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MODELS FOR AN ELEVATOR HOISTWAY VERTICAL DYNAMIC SYSTEM

Yue-Qi Zhou

Otis Institute of Technology, Nippon Otis Elevator Company

ABSTRACT

This paper presents two different models for the analysis of elevator hoistway vertical dynamic system. The first is an eight-degrees-of-freedom model, which assumes the ropes of elevator system to be spring & dashpot elements by neglecting the rope mass. The second is an FEA model, which assumes the ropes to be distributed parameter systems and therefore has the rope masses included in the model. The seven natural modes (exclude the first mode at frequency of 0Hz) obtained by the modal analysis for the eight-degrees-of-freedom model are named based on the characteristics of each modes. The effects of the way to model the ropes on those seven modes are clarified by comparing the results from those two different models for rope length being 8m, 16m, 32m, 64m, 128m and 256m. Rope longitudinal wave motion was observed with three modes among those seven modes for long ropes. It is concluded that FEA model should be used for the study of elevator hoistway vertical dynamic system in high buildings.

1. INTRODUCTION

Buildings tend to be higher and higher in big cities like Tokyo. In recent years, many proposals of constructing skyscrapers with heights in excess of 300 meters have been made. For elevators in high buildings, the torque ripples generated by the traction motors can cause the cars to oscillate vertically due to the existence of the long ropes and heavy masses like passenger car etc.. Some elevator companies have already developed models using only lumped parameters for the studies of elevator vertical dynamic system by neglecting the rope mass, but model that assume a rope to be distributed system using a finite element approach has not been developed due to the great complexity [1] [2]. As one can easily predict that the way of modeling the ropes would have its effects on the results for long ropes, it is very important to create an FEA model to understand the limitations of model using only lumped parameters for the elevator vertical dynamic system in high buildings.

2. MATHEMATICAL MODELS

The elevator hoistway vertical dynamic system comprises the ropes, springs, various masses, and isolation pads. The system studied in this paper is shown in Figure 1. Hoist ropes are hung on the driving sheave that directly connects to motor/machine. The torque from machine/motor drives the passenger car up and down via hoist ropes

2.1 EIGHT-DEGREES-OF-FREEDOM MODEL

As there are six lumped masses (machine, counterweight, compensation sheave, compensation hitch plate, cab, carframe) and two inertia masses (driving sheave, compensation sheave), the simplest model for this system would be an eight-degrees-of-freedom model. The hoist and compensation ropes are simply assumed to be spring & dashpot elements by neglecting the rope masses. Then the eight linear differential equations for this model can be written as follows:

