DYNAMIC MODELLING AND ANALYSIS OF ELEVATOR SYSTEMS

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ABSTRACT

DYNAMIC MODELLING AND ANALYSIS OF ELEVATOR SYSTEMS

Cities began to grow unexpected size after the industrial revolution. Then, so many new problems like public health, transportation, housing, food requirement etc appeared. Those problems initiated new scientific fields. Engineering diciplines also solved some of those problems and also provided many benefit to people.

Different approaches at elevator technology were effected by requirements such as hight travel distances and high load capacities. If the new elevators are compared with the old elevators, it is seen that new ones are more silent, faster, safer and even more efficient. Although the elevator technology goes further and further, its applications become more complex.

In this study, in order to find the transient time response of elevator car of the most common elevator types, finite element models of them are developed in ANSYS by using APDL (ANSYS Parametric Design Language). In the analysis, acceleration and deceleration of elevator car are used as input parameters. Time response plots of elevator car are presented.

Keywords: Elevator, vibration, time response

ÖZET

ASANSÖR SİSTEMLERİNİN DİNAMİK MODELLEMESİ VE ANALİZİ

Sanayi devrimi ile birlikte şehirler beklenmedik bir şekilde büyümeye başladı. Böylece, Sağlık problemleri, ulaşım, barınma, beslenme vb. bir çok yeni sorunlar ortaya çıktı. Bu sorunlar yeni bilimsel alanları kışkırttı. Asansör çalışmaları da bu problemlerın bazılarını çözdü ve insanlara bir çok fayda sağladı.

Asansör teknolojisindede farklı yaklaşımlar, yüksek seyahat mesafeleri ve yüksek yük kapasiteleri gibi gereksinimlerden etkilenmiştir. Yeni asansörler eski asansörler ile karşılaştırılırsa, yenilerinin daha sessiz, daha hızlı, daha güvenli ve hatta daha verimli olduğu görülür. Asansör teknolojisi daha ileriye gittikçe, onun uygulamaları da çok karmaşık olmaktadır.

Bu çalışmada, en çok kullanılan asansör tiplerinin asansör kabinindeki geçici zaman tepkisini bulmak için, ANSYS'de bunların sonlu elemanlar modelleri APDL (ANSYS Parametrik Tasarım Dili) kullanılarak geliştirilmiştir. Analizde, giriş parametreleri olarak asansör kabininin hizlanma ve yavaşlama ivmeleri kullanılmıştır. Asansör kabininin zaman tepki grafikleri sunulmuştur.

Anahtar Kelimeler : Asansör, titreşim, zaman cevabı.

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LIST OF SYMBOLS

a	accelaration
A	area
c	damping factor
E	Young's modulus of steel
E_r	Young's modulus of rope
F	force
g	gravity
I_s	mass moment of inertia of sheave
k_c	stiffness of car rope
k_{c1}	stiffness of car rope fixed to suspension spring in 2:1 roping system
k_{c2}	stiffness of car rope going to diverting sheave in 2:1 roping system
k_{cc}	stiffness of car cabinet springs
k_s	stiffness of suspension spring
k_{cw}	stiffness of counterweight rope
$k_{com\text{-}c}$	stiffness of compensating rope at car side
$k_{com\text{-}cw}$	stiffness of compensating rope at counterweight side
k_{cw1}	stiffness of counterweight rope fixed to suspension spring in 2:1 roping system
k_{cw2}	stiffness of counterweight rope going to driving sheave in 2:1 roping system
KE	kinetic energy
m_{cc}	mass of car cabinet
m_{cf}	mass of car frame
m_{com}	mass of compensating mass
m_{cw}	mass of counterweight
m_s	mass of sheave
PE	potential energy
t	time
v	velocity
v_c	velocity of car
v_{cw}	velocity of counterweight

v_{com}	velocity of compensating mass
V	volume
x, u	displacement
θ	angular velocity
θ_{ts}	angular velocity of traction sheave
θ_{cs}	angular velocity of compensating sheave
v	poisson ratio
ρ	density
σ	stress

CHAPTER 1

GENERAL INTRODUCTION

1.1. History of Elevators

Development of elevators is directly related with the industrial era products. In the following paragraphs, main mile stones are presented briefly.

In 1743, a counterweighted personal lift appeared in France. A belt-driven elevator was installed in an English factory in 1835. The first hydraulic industrial lift powered by water pressure appeared in 1846.

In 1852, Elisha Otis started to study on elevator system. On September 20, 1853, Otis opened his own shop. In order to promote his new venture, he decided to stage a demonstration of his new safety elevator at the Crystal Palace Exposition in New York as shown in Figure 1.1. On March 23, 1857, the world's first passenger safety elevator went into service in a store at Broadway and Broome Street in New York City. The elevator was powered by steam through a series of shafts and belts. In 1889, the first direct-connected electric elevator machine produced. This worm-gear electric unit was primarily used for carrying freight. In 1903, the gearless traction electric elevator started to use in buildings of any height.

Figure 1.1 Elisha Otis demonstrating his safety system
(Source: Otis, 2016)

1.2. Literature Review

Focusing on the thesis title, the last critical literatures appeared in the last century are presented below:

Kang and Sul (2000) proposed a vibration suppression strategy for improving the riding comfort of an elevator by using car acceleration feedback compensation. Vibration of a lift car in vertical direction is excited by the resonance of elastic ropes between the car and the sheave, thus resonant frequency of the system is dependent on both mass and position of lift car. Computer simulations based on simultaneous estimation of car acceleration and the identification of mechanical parameters and experimental results obtained from the system shown in Figure 1.2 affirm the feasibility of the proposed vibration controller.

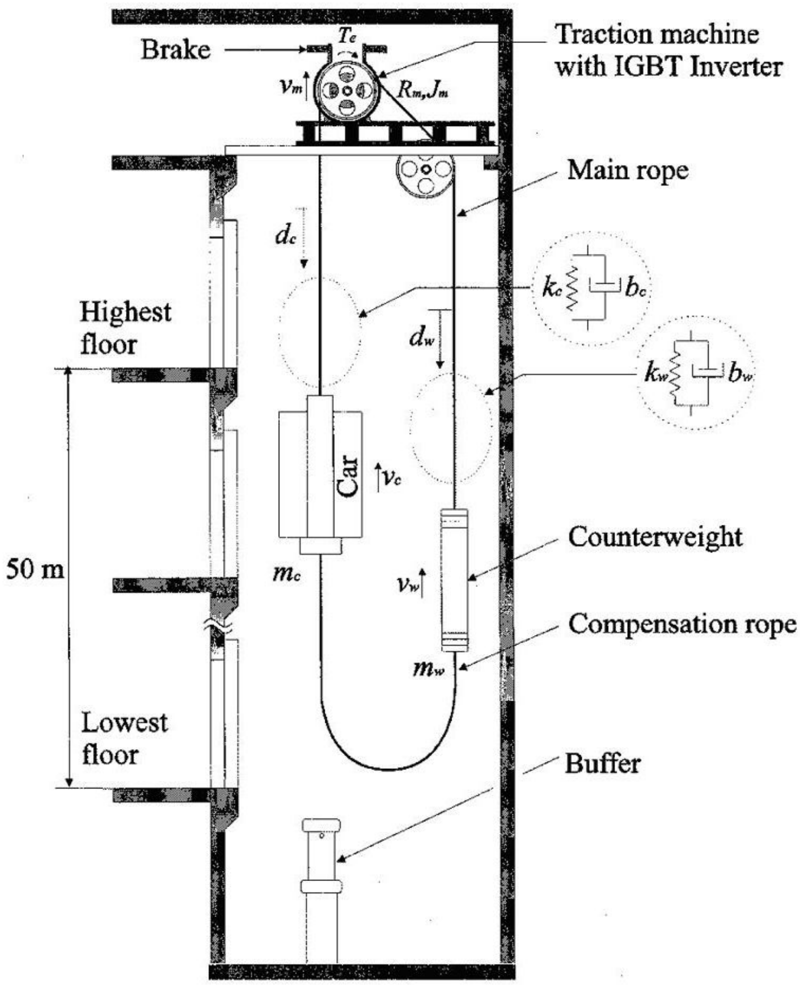


Figure 1.2 Simplified schematic of an experimental elevator system
(Source: Kang and Sul, 2000)

