IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Vibration response analysis technique for elevator wire rope

To cite this article: Keisuke Minagawa and Satoshi Fujita 2023 *IOP Conf. Ser.: Mater. Sci. Eng.* **1289** 012015

Vibration response analysis technique for elevator wire rope

Keisuke Minagawa[1,*], Satoshi Fujita[2]

[1] Department of Mechanical Engineering, Saitama Institute of Technology, Saitama 330-0293, Japan
[2] Department of Mechanical Engineering, Tokyo Denki University, Tokyo 120-8551, Japan

[*] Corresponding author's e-mail: mina@sit.ac.jp

Abstract. Wire rope is an element often used in transportation infrastructure and systems such as bridges, elevators, ropeways, funiculars and so on. Generally, wire ropes require a high level of safety because they suspend heavy and important components such as roadways in bridges, cages and cabins in elevators, ropeways and funiculars. In addition to dead loads like roadways, wire ropes are subjected to dynamic loads caused by earthquakes, wind and moving cars, etc. Therefore, it is important to accurately simulate the dynamic response of wire ropes to dynamic loads to ensure safety of wire ropes. This paper deals with techniques for vibration response analyses of wire ropes. Techniques in this paper specially focused on a transverse vibration of wire ropes for elevators because their response is complicated by the moving cage and tension distribution. Vibration response analysis techniques using the difference method and a simplified mass point model will be introduced in this paper.

1. Introduction

Wire rope is an element commonly used in transportation infrastructure and systems such as bridges, elevators, ropeways, funiculars and so on. In general, A wire rope consists of multiple strands twisted around a core, and a strand consists of thinner wires. Due to its high tensile strength and flexibility, it is used in various structures such as roadways in bridges, cages and cabins in elevators, ropeways, funiculars and so on. Among these, an elevator is a familiar structure used by many people and requires a high level of safety.

The elevator is one of the indispensable vertical transportation systems installed in buildings in a modernized society. Modern elevators have been popularized since the middle of the 19th century, and their safety and speed have been improved so far. In general, elevators use wire ropes to suspend cabs and cages, so a high level of safety is required for wire ropes. The ropes in elevator systems are long, and when the rope length is the same as the building height, the natural period of a rope and the natural period of a building are close to each other. In addition, the damping ratio of the rope is small. Hence, when a building vibrates due to external factors, there is a risk that the ropes will vibrate significantly.

Natural factors such as earthquakes or strong winds from typhoons, etc. can shake buildings and cause elevator ropes to vibrate. In fact, the Great East Japan Earthquake and other earthquakes in Japan caused rope resonance in many elevators [1]. If an elevator is stopped in an emergency due to rope resonance caused by an earthquake, people will be trapped in the elevator, or it will take a long time to restore the elevator, preventing residents from returning to their normal lives. Therefore, it is necessary to suppress the vibration of elevator ropes. If such rope vibration can be predicted in advance by simulation analysis, it would be effective in reducing the damage.

The vibrations of a string with time-variable length, which is the basis of the vibration of elevator ropes, was studied by Kodera [2] and Yamamoto et al. [3]. Then Blodgett et al. applied the wave equation to elevator ropes and theoretically investigated the resonant frequency, mode shapes and so on [4]. Terumichi et al. developed an analytical model of elevator ropes that considers the interaction with elevator cages, and validated the analytical method experimentally using a simple experimental setup [5]. Teshima et al. proposed a numerical analysis technique using the finite difference method and evaluated a fundamental vibration response of elevator ropes [6]. Using Teshima's method, Kimura et al. investigated various responses of elevator ropes, such as forced vibration [7] and vibration with suppressor [8], and compared calculated results and experimental results using actual elevator ropes [9]. Kimura also proposed a simplified calculation method that replaces the wave equation with a single-degree-of-freedom system model [10]. As other methods for calculating the vibration response of elevator ropes, Hashimoto proposed a method using the finite element method [11], and Nakazawa et al. proposed a method using multi-body dynamics [12]. Nguyen et al. obtained the response of ropes by numerical analysis using the Newmark-β method and developed a control method for rope vibration [13]. However, most of the above studies are related with a fundamental rope response with sinusoidal input and rope vibration during normal operation, and there are few practical studies that focus on seismic response of elevator ropes.