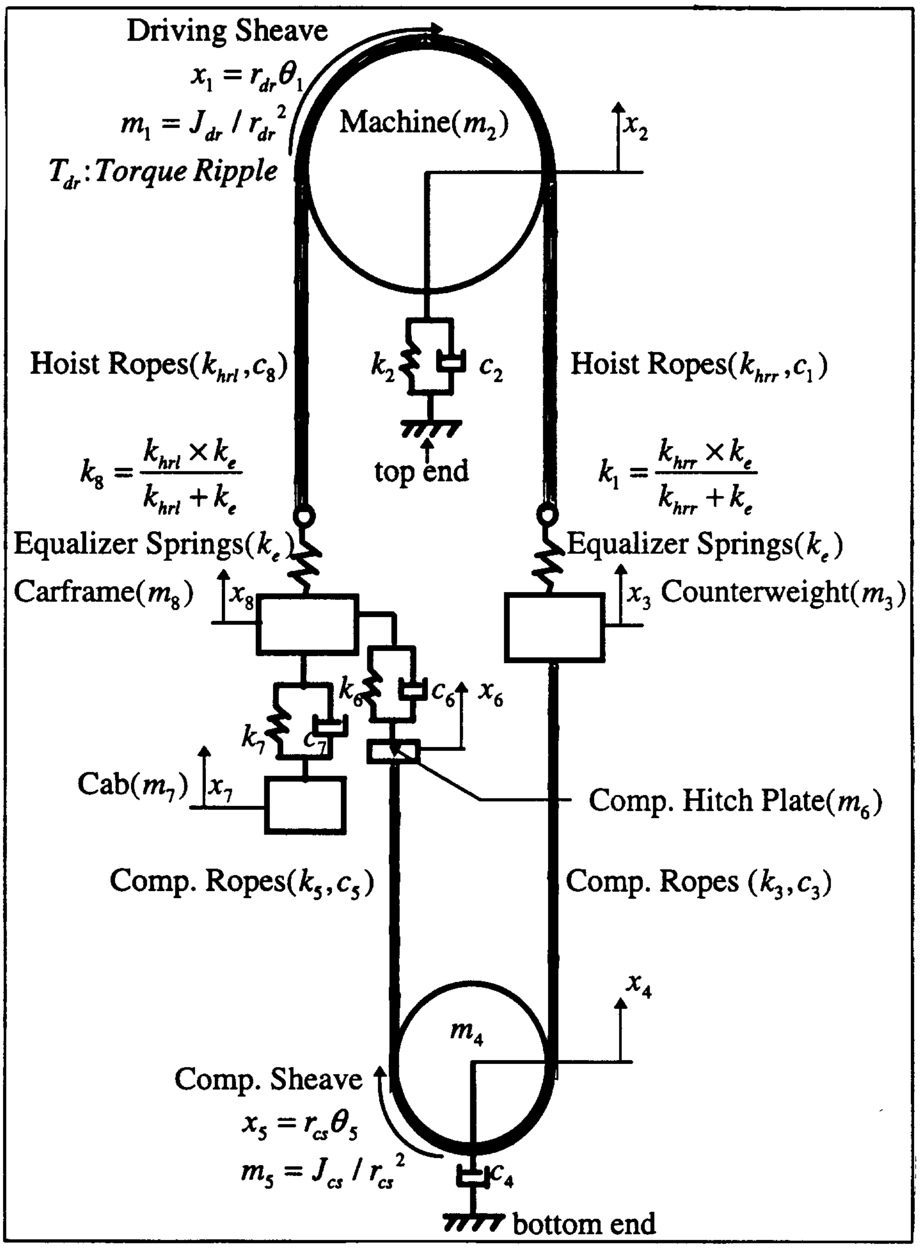


Figure 1. Elevator Vertical Dynamic System

Driving sheave (rotation):

$$m_1\ddot{x}_1 + k_1(x_1 - x_2 + x_3) + c_1(\dot{x}_1 - \dot{x}_2 + \dot{x}_3) + k_8(x_1 - x_8 + x_2) + c_8(\dot{x}_1 - \dot{x}_8 + \dot{x}_2) = T_{dr} / r_{dr}$$

Machine (vertical):

$$m_2\ddot{x}_2 + k_2 x_2 + c_2\dot{x}_2 + k_1(x_2 - x_3 - x_1) + c_1(\dot{x}_2 - \dot{x}_3 - \dot{x}_1) + k_8(x_2 - x_8 + x_1) + c_8(\dot{x}_2 - \dot{x}_8 + \dot{x}_1) = 0$$

Counterweight (vertical):

$$m_3\ddot{x}_3 + k_1(x_3 - x_2 + x_1) + c_1(\dot{x}_3 - \dot{x}_2 + \dot{x}_1) + k_3(x_3 - x_4 + x_5) + c_3(\dot{x}_3 - \dot{x}_4 + \dot{x}_5) = 0$$

Compensation sheave (vertical):
$$m_4\ddot{x}_4 + k_3(x_4 - x_3 - x_5) + c_3(\dot{x}_4 - \dot{x}_3 - \dot{x}_5) + c_4\dot{x}_4 + k_5(x_4 - x_6 + x_5) + c_5(\dot{x}_4 - \dot{x}_6 + \dot{x}_5) = 0$$
Compensation sheave (rotation):
$$m_5\ddot{x}_5 + k_3(x_5 - x_4 + x_3) + c_3(\dot{x}_5 - \dot{x}_4 + \dot{x}_3) + k_5(x_5 - x_6 + x_4) + c_5(\dot{x}_5 - \dot{x}_6 + \dot{x}_4) = 0$$
Compensation hitch plate (vertical):
$$m_6\ddot{x}_6 + k_5(x_6 - x_5 - x_4) + c_5(\dot{x}_6 - \dot{x}_5 - \dot{x}_4) + k_6(x_6 - x_8) + c_6(\dot{x}_6 - \dot{x}_8) = 0$$
Cab (vertical)
$$m_7\ddot{x}_7 + k_7(x_7 - x_8) + c_7(\dot{x}_7 - \dot{x}_8) = 0$$
Carframe (vertical)
$$m_8\ddot{x}_8 + k_6(x_8 - x_6) + c_6(\dot{x}_8 - \dot{x}_6) + k_8(x_8 - x_2 - x_1) + c_8(\dot{x}_8 - \dot{x}_2 - \dot{x}_1) + k_7(x_8 - x_7) + c_7(\dot{x}_8 - \dot{x}_7) = 0$$