Herrera et al (2010) presented an approach to identify the stiffness and damping characteristics of an elevator car system shown in Figure 1.3. They simplified the car-passenger subsystem by considering only vertical motions as two degree of freedom model shown in Figure 1.4. It can be seen from Figure 1.4 that the car frame is under the base excitation y_{FR}. Also, in the same figure, y_{PA} and y_{CA} represent the vertical displacements of the passenger and the car enclosure, respectively. They obtained the displacement transmissibility $G=y_{CA}/y_{FR}$ by using the differential equation of motion of the car-passenger system. They verified their formulation experimentally.

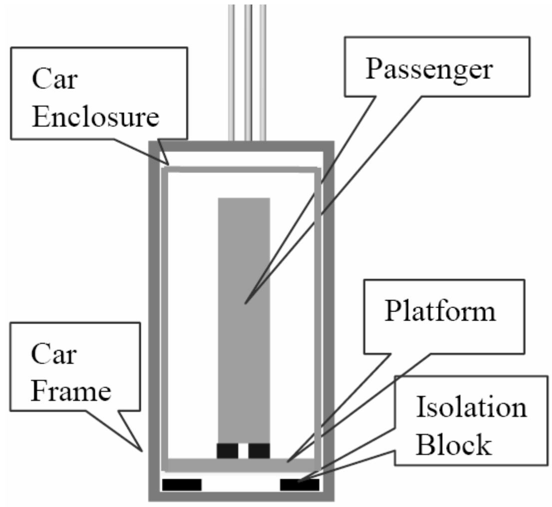


Figure 1.3. The car-passenger subsystem
(Source: Herrera et al, 2010)

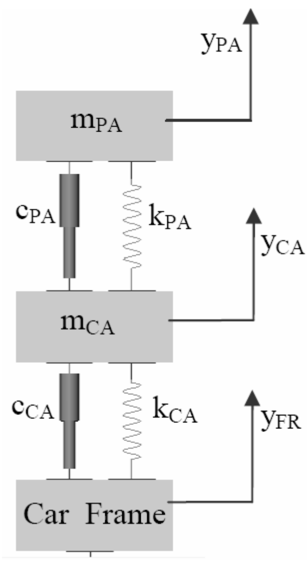


Figure 1.4. A model of the car-passenger system
(Source: Herrera et al, 2010)

Watanabe et al (2013) studied on the elevator dynamic model to evaluate the vertical motion of the compensating sheave. They investigated vertical motion of compensating sheave during upward and downward movement of elevator car for several cases such as normal operation, emergency brake operation. Also, vertical motion of sheave during buffer strike is presented. They derived the equation of motion by using total potential and kinetic energies of an elevator system shown in Figure 1.5. They validated their own theoretical model by experiments and clarified the most influenced factor for the vertical motion of the sheave.

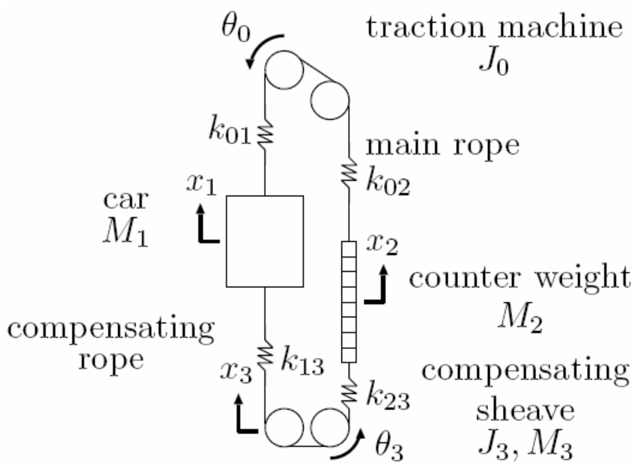


Figure 1.5. A model of the car-passenger system
(Source: Watanabe et al, 2013)

Arrasate et al (2014) presented a study related with the vertical vibrations excited by torque ripple generated at the elevator drive system. The machine torque is estimated from the current intensities. Their elevator system model includes the followings:

1. Drive system model: electric motor model
2. Vertical vibration model:
   - distributed parameter appraches: rope is modeled in continuous domain
   - lumped parameter appraches: rope is modeled by spring

The elevator components is shown in Figure 1.6. In order to simulate the acceleration response in computer, a dynamic model of an elevator by accommodating the drive system dynamics is developed. It is found that the elevator car vibrates at machine frequencies, especially when they are close to the system natural frequencies and also, only two modes contribute to the car and counterweight vibrations.

