wire ropes for operation. Since elevators also run faster in such buildings, the ropes might induce lateral vibration while the car is running. Especially, concerning compensation ropes which are used in high-rise elevators, the weight of the compensation sheave which gives tension to the compensation ropes affects the lateral vibrations of the ropes. Therefore, it is important to clarify the relationship between the compensation sheave weight and the lateral vibrations of the rope. However, since it is impossible to observe the rope behavior of the elevator in high-rise building before installation, it is necessary to check the rope lateral motion by simulation, in advance.

The dynamics of flexible structures such as elevator ropes has been studied by many researchers. Zhu[1] investigated the dynamics of a class of translating media with an arbitrarily varying length. The motion of a tethered system with large deformation and large displacement is described by Takehara[2]. Watanabe[3] derived a traveling cable model based on a lumped mass-spring model and validated it by experiments. While the above works mainly deal with the behavior of the flexible structures under the specific tension condition, an analysis of the relationship between the behavior of the ropes and this tension has not been investigated in detail.

In this study, an analytical model to calculate the static and dynamic behavior of the compensation rope is proposed. In an attempt to illustrate the dynamics of the compensation rope, the model is derived as a lumped mass-spring model by using the multi-body dynamics theory. Throughout experiments at the elevator test tower, the rope bending stiffness and the contact force against the sheave are validated by several sheave weight conditions. By identified simulation parameters, the static suspended shape and lateral vibrations of the compensation rope are calculated under several elevator conditions. All the simulation results match the experimental ones precisely. Using the proposed simulation model, influence of the sheave weight on rope vibrations is also investigated.

2 CONFIGURATION OF ELEVATOR

Fig.1 shows a configuration of traction type elevator. In high-rise buildings, elevators are often actuated by a motor that drives traction ropes using traction between the rope and the main sheave. As the total weight of traction rope increases proportionally to the height of elevators, weight unbalance is not ignored when the car is near the top or bottom of the shaft. To prevent such weight unbalance, compensation ropes are suspended under the car and the counterweight. The compensation ropes are supported by a compensation sheave in order to suppress the lateral vibration of the compensation ropes by giving tension by the sheave weight.

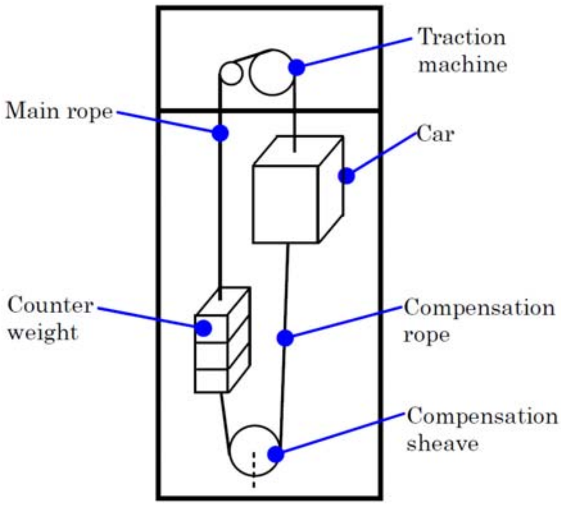

Fig. 1 Configuration of elevator

3 ANALYTICAL MODEL

The dynamics of flexible mechanical element such as wire ropes can be described as the combination of lumped mass, spring and damper. In this paper, to evaluate the lateral vibration caused by the rotation of the compensation sheave, we focus on the lateral vibration of the compensation ropes in a two-dimensional plane which is vertical to the rotation axis of the compensation sheave. Compensation ropes are divided into lumped masses which are connected by spring and damper to each other. As described above, the compensation ropes rotate around to the sheave. To deal with the contact phenomenon, the contact force between ropes and sheave is approximated by spring force. We give the two degrees of freedom to motion of a divided mass. Let us denote the downward direction as *x* axis, and the rightward direction which is orthogonal to *x* axis as *y* axis.