MATLAB computer code developed by The MathWorks, Inc. was used for solving these eight linear differential equations in this study.

2.2. FEA MODEL

The ropes (hoist and compensation) play an important role in the elevator vertical dynamic system. An FEA model for the elevator vertical dynamic system shown in Figure 1 is created in this study using ANSYS computer code developed by ANSYS Inc.. Rope was modeled using a 2-D Spar element. Each of the hoist and compensation ropes at car-side and counterweight-side was divided into 100 elements. Displacements at all nodes in horizontal direction were set to be 0. Rotations at all nodes except the two nodes for driving sheave and compensation sheave were fixed. In addition, the vertical displacements at top and bottom ends (indicated in Figure 1) were also fixed.

3. MODAL ANALYSIS RESULTS

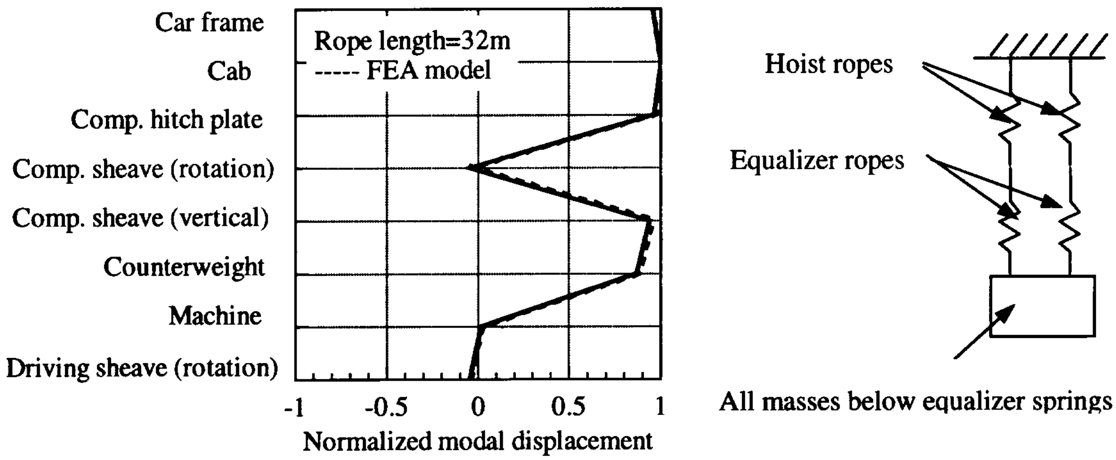
Modal analysis for the eight-degrees-of-freedom model was performed when passenger car is positioned at the middle floor of the buildings (therefore the lengths of hoist and compensation ropes are equal). Damping of all components was neglected for modal analysis. Its solution yields a set of seven natural modes and seven associated natural frequencies (exclude the mode at frequency of 0Hz). Due to the fact that natural modes of vibration play a predominant role in the field of vibrations, in the following the seven modes are named based on its characteristics and discussed in detail.

To clarify the effects of the way to model the rope on those seven modes for elevator vertical system, comparisons between the modal analysis results for the eight-degree-of-freedom model and the FEA model are performed for the rope length being 8m, 16m, 32m, 64m, 128m and 256m. The rope mode shapes for FEA model are investigated, and the limitations of using the eight-degrees-of freedom model for high-rise elevator system are discussed.