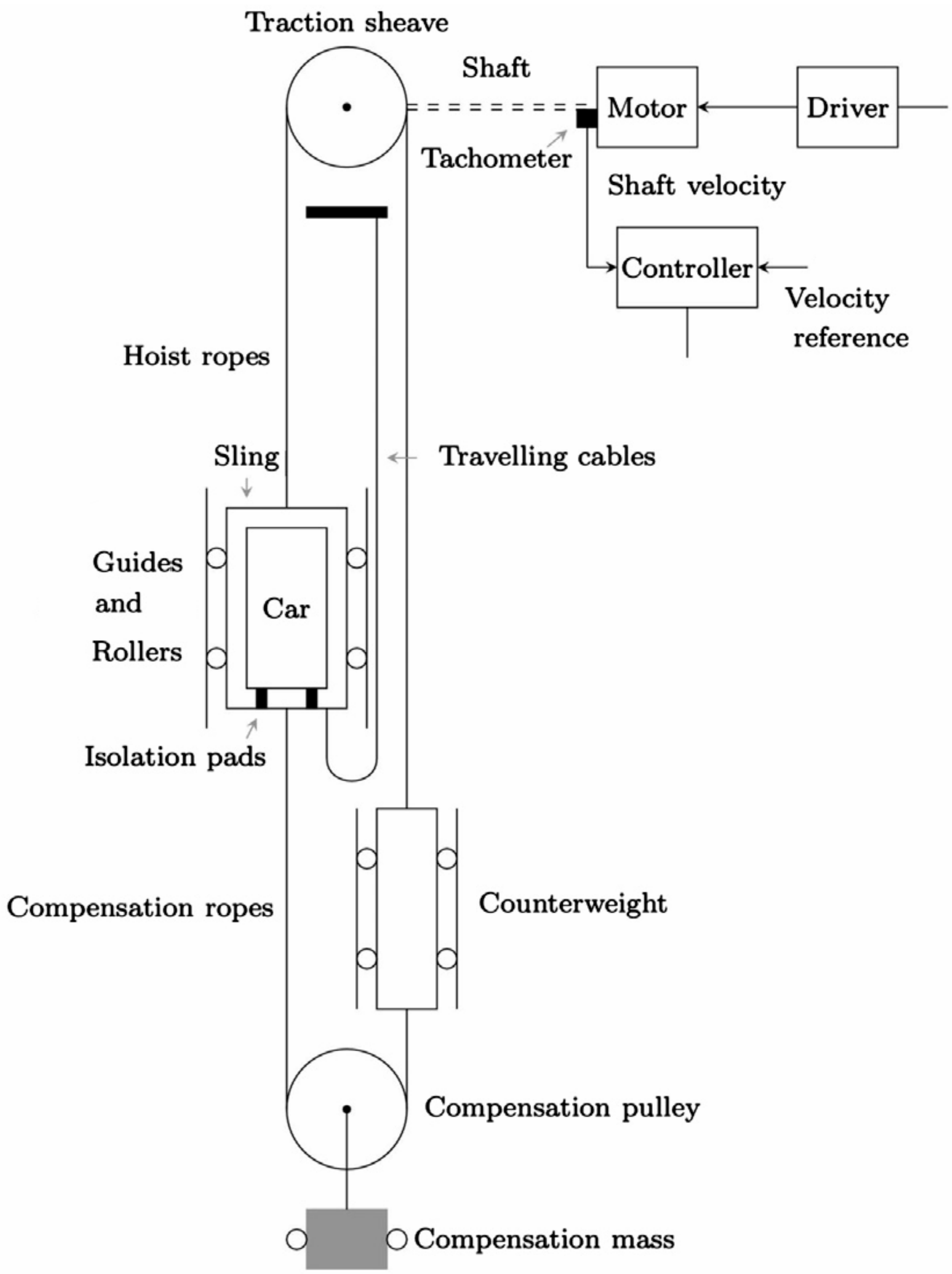


Figure 1.6. Elevator components
(Source: Arrasate et al, 2014)

Chen et al (2014) published a paper titled "Dynamic modelling and input-energy comparison for the elevator system". Their mathematical model of the elevator system includes the electrical and mechanical equations. In their paper, angular position variations are designed by using different approaches such as trapezoidal, cycloidal, five-degree (5-D) and seven-degree (7-D) polynomials. They compared the variations of angular position styles by considering the viewpoint of the human comfortable and energy consumptions. Their model is shown in Figure 1.7.

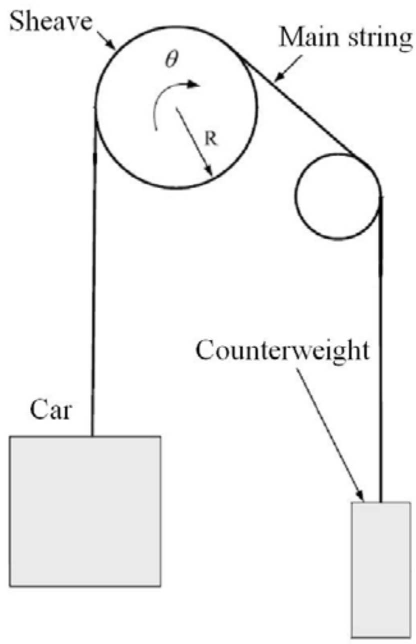


Figure 1.7. Elevator components
(Source: Chen et al, 2014)

1.3. Objectives of Study

Determination of dynamic characteristics of the elevator components are very important engineering problem, especially for safety and comfort. In this issue, low vibration and noise levels are related with fulfillment of the design requirements generally determined by standards and own experience of elevator company.

The most common elevators are driven by the traction machine and have car, rope, counter weight. Other ones have also compensating system including rope, sheave and etc. Another important concept in elevators is rope ratio. For example: if the rope ratio is 2:1, speed of the mass, either car or counter weight, connected to rope is reduced to 1/2.

Due to the commercial reasons, the available literatures on elevator systems are limited. The available ones are presented last section. In this study, the car-passenger subsystem modeled by Herrera et al (2010) and the most common type analyzed by Chen et al (2014) are combined to see the rope effect on the riding comfort.

CHAPTER 2

FUNDAMENTAL TOPICS

2.1. Elevators

2.1.1. Introduction

Elevator or lift is vertical transport equipment like a box raised and lowered by a cable driven by electric motors or hydraulic system. This transport equipment moves people or goods between floors of a building or other similar structures. It has generally counterweight systems to operate easily.

According to the European elevator standard coded by EN 81-1, elevator is defined as a car designed for the transportation of persons or persons and goods, suspended by ropes or chains and moving between guide rails inclined not more than 15° to the vertical.

American elevator standard is ASME A17.1 defines an elevator which has a hoisting and lowering mechanism, equipped with a car, which moves within guides and serves two or more landings.

In this section, types and components of elevators are presented.

2.1.2. Types

Elevator categorization is not easy due to the usage area in daily life, common elevator market, technological development and standards. However, the most reasonable classification for elevators is listed below:

<u>1. Elevators according to the hoist mechanism:</u>

- Hydraulic Elevators are supported by a piston at the bottom of the elevator that pushes the elevator up. They are used for low-rise applications of 2 to 8 stories and generally travel at a maximum speed of 0.60 m/s or 1 m/s. The machine room for hydraulic elevators is usually located at the lowest level adjacent to the elevator shaft. Hydraulic elevators have two main types as direct and in-direct. Direct or in-direct drive of elevator car is possible for different applications. If the car is directly pushed by piston, system is defined direct type; but if the car is suspended to pistons with ropes, the system is in-direct type, respectively. Figure 2.1 shows elevators driven by hydraulic system.

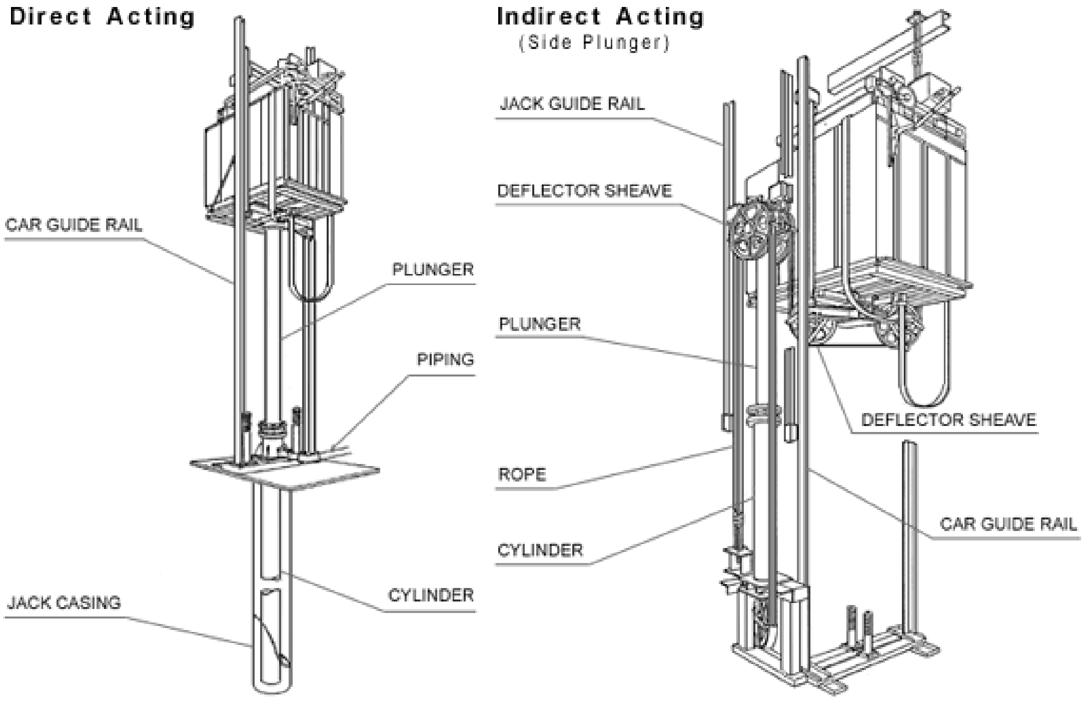


Figure 2.1. An elevator driven by hydraulic system
(Source: Mitsubishi, 2016)