This paper deals with techniques for vibration response analysis of wire ropes for seismic input. The techniques in this paper specially focused on a transverse vibration of wire ropes for elevators because their response is complicated by the moving cage and tension distribution. Vibration response analysis techniques using the finite difference method based on the wave equation and a simplified mass point model are introduced and the feature and analytical results for seismic input are discussed in this paper.

2. Elevator system

An elevator system has many components as shown in Figure 1.

The main components of an elevator system are a cage in which passengers enter, hoist ropes that

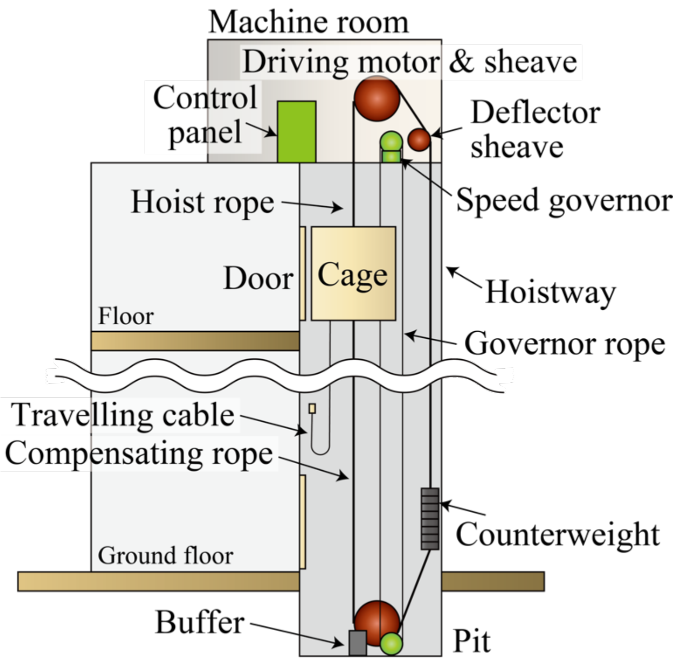

Figure 1. Elevator system.

suspend the cage, a driving motor that lifts the cage via the hoist ropes, counterweights and compensating ropes for balancing. In addition, there are various long ropes or cables as governor ropes to detect excessive speed and traveling cables to supply power and signal into the cage. The ropes and the cables locate in a hoistway, if the ropes vibrate, they may catch on rail brackets or equipment in the hoistway.

3. Analytical technique for rope vibration

3.1. Wave equation

The wave equation is a well-known method to express vibration of continuous systems such as strings, beams and so on.

If the vibration of elevator ropes with length l is regarded as the vibration of a string, the following wave equation can be applied to describe the motion.

$$\frac{\partial^2 u}{\partial t^2} = \frac{T}{\rho A}\frac{\partial^2 u}{\partial y^2} \tag{1}$$

where t is a time, y is a spatial coordinate, $u(y,t)$ is the displacement of a particle in the system whose equilibrium position is identified by y, T is tension, and ρA is the linear density of the rope, that is the mass of the rope per unit length. The boundary conditions are as follow.

$$u(0,t) = u(l,t) = 0 \tag{2}$$

The response of the rope can be easily obtained by computer by solving Equation (1) using the finite difference methods (FDM).

3.2. Substitution into single-degree-of-freedom model

It is known that the theoretical solution of Equation (1) is represented by the superposition of several vibration modes.