Gross weight jump mode

Figure 2(a) shows the mode shape of one of the seven nature modes for rope length being 32m. Horizontal axis shows normalized mode displacement values, while vertical axis shows the eight components (six masses & two inertial masses) of elevator dynamic system.

From Figure 2(a), it is clear that for this mode the compensation sheave (vertical), driving sheave (rotation) and machine (vertical) are almost at rest, while the displacements for other components are almost same. Therefore for this mode the elevator system shown in Figure 1 can be approximately simplified to a one-degree-of-freedom system shown in Figure 2(b). This is the mode that all weights, suspended on hoist ropes/equalizer springs, act as one big mass and therefore is named 'Gross weight jump mode' in this study.



(a) mode shape (b) simplified system

Figure 2. Gross weight jump mode

No longitudinal rope wave motion was observed for all rope lengths by checking the modal analysis results for the FEA model. The mode shapes from those two models for rope length being 8~256m achieved good agreement. In addition, the following table shows that the 8-degrees-of-freedom model can also predict the mode frequencies with good accuracy. Even for rope length being 256m (building will be over 500m high), the eight-degrees-of –freedom model only overpredicts the FEA model by 0.15Hz.

Rope length	8m	16m	32m	64m	128m	256m
8-degrees-of-freedom model, f_1	2.12Hz	2.04Hz	1.91Hz	1.71Hz	1.45Hz	1.16Hz
FEA model, f_0	2.11Hz	2.03Hz	1.88Hz	1.66Hz	1.36Hz	1.01Hz
$\lvert f_1 - f_0 \rvert$	0.01Hz	0.01Hz	0.03Hz	0.05Hz	0.09Hz	0.15Hz

Comp. sheave jump mode

The mode shapes in Figure 3 shows that driving sheave rotation is dominant for this mode. Therefore this mode is named 'Comp. sheave jump mode'.

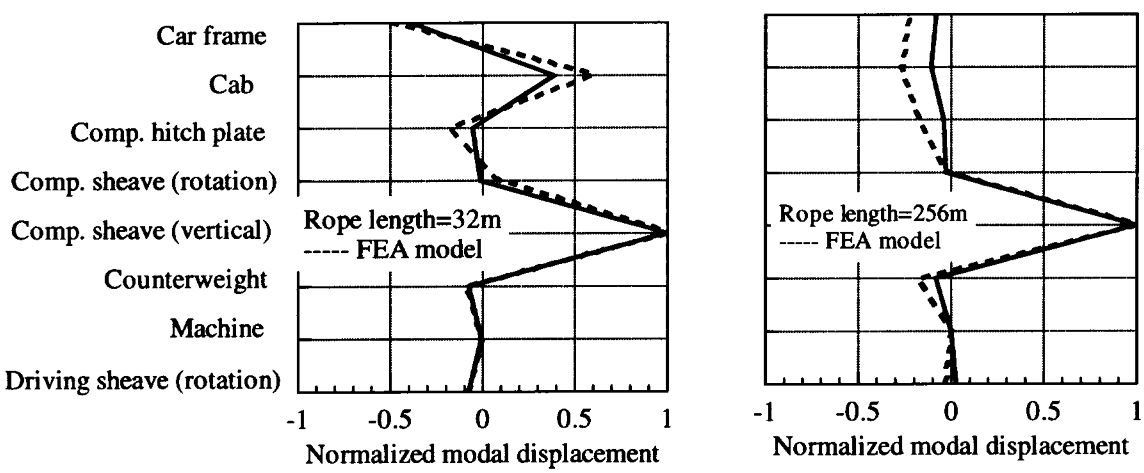


Figure 3. Comp sheave jump mode

No notable longitudinal rope wave motion was observed by checking the results from the FEA model for all rope lengths. The comparisons of mode shapes between two different models for rope length being 32m and 256m are shown in Figure 3, and the mode frequencies are listed in the following table. The mode shapes and mode frequencies in general agreed with each other well for those two different models. However if more accurate predictions are expected for high-rise elevator system, rope masses should be included into the eight-degrees –of-freedom model as lumped parameters, although it is not necessary to consider the rope longitudinal wave motion for this mode.