- Traction Elevators are the most common choice for architects and engineers because of its basic characteristic for assembly and maintenance conditions. Traction elevators are lifted by ropes, which pass over a sheave attached to an electric motor usually above or rarely below the elevator shaft. They are used for every kind of applications and have much higher travel speeds than hydraulic elevators. A counter weight makes the elevators more efficient. Traction elevators have two main types: (i) geared traction machine and (ii) gearless traction machine. Gearless traction machines are more expensive but faster, need less maintenance service than geared traction machines. Also, gearless traction machines consume less energy. Figure 2.2 shows two types of tractions.

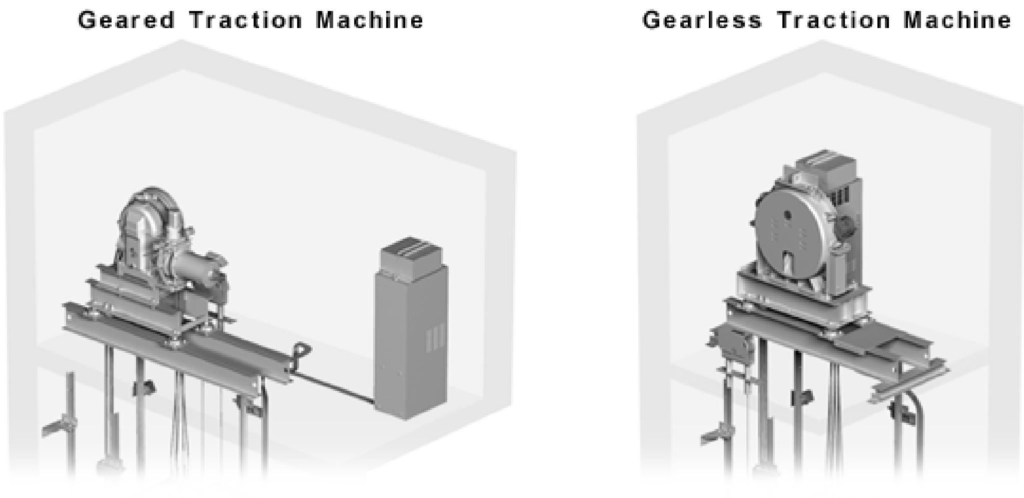


Figure 2.2. Traction elevators
(Source: Mitsubishi, 2016)

- Roping systems are various as shown in the Figure 2.3. The list given below is related with the Figure 2.3 and summarizes the usage areas of the systems.

a) Roping ratio 1:1 > Half wrap (single wrap): Mid-, low-speed elevators
b) Roping ratio 1:1 > Full wrap (double wrap): High-speed elevators
c) Roping ratio 1:1 > Drum winding: Home elevators
d) Roping ratio 1:1 > Drum winding: Small, low-speed elevators
e) Roping ratio 2:1 > Full wrap (double wrap): High-speed elevators
f) Roping ratio 2:1 > Half wrap (single wrap): Freight elevators
g) Roping ratio 2:1 > Half wrap (single wrap): Machine-room-less elevators
h) Roping ratio 3:1 > Half wrap (single wrap): Large freight elevators
i) Roping ratio 4:1 > Half wrap (single wrap): Large freight elevators

Although they vary according to the traction speed, rated load, and other factors, roping should be kept as simple as possible. Reducing the number of deflectors and suspension sheaves improves longevity and efficiency of the ropes. With 2:1 or 4:1 roping, car speed is reduced to 1/2 or 1/4, respectively, of the rope speed, because suspension sheaves are provided above (or below) the car and counterweight, and both ends of the rope are attached to the machine room beams. With these roping systems, loads on the rope is reduced to 1/2 or 1/4 as well, hence the diameter and number of ropes can be reduced.

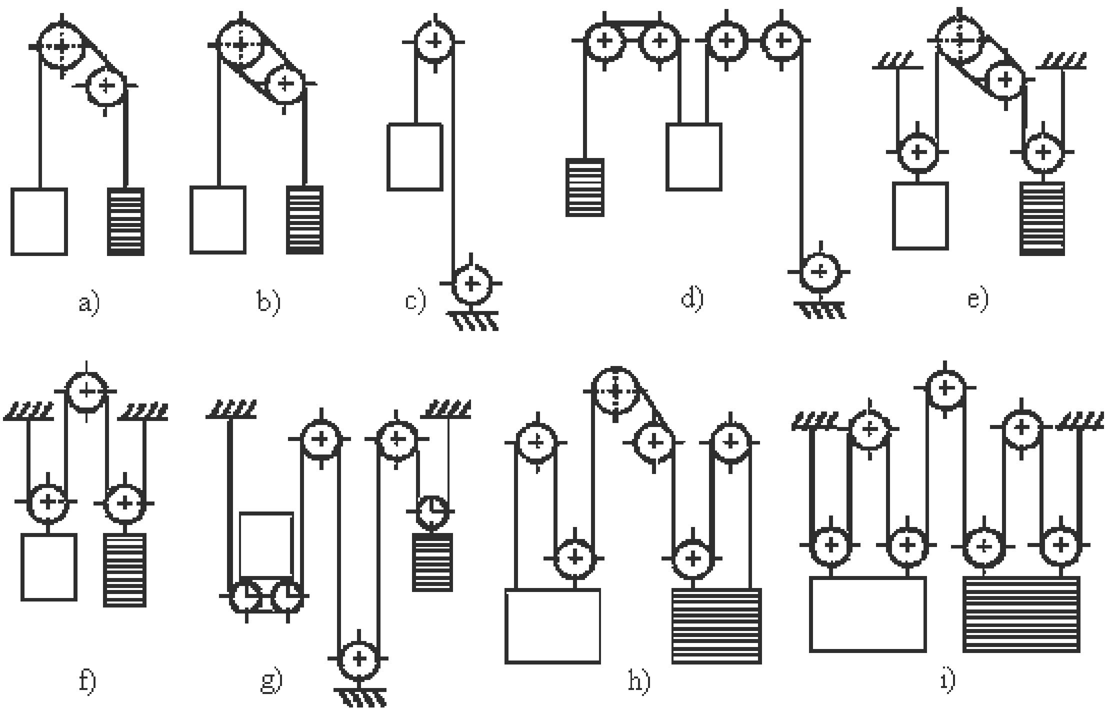


Figure 2.3. Roping systems
(Source: Mitsubishi, 2016)

- Climbing elevators are driven by mostly electric or combustion engine mounted on elevator car. They are used in construction areas. A sample one is shown in Figure 2.4.