In our compensation rope model, the equations of the motion of the lumped masses are described as follows

$$\begin{aligned} m_i \ddot{x}_i &= T_{ix} + B_{ix} - D_{ix} + G - F_{ix} + P_{ix} \\ m_i \ddot{y}_i &= T_{iy} + B_{iy} - D_{iy} - F_{iy} + P_{iy} \end{aligned} \tag{1}$$

The equations of the vertical motion and rotation of the sheave are written as follows

$$\begin{aligned} M\ddot{x}_s &= Mg - \sum_{i=1}^{N} P_{ix} \\ J\dot{\omega} &= \sum_{i=1}^{N} F_{ir} r \end{aligned} \tag{2}$$

The schematic diagram of the model is illustrated in Fig.2. The notation of (1) and (2) are shown in Table.1. The subscript *i*, *x*, *y* and *r* indicate the number of a lumped mass, *x* and *y* axis in the coordinate system, and tangential direction to the sheave. The properties of the proposed model are summarized as follows.

- Each lumped mass is connected by spring and damper
- Bending force is considered against the lateral deformation of the rope
- Downward gravity force is always constant, regardless of rope position
- Contact force affects between the rope and the sheave

- The sheave is rotated by the friction force between the rope and the sheave

Since the model contains above properties, the rope behavior can be calculated by the numerical integration of (1) and (2). In this paper, we apply Newmark β method for the simulation.

In the following simulation, rope unit length is assigned to around 5cm to evaluate the bending force appropriately.

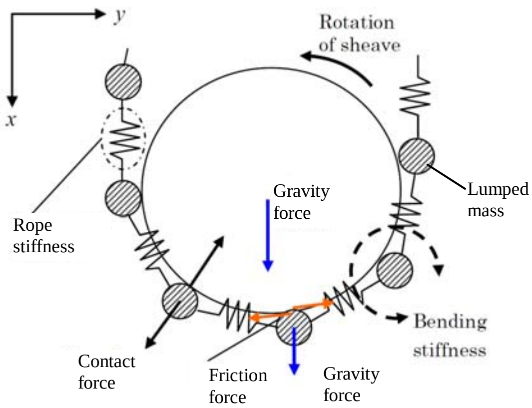

Fig. 2 Compensation rope and compensation sheave model

Table.1 Notation of equations of motion

m_i	Divided mass of rope
M	Mass of compensation sheave
J	Moment of inertia of compensation sheave
x_i, y_i, x_s	Displacement
ω	Angular velocity of compensation sheave
r	Radius of compensation sheave
T_{ix}, T_{iy}	Tension
B_{ix}, B_{iy}	Bending force
D_{ix}, D_{iy}	Damping force
G	Gravity force
F_{ix}, F_{iy}, F_{ir}	Friction force
P_{ix}, P_{iy}	Contact force

4 EXPERIMENTS

In this section, to evaluate the rope's static and dynamic behavior, the displacement of the rope is measured under some conditions as follows.

(i) The static displacement of the rope under several weight conditions of the compensation sheave.

(ii) The dynamic lateral displacement of the rope, while in car running from the bottom to the top of the shaft.

Table.2 shows the conditions of the experiments, and Fig.3 shows the sensor position. Note that the sheave weight is changed by jacking up the compensation sheave at the bottom.

Table.2 Experiment conditions

Elevator shaft height [m]	50
Floors	15
Destination	50 m from bottom floor
Rated speed [m/min]	150
Acceleration [m/s^2]	0.80

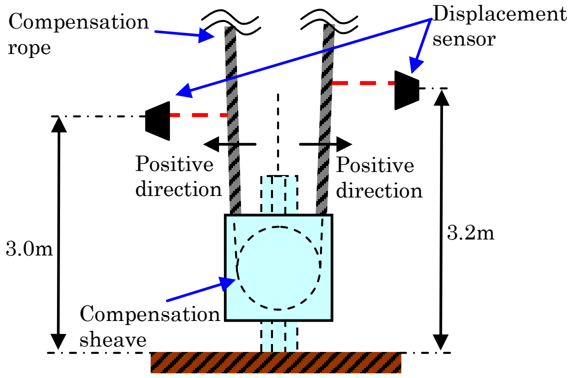

Fig.3 Experimental setup

4.1 Static behavior

The rope's static suspended shape is calculated under the same conditions as the experiments. Fig.4 shows the comparison between the experimental and the simulation results. Fig.4 illustrates the relationship between the rope's static displacement at the counterweight side measured point and the compensation sheave weight. Note that the lateral axis is normalized by the nominal sheave weight which gives enough tension to the ropes to satisfy the straight line in the vertical direction. The vertical axis of Fig.4 indicates the relative displacement which is measured from the displacement under the nominal weight, and the relative displacement is normalized by maximum value in the experimental result. The direction of the coordinate is defined outward from the center of the sheave as shown in Fig.3.