Rope length	8m	16m	32m	64m	128m	256m
8-degrees-of-freedom model, f_1	19.66Hz	16.04Hz	12.71Hz	8.57Hz	6.26Hz	4.49Hz
FEA model, f_0	19.15Hz	15.49Hz	12.37Hz	7.65Hz	5.16Hz	3.27Hz
$\lvert f_1 - f_0 \rvert$	0.51Hz	0.55Hz	0.34Hz	0.92Hz	1.10Hz	1.22Hz

Comp. sheave rotation mode

The mode shapes in Figure 4 shows that driving sheave rotation is dominant. Therefore this mode is named 'Comp. sheave rotation mode'.

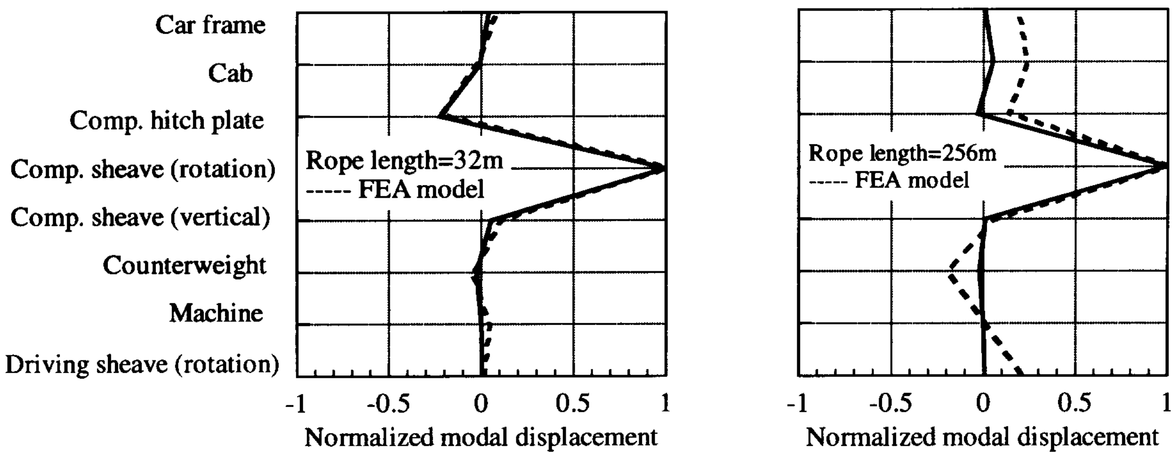


Figure 4. Comp sheave rotation mode

Again, no notable longitudinal rope wave motion was observed by checking the results from the FEA model for all rope lengths. By comparing the mode shapes in Figure 4 for two different rope lengths, it can be concluded that rope masses should be included into the eight-degrees-of-freedom model as lumped parameters if more accurate predictions of mode shape are expected for long ropes. As for the mode frequencies, the following table shows that mode frequency values are very sensitive to rope mass for this mode. Therefore rope masses should be included into the eight-degrees-of-freedom model as lumped parameters, especially for long ropes.

Rope length	8m	16m	32m	64m	128m	256m
8-degrees-of-freedom model, f_1	40.30Hz	30.23Hz	22.48Hz	16.44Hz	12.11Hz	8.35Hz
FEA model, f_0	37.80Hz	26.78Hz	18.19Hz	12.25Hz	6.73Hz	3.91Hz
$\lvert f_1 - f_0 \rvert$	2.50Hz	3.45Hz	4.29Hz	4.19Hz	5.38Hz	4.44Hz

Driving sheave rotation mode

The mode in Figure 5 shows that driving sheave rotation is dominant, and therefore is named 'Driving sheave rotation mode'.