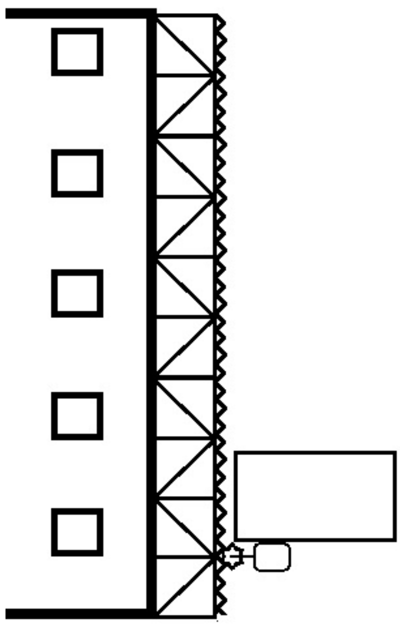


Figure 2.4. Climbing elevator

- Pneumatic Elevators are similar to hydraulic elevators, but the difference is driver system. In this case it is driven by air pressure. In other words, elevator car is raised and lowered by controlling air pressure in a chamber in which the elevator sits. A sample for pneumatic elevator is shown in Figure 2.5.

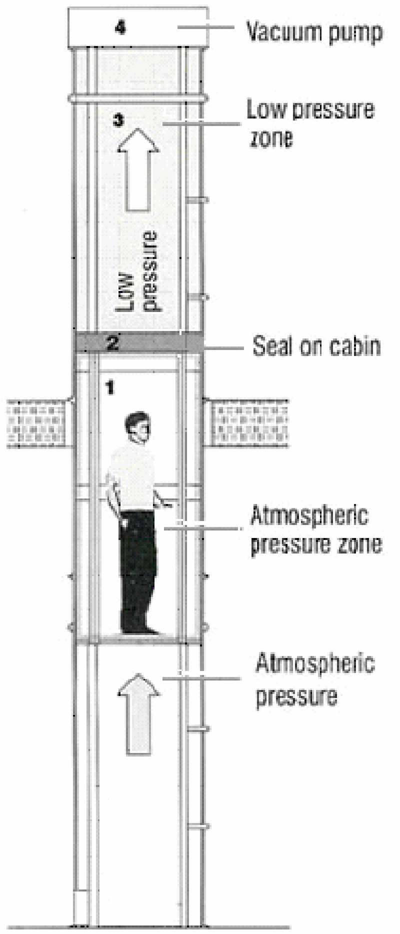


Figure 2.5. Pneumatic Elevator
(Source: Daytona Elevator, 2016)

<u>2. Elevators according to building height:</u> This classification is based on the travel distance of the elevator.

<u>3. Elevators according to building type:</u> Due to the different laws, regulations and standards for different building, the following classification is possible:

- Hospital elevators
- Residential or domestic elevators
- Industrial elevators
- Commercial elevators
- Firefighter elevators

2.1.3. Components

The sample geared traction elevator is shown in Figure 2.6. It can be seen from Figure 2.6 that the main components of this system are geared machine, hoisting ropes, car and its components, counterweight, elevator rail and compensation components.

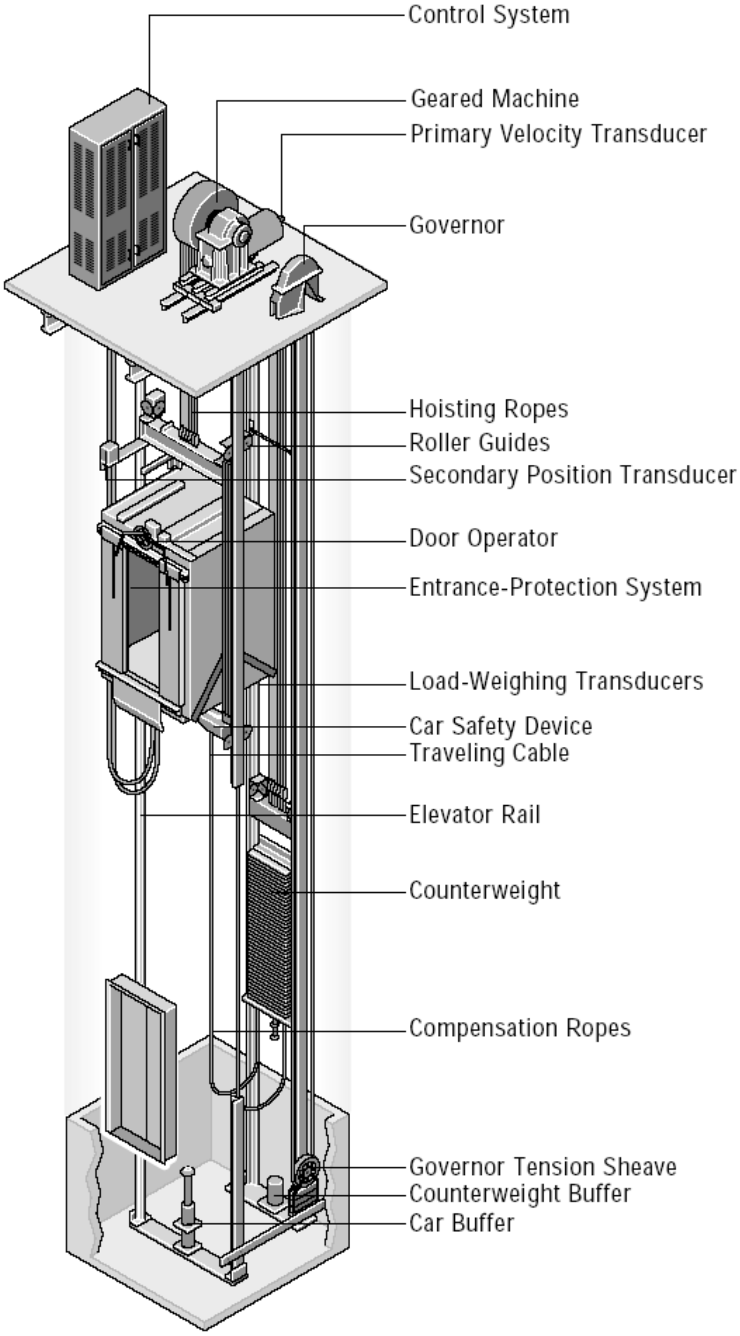


Figure 2.6. Elevator components
(Source: OTIS, 2016)

Hoistway shown in Figure 2.7 is the space enclosed by fireproof and strong enough walls and elevator doors for the travel of one or more elevators. Hoistway includes guide rails, pit and buffers.

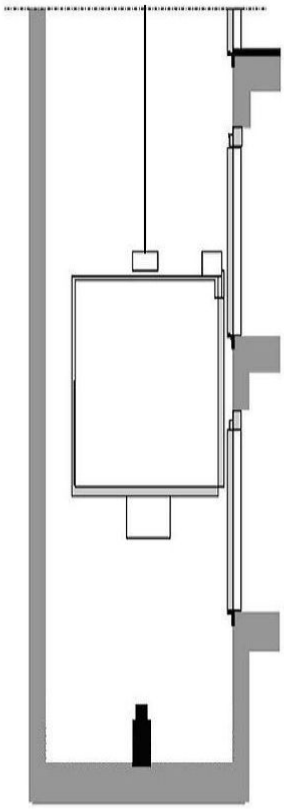


Figure 2.7. Hoistway

Isolation pads shown in Figure 2.8 are made of and located between car and frame for preventing passengers from effects of vibration.

Figure 2.8. Rubber isolators

2.2. Vibration of Multi-Degree-of-Freedom Systems

2.2.1. Derivation of Equation of Motion

A multi-degree-of-freedom system has multi independent coordinates to specify the positions of the masses of the system (Seto, 1983). For example, the system shown in Figure 2.9 has two degrees of freedom. It is also described by using excitation and damping types, i.e., “force excited viscously damped system”.