The n-order natural circular frequency ω_n and its mode shape $Y'_n(y)$ of a rope that has the length l can be expressed by the following equations.

$$\omega_n = \frac{n\pi}{l}\sqrt{\frac{T}{\rho A}} \quad (n = 1, 2, \cdots) \tag{3}$$

$$Y'_n(y) = \sin\frac{n\pi}{l}y \tag{4}$$

Then the motion of the rope is obtained by the sum of all vibration modes.

$$u(y,t) = \sum_{n=1}^{\infty} Y'_n(y)(C_{1n}\cos\omega_n t + C_{2n}\sin\omega_n t) \tag{5}$$

Where C_{1n} and C_{2n} are constants.

If each vibration mode is replaced by a single-degree-of-freedom system as shown in Figure 2, the response of n-order vibration mode q_n against a disturbance force F_n can be obtained as follow.

$$\ddot{q}_n + 2\zeta_n\omega_n\dot{q}_n + \omega_n^2 q_n = F_n \tag{6}$$

Although the wave equation as Equation (1) does not include damping, the actual vibration of elevator ropes has damping as shown in Equation (8) below. Hence, the modal damping ζ_n was taken into account in Equation (6).

The response of each mode in Equation (6) can be calculated numerical analysis. Thus the response of the rope to an arbitrary input can be obtained by adding them together as shown in Equation (7).

$$u(y,t) = \sum_{n=1}^{\infty} Y'_n(y)q_n(t) \tag{7}$$

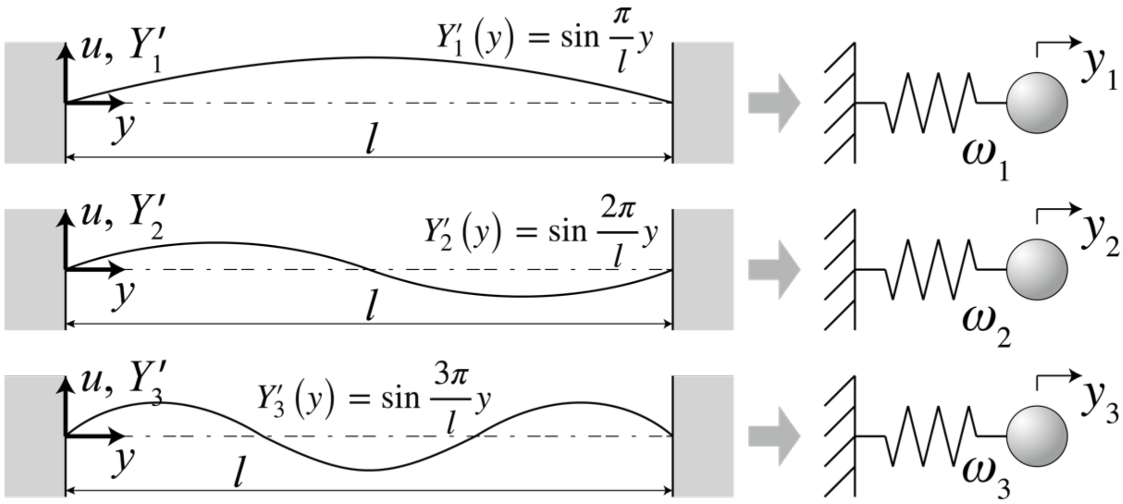

Figure 2. Modal analysis for string vibration.

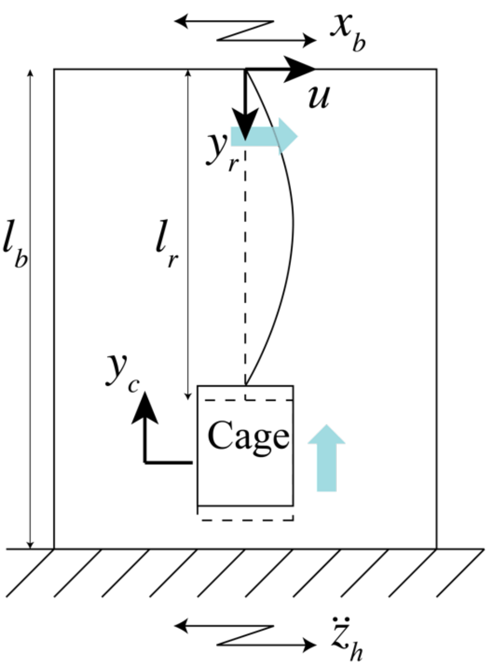

Figure 3. Vibration of elevator rope.