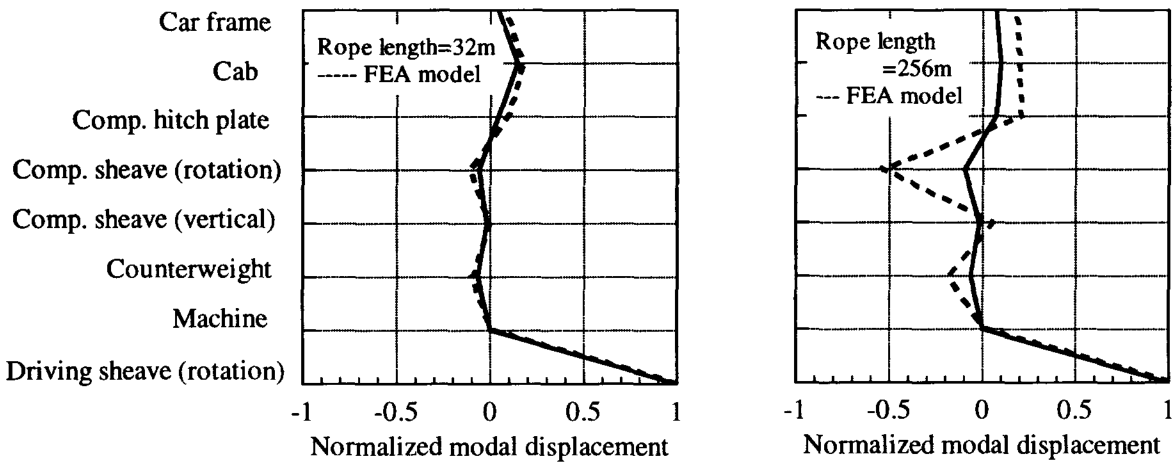


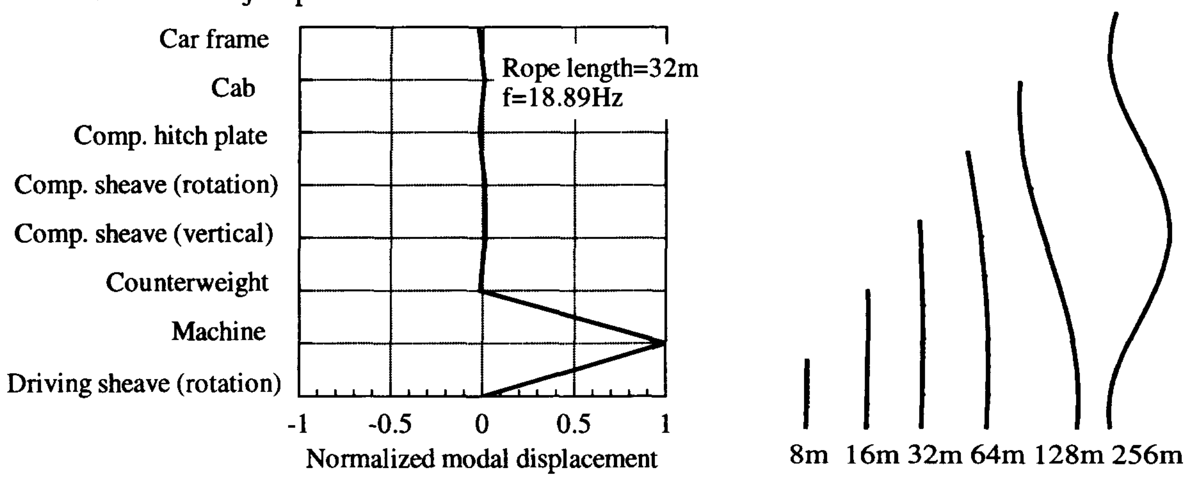
Figure 5. Driving sheave rotation mode

Although no notable rope longitudinal wave motion was observed by checking the results from the FEA model, the agreements of mode shapes shown in Figure 5 and mode frequencies in the following tables become worse for long ropes. Therefore rope masses should be included into the eight-degrees-of-freedom model as lumped parameters, if more accurate results are expected for long ropes.

Rope length	8m	16m	32m	64m	128m	256m
8-degrees-of-freedom model, f_1	8.34Hz	8.05Hz	7.55Hz	6.77Hz	5.74Hz	4.59Hz
FEA model, f_0	7.88Hz	7.28Hz	6.39Hz	5.24Hz	3.96Hz	2.71Hz
$\lvert f_1 - f_0 \rvert$	0.46Hz	0.77Hz	1.16Hz	1.53Hz	1.78Hz	1.88Hz

Machine jump mode

The mode in Figure 6(a) shows that machine vertical motion is dominant, and therefore is named 'Machine jump mode'.