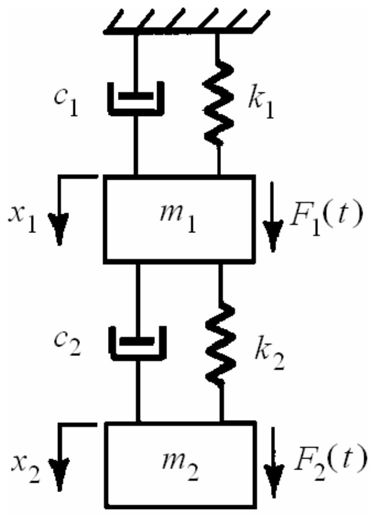


Figure 2.9. Two-degrees-of-freedom system

Generally, equation of motion of multi-degree-of-freedom system can be obtained by Newton’s second law of motion or Lagrange’s equation and expressed in matrix form as follows

$$[M]\{\ddot{x}(t)\}+[C]\{\dot{x}(t)\}+[K]\{x(t)\}=\{F(t)\} \tag{2.4}$$

where [M], [K], and [C] are mass, stiffness, and damping matrices, respectively. Also, $\{x(t)\}$ and $\{F(t)\}$ are displacement and force vectors, respectively.

As known, the Newton’s second law of motion is written for mass m_i under the summation of several forces such as elastic, external, and viscous damping as follows:

$$\sum \vec{F}_i = m_i \ddot{\vec{x}}_i \tag{2.5}$$

where $\ddot{\vec{x}}_i$ is the acceleration of the mass m_i.

Lagrange's equation is given as (Seto, 1983)

$$\frac{d}{dt}\frac{\partial(K.E.)}{\partial \dot{q}_i} - \frac{\partial(K.E.)}{\partial q_i} + \frac{\partial(P.E.)}{\partial q_i} + \frac{\partial(D.E.)}{\partial \dot{q}_i} = Q_i \quad (2.6)$$

where *K.E.*, *P.E.*, and *D.E.* are kinetic, potential and dissipation energies of the system, respectively. Q_i is the generalized external force acting on the system.

2.2.2. Natural Frequencies and Mode Shapes

Natural frequencies of the system can be found by the following methods:

1. Solution of the characteristic equation: when the matrix size is not large, this method is practical. Characteristic equation is obtained as follows,

$$\det([K] - \omega^2 [M]) = 0 \quad (2.7)$$

2. Solution of eigenvalue problem of the system: when the matrix size is large, this method is efficient. Eigenvalue problem is defines as,

$$([K] - \omega^2 [M])\{x\} = \{0\} \quad (2.8)$$

After finding natural frequencies ω_i, associated mode shapes $\{x_i\}$ are found.

2.2.3. Time Response

Time response or transient analysis is interested in finding $\{x(t)\}$ in Equation (2.4). It can be performed numerically by direct integration methods or step-by-step methods (Cook 1989).

In order to find the time response $\{x(t)\}$, the desired time interval $(0, T)$ is divided into N equal time intervals $\Delta t = T / N$. The time response is then calculated approximately at the successive times Δt, $2\Delta t$, $3\Delta t$, . . . , T. The approximation error is of the order $(\Delta t)^2$. The solution procedure for time response based on central difference method is given below (Petyt 2010):

First, solve the following equation

$$[M]\{\ddot{x}_0\}+[C]\{\dot{x}_0\}+[K]\{x_0\}=\{F_0\} \tag{2.9}$$

for the acceleration vector $\{\ddot{x}_0\}$. Second, calculate $\{x_1\}$ by using the next equation:

$$\{x_1\}=\{q_0\}+\Delta t\,\{\dot{x}_0\}+((\Delta t)^2/2)\{\ddot{x}_0\} \tag{2.10}$$

Then, calculate the $\{x_{j+1}\}$ starting with j=1, from the following equation

$$[A]\{x_{j+1}\}=\{F_j\}+[B]\{x_j\}-[D]\{x_{j-1}\} \tag{2.11}$$

where

$$[A]=1/(\Delta t)^2[M]+1/(2\Delta t)[C] \tag{2.12}$$

$$[B]=2/(\Delta t)^2[M]-[K] \tag{2.13}$$

$$[D]=1/(\Delta t)^2[M]-1/(2\Delta t)[C] \tag{2.14}$$

until desired time T. Selection of the value of Δt is critical for numerical stability and accuracy. For good accuracy, it is selected as twenty times of natural period (Petyt 2010).

It is clear that calculation of the $\{x_{j+1}\}$ is required the following matrix algebra,

$$\{x_{j+1}\}=[A]^{-1}\{F_j\}+[A]^{-1}[B]\{x_j\}-[A]^{-1}[D]\{x_{j-1}\} \tag{2.15}$$

2.3. Dynamic Modeling of Elevator Systems

2.3.1. Modeling of Elevators with Roping Ratio 1:1

Elevators with roping ratio 1:1 are shown in Figure 2.10. The conventional elevator is the simplest one which is illustrated at the left side of the Figure 2.10. It has lift car, main rope, traction sheave, deflector sheave, and counterweight.

To eliminate the balance problem of the conventional elevator due to the different rope length in different floor level, compensating rope connecting lift car and counterweight is used. This elevator system is shown at the middle of the Figure 2.10.

Compensating ropes with tensioning pulleys are used if the rated speed of the lift exceeds 2.5 m/s (Bangash and Bangash, 2007). This is shown at the right side of the Figure 2.10.

The selection of the elevator type is based on the travel distance and velocity requirements.

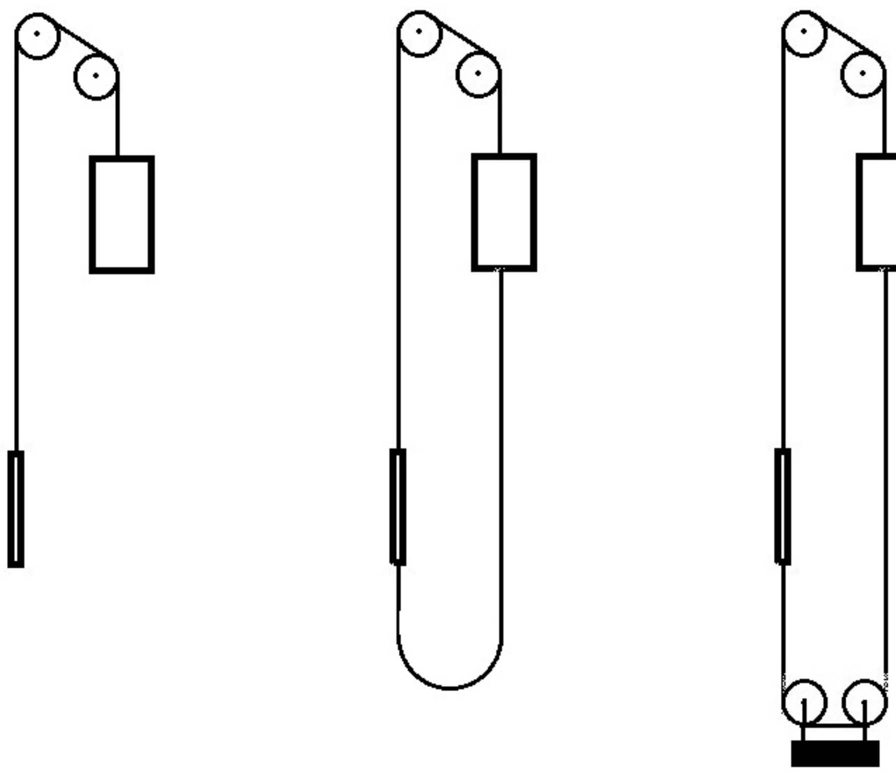


Figure 2.10 Elevators with Roping Ratio 1:1

2.3.2. Modeling of Elevators with Roping Ratio 2:1

Elevators with roping ratio 2:1 are shown in Figure 2.11. The conventional elevator with roping ratio 2:1 is the simplest one which is illustrated at the left side of the Figure 2.11. It has lift car, main rope, traction sheave, deflector sheave, car sheave, counterweight, and counterweight sheave.