The static displacement of the rope is decided by the balance between the tension and the bending force. In the heavy sheave weight condition, the rope receives the large tension correspond to the sheave weight, and the rope becomes straight. On the other hand, under the light sheave weight conditions, the tension decreases. Thus the bending force is superior to the tension. The rope bending shape affects around the sheave. According to Fig.4, the relative displacement is close to zero beyond 75% of the nominal weight. In that weight condition, the tension is larger than the bending force, and the rope forms an almost straight shape. If the sheave weight is less than 75% of the nominal weight, the relative displacement gets larger due to the bending force. As shown in Fig.4, the simulation result matches the experiment.

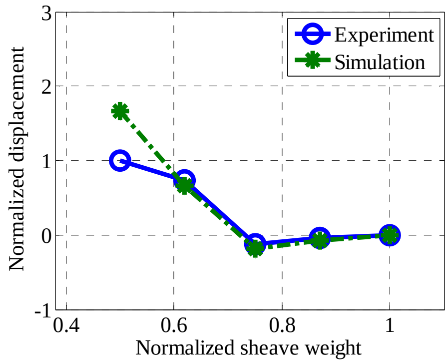

Fig. 4 Lateral displacement of
counter-weight side compensation rope

4.2 Dynamic behavior in car traveling

The lateral vibration of the compensation rope is measured during the motion of the car. Fig.5 shows the transient response of the counterweight side compensation rope while the car moves upward from the bottom to the top of the shaft, where the sheave weight is equal to the nominal weight in Fig.4. In Fig.5, the vertical axis corresponds to the lateral relative displacement. The positive direction of lateral displacement is selected as shown in Fig.4, and the vertical axis is normalized by maximum value of the measurement. As shown in Fig.5, the simulation corresponds to the experimental data, so the result validates our proposed model. Furthermore, the frequency of the displacement increases as shown in Fig.5. The length of the counterweight side compensation rope becomes shorter during the car upward motion. That behavior changes the natural frequency of the compensation rope to the higher frequency band, and the simulation also shows the same behavior.

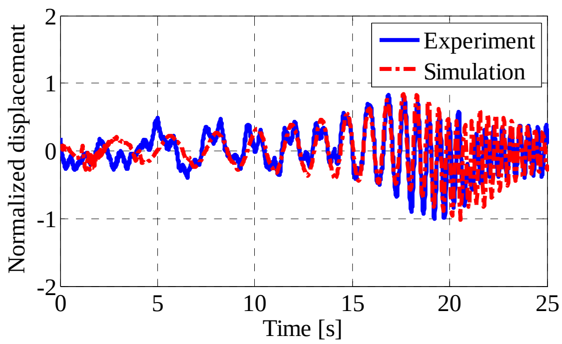

Fig. 5 Lateral displacement of counter-weight side
compensation rope during upward motion

5 EVALUATION OF THE RELATIONSHIP BETWEEN SHEAVE WEIGHT AND THE ROPE'S LATERAL VIBRATION

In the previous section, we showed that the static displacement of the rope is determined according to the sheave weight. In this section, let us evaluate the lateral vibration during the car motion, under several elevator parameters.

5.1 Running distance and rope displacement

A main cause of the lateral vibration of the compensation rope during the car's motion is the winding motion of the rope around the rotating sheave. Now we evaluate the influence against the lateral displacement of the compensation rope. Fig.3 presents the simulation conditions.