3.3. Application into elevator ropes

Elevator ropes are installed vertically, and tension acting on the ropes varies depending on its position. In other words, tension of higher position is larger due to the weight of the rope itself. In addition, the length of the rope varies during vibration because of the operation of the elevator.

Kimura et al. proposed an equation of motion for the transverse vibration of elevator rope [7] as following Equation (8).

$$\rho A\left(\frac{\partial}{\partial t}-V\frac{\partial}{\partial y_r}\right)^2 u+C\left(\frac{\partial}{\partial t}-V\frac{\partial}{\partial y_r}\right)u-\frac{\partial}{\partial y_r}\left[T(y_r)\frac{\partial u}{\partial y_r}\right]=0 \tag{8}$$

Where y_r is a spatial coordinate whose origin is the top of the building, $u(y_r, t)$ is the transverse displacement of the rope, V is the velocity of the cage and C is the damping coefficient of the rope. If the building deforms in proportional to its height the boundary conditions are as follows.

$$u(0,t) = x_b,\ u(l_r,t) = x_b(1 - l_r/l_b) \tag{9}$$

Where x_b is the displacement of the building, l_r is the length of the rope, l_b is the height of the building, respectively. The exact solution of this problem was proposed by Kimura et al. [7].

In addition, the vertical position of the cage varies by transverse vibration of the rope. In other words, when response of the rope u is large, the cage will lift as shown in Figure 3, and the inertia force based on the movement of the cage causes variation of tension of the rope. This variation of tension induces nonlinear vibration.

4. Vibration response analysis

4.1. Comparison of analytical techniques by sinusoidal wave

In this section, the response of a rope to sinusoidal inputs is calculated by the methods described above, and the analytical results are compared.

Table 1 shows the specification of an elevator rope [14]. General elevator dimensions were used for the analysis. Sinusoidal waves having amplitude of 0.1m, various frequencies are input to the top of the rope, then the amplitude factor, i.e. the ratio of the maximum response displacement to the input amplitude, is obtained.

Figure 4 shows comparison of the resonance curve. As shown in Figure 4, the 1st vibration mode is equivalent for each analytical technique. The single-degree-of-freedom model is a very simple technique to estimate rope response, but cannot represent vibration response above 2nd vibration modes. The result by the modal analysis method agrees well with the result by the finite difference method without vertical motion of the cage, although the amplitude at the resonance point is slightly small because the modal analysis method does not take into account the distribution of tension by the weight of the rope itself. In the results by the finite difference method with vertical motion of the cage, that is the most accurate technique, the resonance points tilt because of changes of tension on the rope by vertical motion of the cage. This behavior represents the actual response of the ropes [15], but the calculation time is the longest among the analytical techniques due to its nonlinearity. Therefore it is important to select an analytical method that is appropriate for the purpose of the analysis.

Table 1. Specification of elevator rope.

Weight of cage [kg]	2350
Weight of compensating sheave [kg]	554
Roping of rope	2:1
Number of ropes	6
Linear density [kg/m]	0.494
Length of rope	238
Damping ratio of rope [%]	0.2