As mentioned in last section, the balance problem of the conventional elevator due to the different rope length in different floor level is eliminated by compensating rope connecting lift car and counterweight. If the elevator system shown at the middle of the Figure 2.11 is compared with its counterpart in Figure 2.10, it is seen that car sheave and sheave are added to system to reduce the velocity of the car and counterweight, but increase the load capacity of car.

Similar modification for roping ratio 2:1 can be seen in the system at the right side of the Figure 2.11.

Therefore, it is clear that selection of the elevator type is also based on the load capacity of the car.

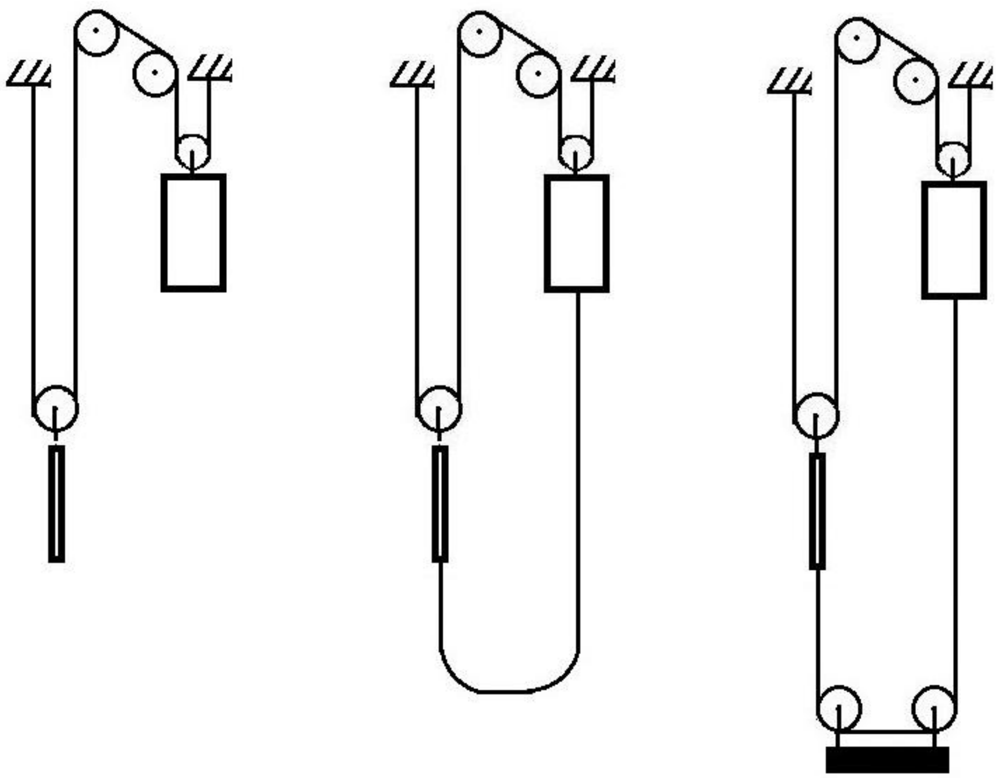


Figure 2.11 Elevators with Roping Ratio 2:1

2.4. Dynamic Analysis of Elevator Systems

In order to perform dynamic analysis of elevator system, equation of motion of it is needed. In this section, energy based discrete model approach is employed. Elevator cars shown in Figures 2.10 and 2.11 are not detailed due to the size of the figures. Now, in this section, it is detailed for dynamic analysis and shown in Figure 2.12.

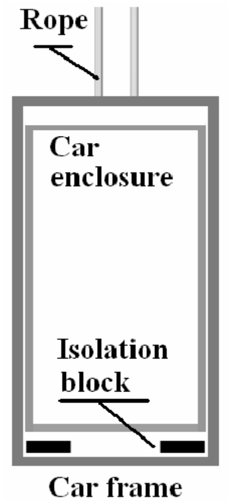


Figure 2.12. Elevator car suspension system

To physically model the elevator systems, the following assumptions are made:

1. All components except the ropes are rigid,
2. All ropes can be modeled by spring with variable length in piecewise fashion,
3. Motion of car and counterweight are perfectly vertical.

The kinetic energy of an object, with mass m and mass moment of inertia I, in general motion with linear velocity v and angular velocity ω can be expressed as

$$K.E. = 0.5(mv^2 + I\omega^2) \tag{2.16}$$

The elastic potential energy of the rope with stiffness k under the elongation x is

$$P.E. = 0.5kx^2 \tag{2.17}$$

Equations (2.16) and (2.17) are written for each related component and then substituted into Equation (2.6) to find the equation of motion of the elevator system.

2.5. Modeling and Analysis in ANSYS

2.5.1. Finite Element Method

This is a numerical analysis method based on the divisions of the complex domain into simple geometrical domains which are known as finite elements. This is done since the complex domain has no analytical solution generally; however approximate solutions for simple geometrical domains are available. The solutions may be found by using one of the four approaches: the direct approach, the variational approach, the weighted residual approach, or the energy balance approach.

In a continuum problem of any dimension the field variable (whether it is pressure, temperature, displacement, stress or some other quantity) possesses infinitely many values because it is a function of each generic point in the body or solution region. Consequently, the problem is one with an infinite number of unknowns. The finite element discretization procedure reduce the problem to one of a finite number of unknowns by dividing the solution region into elements and by expressing the unknown field variable in terms of assumed approximating function with each element. The approximating functions (interpolation functions) are defined in terms of the values of the field variables at specified points called nodes. Nodes usually lay on the element boundaries where adjacent elements are connected. In addition to boundary nodes, an element may also have a few interior nodes. The nodal values of the field variable and the interpolation functions for the elements completely define the behavior of the field variable within the elements. For the finite element representation of a problem the nodal values of the field variable become the unknowns. Once these unknowns are found, the interpolation functions define the field variable throughout the assemblage of elements.

Clearly, the nature of the solution and the degree of approximation depend not only on the size and number of the elements used but also on the interpolation functions selected. The functions can not be chosen arbitrarily, because certain compatibility conditions should be satisfied. Often functions are chosen so that the field variable or its derivatives are continuous across adjoining element boundaries.

An important feature of finite element method is the ability to formulate solutions for individual elements before putting them together to represent the entire problem. In essence, a complex problem reduces to considering a series of greatly simplified problems.

Regardless of the approach used to find element properties, the solution of a continuum problem by the finite element method always follows an orderly step-by-step process. These steps are summarized as follows:

1. Discretize the continuum: The continuum or solution region is divided into elements. A variety of element shapes may be used, and different element shapes may be employed in the same solution region.