Fig.6 shows the simulation result under the several running distance conditions. The lateral axis of Fig.6 indicates the running distance from the bottom of the shaft. The vertical axis corresponds to the maximum value of the rope displacement when the car runs to the assigned distance, and is normalized by the maximum value in Fig.6. The displacement reaches the peak at 22m distance. The corresponding acceleration profile of the car is shown in Fig.7. The time period of the car motion is 10.2 seconds. The natural period of the compensation rope is 10.27 seconds when the car is 22m from the base. Hence this result indicates that if the natural period of the compensation rope is close to the car acceleration, the lateral vibration of the compensation rope increases.

Table.3 Simulation conditions

Elevator shaft height [m]	200
Rated speed [m/min]	540
Acceleration [m/s^2]	1.1

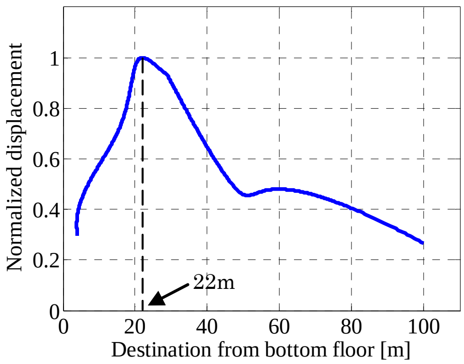

Fig. 6 Effect of traveling distance

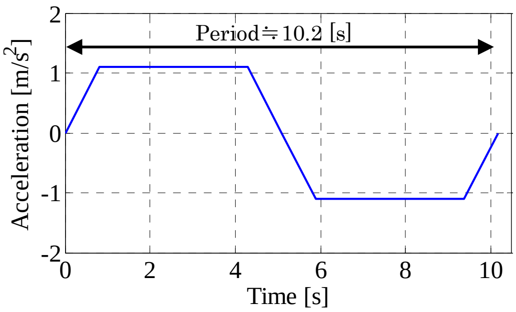

Fig. 7 Car acceleration which induces maximum displacement in Fig. 6

5.2 Compensation sheave weight and lateral vibration

Next we evaluate the lateral vibrations of the compensation rope with respect to the sheave weight conditions. In this simulation, the car runs with the acceleration pattern whose period corresponds to the natural period of the rope. Fig.8 shows the calculated maximum displacement of the rope during the car upward motion with various sheave weight conditions. The rope displacement increases in light weight conditions as shown in Fig.8. As the bending force become larger than the tension, the shape of the rope around the sheave is bent in such light weight conditions. Therefore the lateral vibration can occur easilly at the sheave side boundary point of the rope with a light weight sheave.

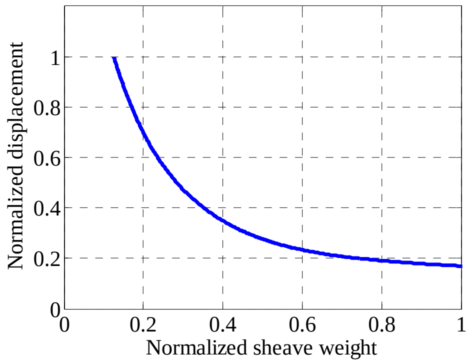

Fig. 8 Effect of compensation sheave weight

6 CONCLUSIONS

This study has discussed the static and dynamic behavior of the compensation rope. A two-dimensional rope model was derived to calculate its static shape and vibrations. Since the static shape around the compensation sheave is affected by the sheave weight, the rope shape is estimated in each sheave weight condition. We have shown that there is a boundary weight condition concerning the static displacement of the rope. Under the heavy weight condition beyond the boundary weight, the static displacement is close to zero. On the other hand, the static displacement increases in light weight conditions which are less than the boundary weight.

The dynamic behavior was also validated with the experiment and simulation result. Furthermore, we have shown that not only the sheave weight, but also the running distance influence the lateral vibration of the rope during the car's motion. The lateral displacement of the rope increases depending on the acceleration profile of the car, and the displacement also grows exponentially as the weight becomes lighter.

Since the proposed rope model can properly simulate its static and dynamic behavior, the weight condition of the sheave is examined during the compensation sheave weight design. Therefore, the proposed model can be applied to estimate sufficient weight conditions of the compensation sheave.

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