(a) mode shape (b) hoist rope wave motion

Figure 6. Machine jump mode

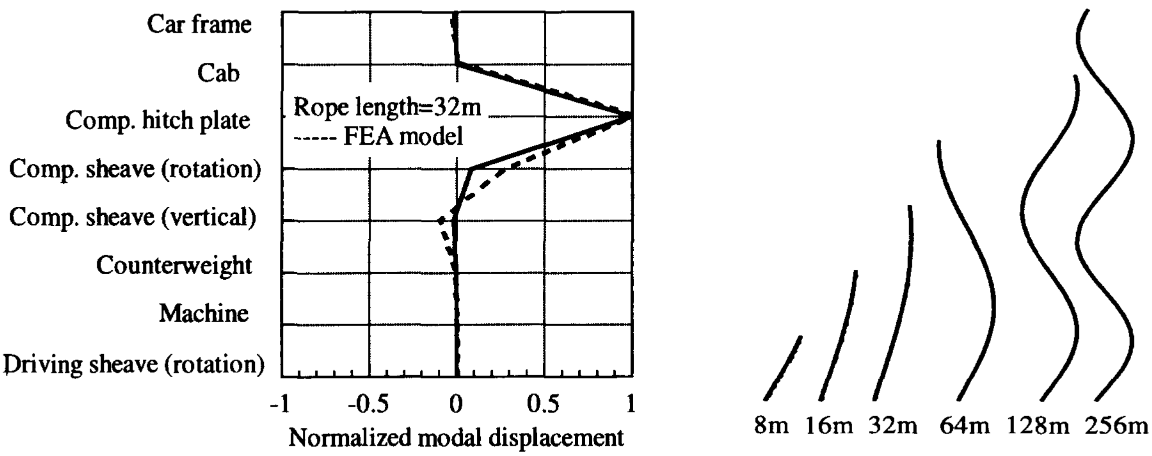
As shown in Figure 6(b), longitudinal wave motion was observed for hoist ropes being longer than 64m. Therefore it is necessary to use the FEA model for rope lengths being longer than 64m for the studies of this mode. As for the mode frequency values, the mode frequency does not change with the rope length due to the fact that mode frequency of this mode can mainly be determined by the machine weight and spring constant of pads under the machine.

Therefore the eight-degrees-of-freedom model can also predict accurately the mode frequency values for all rope lengths for this mode.

Rope length	8m	16m	32m	64m	128m	256m
8-degrees-of-freedom model, f_1	18.92Hz	18.91Hz	18.89Hz	18.85Hz	18.81Hz	18.77Hz
FEA model, f_0	18.76Hz	18.62Hz	18.28Hz	16.49Hz	18.51Hz	18.11Hz
$\lvert f_1 - f_0 \rvert$	0.16Hz	0.29Hz	0.61Hz	2.36Hz	0.30Hz	0.66Hz

Comp. hitch plate jump mode

The mode in Figure 7(a) shows that compensation hitch plate motion is dominant, and therefore is named 'Comp. hitch plate jump mode'.