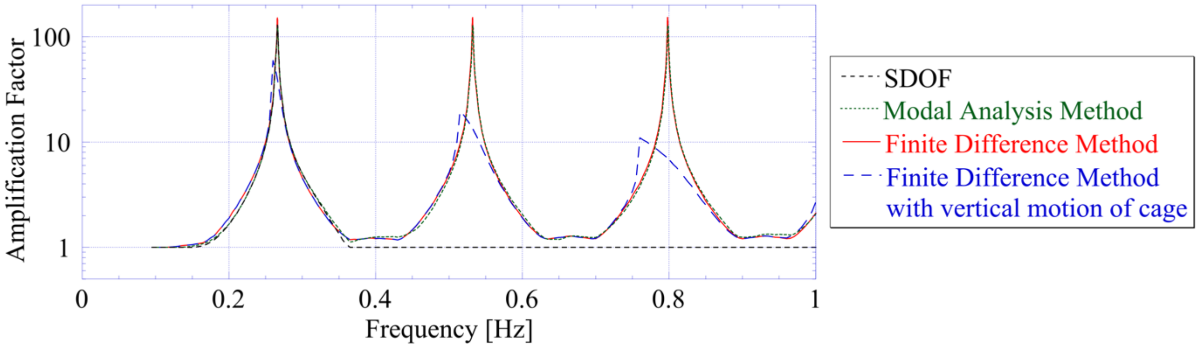

Figure 4. Comparison of resonance curve.

4.2. Comparison of analytical techniques by seismic wave

In this section, the response of a rope to seismic wave is calculated by the methods described above, and the analytical results are compared.

Table 2 shows the specification of an analytical model for a building [14]. The target of the analysis is an elevator in a high-rise building with a height of 240 m and the building was modeled as a single-degree-of-freedom model. Figure 5 shows input wave. A ground motion observed at Shinjuku NS direction in the Great East Japan Earthquake in 2011 was used for a seismic response analysis of the building model, then the response displacement of the top of the building was input into the top of the elevator rope.

Figure 6 shows the maximum rope displacement of each time step of each analytical technique. Due to the complex vibration shapes of the rope, the position of maximum rope displacement varies from moment to moment. Thus, Figure 6 is not the time histories of a specific point, but the absolute value of the maximum displacement of the rope, which is the threshold for the rope to collide with a hoistway wall or other objects. As shown in Figure 6 (a)-(d), there is little difference in response between the techniques compared to the sinusoidal wave response above. This is because the response factor of the rope to the top of the building was at least approximately twice that of the building, and the influence of the nonlinear vibration that appeared in Figure 5 was almost negligible. Figure 6 (e) is detailed comparison of each technique. As shown in Figure 6 (e), the result by the single-degree-of-freedom model is slightly small compared with the other techniques due to higher vibration modes. However the single-degree-of-freedom model has enough accuracy to estimate the seismic response of the elevator ropes.

In this specification of the elevator and building, the 1st natural period of the elevator rope is 3.8s and that of the building is 6.0s, so the amplitude of the elevator rope was relatively small. However, the maximum response displacement of the rope is more than 0.6 m, which may result in a collision with the hoistway wall. Therefore, it will be necessary to consider the specifications or operation of the elevators to suppress the rope vibration.

Table 2. Specification of analytical model for building.

Height of building [m]	240
Natural period of building [s]	6
Damping ratio of building [%]	2

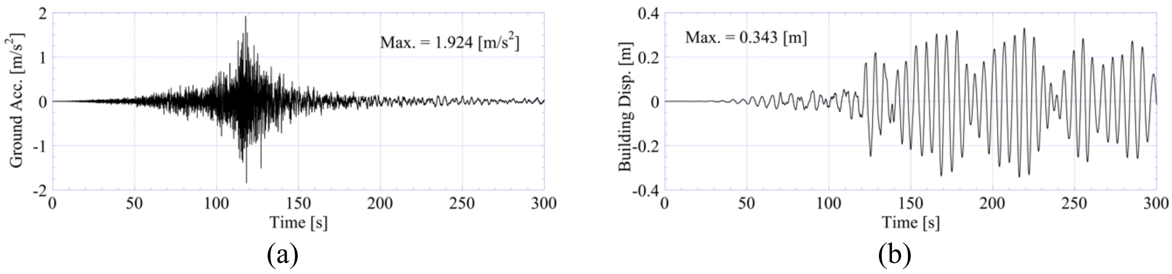

Figure 5. Input wave: (a) Ground acceleration, (b) Response displacement of the top of the building.

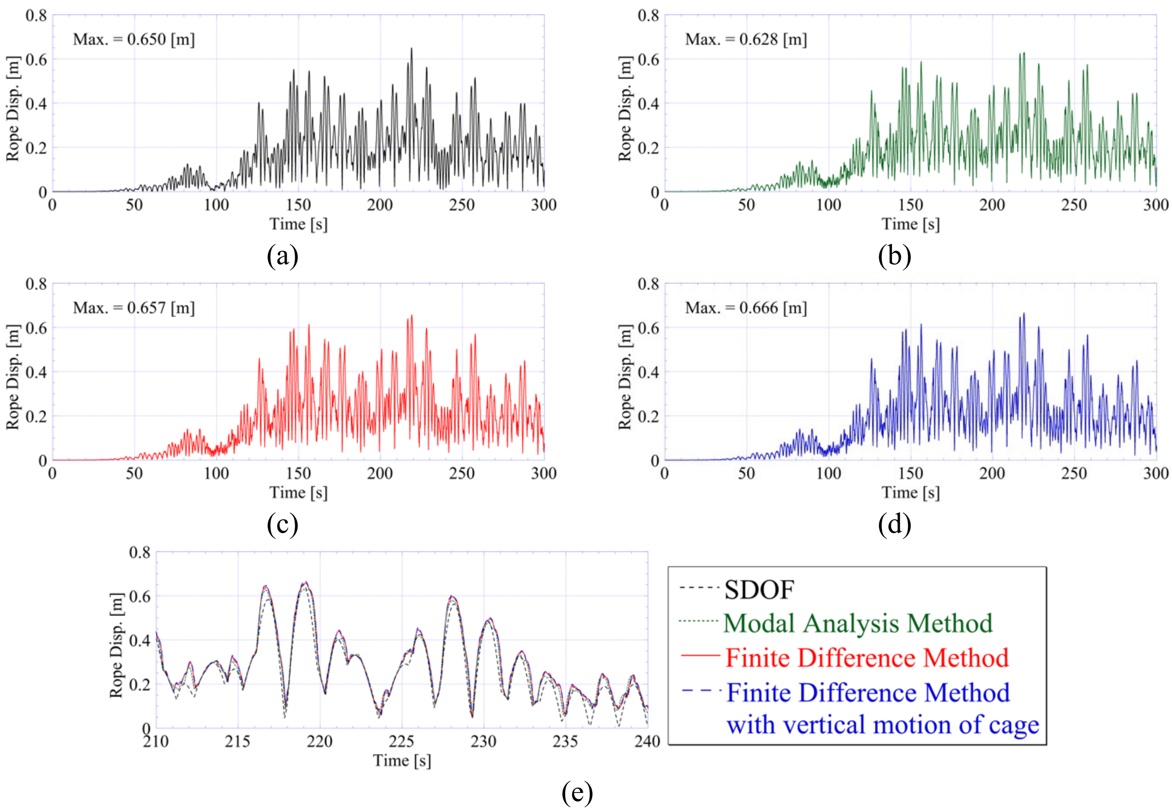

Figure 6. Maximum rope displacement of each time step: (a) Single-degree-of-freedom model, (b) Modal analysis method, (c) Finite difference method without vertical motion of cage, (d) Finite difference method with vertical motion of cage, (e) Comparison of all method.

5. Conclusions

This paper introduced 4 techniques for response analysis of transverse vibration of wire ropes, that is the single-degree-of-freedom model, the modal analysis method and finite difference method with/without vertical motion of the cage. Then the results of each technique for sinusoidal and seismic input were compared. Each technique has its advantages and disadvantages. For example, the single-degree-of-freedom model is a very simple approach to estimate the vibration response of elevator ropes, but it cannot take into account the higher vibration modes and the distribution of tension. On the other hand, the finite difference method with vertical motion of the cage accurately represents the vibration response, but it requires complicated calculation processes and sufficient computation time. Therefore, it is important to select an analysis method that is appropriate for the purpose of the analysis. In addition, it was confirmed that the response of the elevator ropes by seismic input could be large. Therefore, the response of elevator ropes under various elevator specifications and seismic motions will be investigated in the future.