(a) mode shape (b) comp. rope wave motion

Figure 7. Comp. hitch plate jump mode

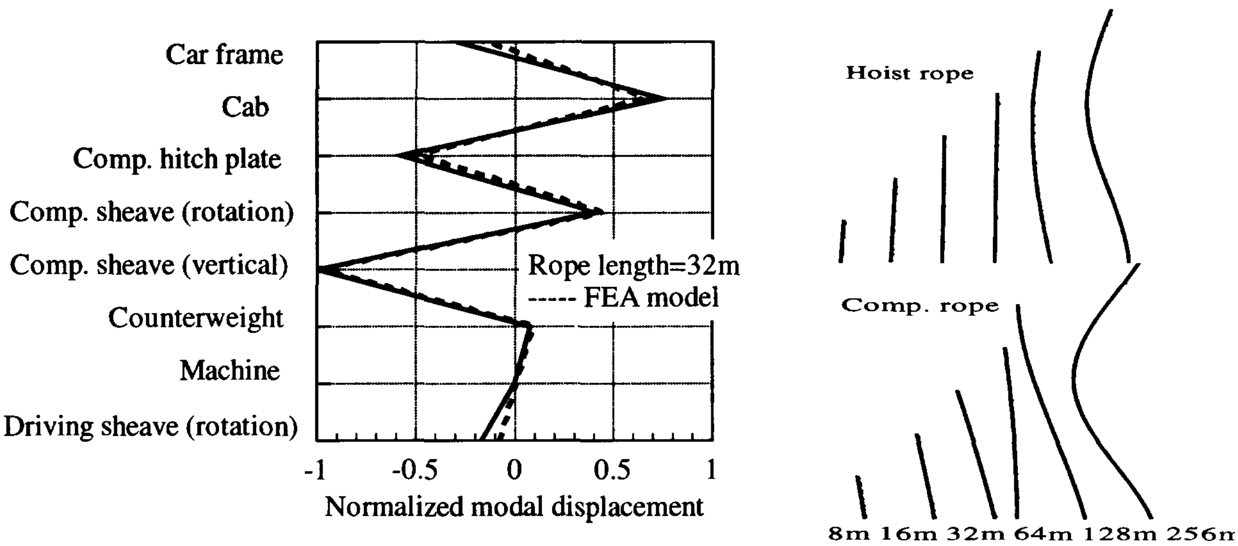
For this mode, longitudinal wave motion was observed for compensation ropes being longer than 32m as shown in Figure 7(b). As for the mode frequency values, the following table shows that the eight-degrees-of-freedom model largely overpredicts the FEA, especially for long ropes. Therefore the FEA model is necessary for the studies of this mode for rope length being longer than 32m.

Rope length	8m	16m	32m	64m	128m	256m
8-degrees-of-freedom model, f_1	86.32Hz	71.04Hz	62.75Hz	58.55Hz	56.48Hz	55.45Hz
FEA model, f_0	80.76Hz	61.47Hz	45.59Hz	50.86Hz	42.79Hz	30.37Hz
$\lvert f_1 - f_0 \rvert$	5.56Hz	8.29Hz	17.16Hz	7.69Hz	13.69Hz	25.08Hz

Frequency fixed mode

Although the mode shape in Figure 8(a) shows that the displacements of all other masses except for counterweight, machine and driving sheave are relatively large, the table below shows that mode frequencies almost keep to be a constant value of approximately 11Hz for rope length being 8m~256m. Therefore this mode is named 'Frequency fixed mode'.

For this mode, as the longitudinal wave motion was observed for both hoist ropes and compensation ropes being longer than 128m as shown in Figure 8(b), the FEA model is necessary for rope length being longer than 128m. However the mode frequency is fixed for any rope lengths, and the 8-degrees-of-freedom model can also give accurate predictions on mode frequency values.



(a) mode shape (b) hoist & comp. rope wave motion

Figure 8. Frequency fixed mode

Rope length	8m	16m	32m	64m	128m	256m
8-degrees-of-freedom model, f_1	11.23Hz	11.12Hz	10.66Hz	11.55Hz	11.10Hz	11.41Hz
FEA model, f_0	11.17Hz	10.98Hz	10.16Hz	10.77Hz	11.48Hz	11.60Hz
$\lvert f_1 - f_0 \rvert$	0.06Hz	0.14Hz	0.50Hz	0.78Hz	0.38Hz	0.19Hz

4. COUNCLUSIONS

Two different models, an eight-degrees-of-freedom and an FEA model, are created for the analysis of elevator vertical dynamic system in this study. The seven modes (exclude the first mode at frequency of 0) from the eight-degrees-of-freedom model are named based on their mode shape characteristics. Comparisons and discussions between those two different models with emphasis on the effects of rope modeling to the seven modes have been made. The following conclusions are obtained:

(1) For 'Gross weight jump mode', the eight-degrees-of-freedom model can also predict the results with good accuracy.

(2) For 'Comp. sheave jump mode', 'Comp. sheave rotation mode' and 'Driving sheave rotation' modes, much more accurate predictions could be achieved if rope masses are included into the eight-degrees–of-freedom model as lumped parameters. It is not necessary to consider the rope longitudinal wave motion for those three modes.

(3) For 'Machine jump mode', 'Comp. hitch plate jump mode' and 'Frequency fixed mode', an FEA model is necessary for the studies of high-rise elevator vertical dynamic system.

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