Acknowledgment
The authors would like to express their appreciations to the members of the Rope Vibration Working Group in the Japan Society of Mechanical Engineers for their valuable advice to improve the analytical techniques of transverse vibration of wire ropes.

References

[1] Fujita S, Shimoaki M and Minagawa K 2021 Report on seismic damage of lifts and escalators by large earthquakes in Japan *Transportation Systems in Buildings* **3** 1
[2] Kodera T 1978 Vibrations of a string with time-variable length *Bulletin of the Japan Society of Mechanical Engineers* **21** 160 1469-1474
[3] Yamamoto T, Yasuda K and Kato M 1978 Vibrations of a string with time-variable length *Bulletin of the Japan Society of Mechanical Engineers* **21** 162 1677-1784
[4] Blodgett RE and Majumdar AK 1983 An analysis of elevator rope vibration in tall buildings *Journal of Vibration, Acoustics, Stress, and Reliability in Design* **105** 5-10
[5] Terumichi Y, Ohtsuka M, Yoshizawa M, Fukawa Y and Tsujioka Y 1997 Nonstationary vibrations of a string with time-varying length and a mass-spring system attached at the lower end *Nonlinear Dynamics* **12** 39-55
[6] Teshima N, Sasaki Y, Onishi S and Nagai M 2002 Vibration characteristics of wire-rope in the high speed elevator (Numerical analysis by the difference method) *Transactions of the Japan Society of Mechanical Engineers Series C* **68** 675 3202-3208
[7] Kimura H, Ito H and Nakagawa T 2007 Vibration analysis of elevator rope (Forced vibration of rope with time-varying length) *Journal of Enviornment and Engineering* **2** 1 87-96
[8] Kimura H and Nakagawa T 2005 Vibration analysis of elevator rope with vibration suppressor *Transactions of the Japan Society of Mechanical Engineers Series C* **71** 702 442-447
[9] Kimura H, Iijima T, Matsuo S and Fujita Y 2008 Vibration analysis of elevator rope (Comparison between experimental results and calculated results) *Transactions of the Japan Society of Mechanical Engineers Series C* **71** 706 1871-1876
[10] Kimura H, Min Z, Iijima T, Ishii T and Itenishi M 2009 Vibration analysis of elevator rope (Simplified calculation method for detecting rope deflection during earthquake) *Transactions of the Japan Society of Mechanical Engineers Series C* **75** 757 2483-2488
[11] Hashimoto Y 2004 Finite element dynamic response analysis of a string with time-varying length *Transactions of the Japan Society of Mechanical Engineers Series C* **70** 693 1263-1267
[12] Nakazawa D, Watanabe S, Daiki F and Okawa T 2013 Lateral vibration analysis for elevator compensation rope *Proceedings of 11th International Conference on Vibration Problems*
[13] Nguyen TX, Miura N and Sone A 2019 Analysis and control of vibration of ropes in a high-rise elevator under earthquake excitation *Earthquake Engineering and Engineering Vibration* **18** 447–460
[14] Tanaka H, Ishii A, Fujita S, Tanaka K and Ogawa Y 2017 Fundamental study on rope damage reduction using intermediate transfer floor of high rise buildings *Proc. of the 7th Symposium on Lift & Escalator Technologies* (Northampton, UK) **27** 1-10
[15] Kaneko M, Nakagawa J and Arai S 2008 Experiment Verification of Elevator Rope Vibration Analysis Model *Proceedings of the 17th TRANSLOG of the Japan Society of Mechanical Engineers* 87-90