2. Assign nodes and select interpolation functions: The field variable may be a scalar, a vector, or a higher-order tensor. Often, polynomials are selected as interpolation functions for the field variable because they are easy to integrate and differentiate. The degree of the polynomial chosen depends on the number of nodes assigned to the elements, the nature and number of unknowns at each node, and certain continuity requirements imposed at the nodes and along the element boundaries. The magnitude of the field variable as well as the magnitude of its derivatives may be the unknowns at the nodes.

3. Find the element properties: Once the finite element model has been established, the matrix equations expressing the properties of the individual elements can be determined.

4. Assembly the element properties to obtain the system equations: In this step, the properties of the overall system modeled by the network of elements are found. In other words, the matrix equations expressing the behavior of the elements are combined. The matrix equations for the system have the same form as the equations for an individual element except they contain many more terms because they include all nodes. The basis for the assembly procedure stems from the fact that at a node, where elements are interconnected, the value of the field variable is the same for each element sharing that node. Before the system equations are ready for solution they must be modified to account for the boundary conditions of the problem.

5. Solve the system equations: The assembly process of the preceding step gives a set of simultaneous equations that we can solve to obtain the unknown nodal values of the field variable.

6. Make additional computations if desired: Sometimes we may want to use the solution of the system equation to calculate other important parameters.

2.5.2. ANSYS Parametric Design Language

ANSYS Parametric Design Language is abbreviated as APDL. This is a scripting language that can be used to automate common tasks or even build the model in terms of parameters (variables). In other words, APDL utilizes concepts and structures very similar to common scientific programming languages such as BASIC, FORTRAN, etc. While all ANSYS commands can be used as part of the scripting language. Moreover, it encompasses a wide range of other features such as repeating a command, macros, if-then-else branching, do-loops, and scalar, vector and matrix operations.

While APDL is the foundation for sophisticated features such as design optimization and adaptive meshing, it also offers many conveniences that can be used in day-to-day analyses. The common APDL commands are given below:

/CLEAR	Clears the database
/PREP7	Enters the model creation preprocessor
/SOLU	
/POST1	Enters the database results postprocessor
/POST26	Enters the time-history results postprocessor
/FINISH	Exits normally from a processor
/FILNAME	Changes the Jobname for the analysis
/EOF	Exits the file being read
SAVE	Saves all current database information
!	ANSYS ignores the characters to the right of the exclamation mark
*SET	Assigns values to user-named parameters.
*GET	Retrieves a value and stores it as a scalar parameter or part of an array parameter
ET	Defines a local element type from the element library
R	Defines the element real constants
MP	Defines material properties
N	Creates nodes
E	Creates elements
D	Specify DOF constraints on nodes
F	Specifies force loads at nodes

2.5.3. Static Analysis

A static analysis calculates the effects of steady loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time-varying loads. A static analysis can, however, include steady inertia loads (such as gravity and rotational velocity), and time-varying loads that can be approximated as static equivalent loads.

Static analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time. The types of loading that can be applied in a static analysis include:

- Externally applied forces and pressures
- Steady-state inertial forces (such as gravity or rotational velocity)
- Imposed (nonzero) displacements
- Temperatures (for thermal strain)

2.5.4. Modal Analysis

Modal analysis is used to determine the natural frequencies and mode shapes of a structure which are important parameters in the design of a structure for dynamic loading conditions. They are also required if a spectrum analysis or a mode superposition harmonic or transient analysis are needed. Modal analysis can be also performed for a pre-stressed structure. Modal analysis in the ANSYS is a linear analysis. The following mode-extraction methods can be chosen:

- Block Lanczos (default):
- Subspace:
- Power Dynamics:
- Reduced:
- Unsymmetric:
- Damped:
- QR damped: This allows for unsymmetrical damping and stiffness matrices.

2.5.5. Transient Analysis

Transient dynamic analysis also called time-history analysis is used to determine the dynamic response of a structure under the general time-dependent loads. In other words, to determine the time-varying displacements, stresses, strains, and forces in a structure under several types of time dependent loads this analysis is performed.

The basic equation of motion solved by a transient dynamic analysis is given in Equation (2.4). The Newmark time integration method or an improved method called HHT is used in ANSYS to solve the mentioned equation. The time increment between successive time points which is called the integration time step plays a critical role on response.

Three methods are available in ANSYS to perform a transient dynamic analysis:

1. Full method: This method uses the full system matrices to calculate the transient response and is the most general one. It is possible to include all types of nonlinearities in the problem.
2. Mode superposition method: Due to the name of the method, this method sums factored mode shapes obtained from a modal analysis to calculate the structure's response.
3. Reduced method: This method condenses the problem size by using master degrees of freedom and reduced matrices. After the displacements at the master DOF have been calculated, ANSYS expands the solution to the original full DOF set.

2.5.6. Determination of Acceleration of Elevator Car

Velocity and acceleration of the car are design parameters based on the driving system. The coefficient C_1 taking account of acceleration, deceleration and specific conditions of the installation is given by Bangash and Bangash (2007) as

$$C_1 = \frac{g+a}{g-a} \tag{2.18}$$

where g is the gravitational acceleration and a is the acceleration (deceleration) of the car. The following minimum values of C_1 may be permitted:

1.10 for rated speeds $0<v\leq0.63$ m/s;

1.15 for rated speeds 0.63 m/s $<v\leq1.00$ m/s;

1.20 for rated speeds 1.00 m/s $<v\leq1.60$ m/s;

1.25 for rated speeds 1.60 m/s $<v\leq2.50$ m/s.

On the other hand, the velocity and acceleration functions of the elevator car can be plotted as shown in Figure 2.13. It can be seen from velocity and acceleration plots that the velocity function between t_0 and t_1 can be expressed as cubic polynomial function and then the acceleration function between t_0 and t_1 is expressed as quadratic function. The coefficients of the functions can be calculated by using the terminal values of velocity and accelerations.

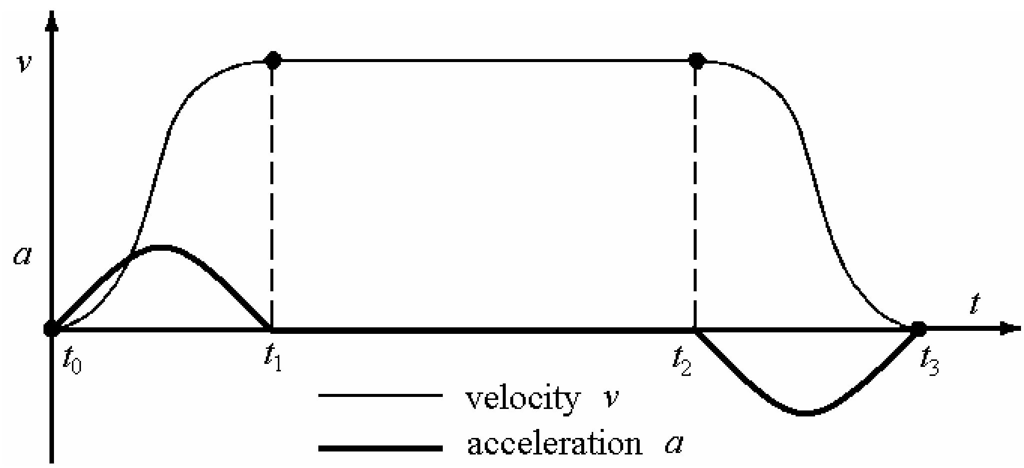


Figure 2.13. Velocity function of the elevator car

This section is used to apply the inertia loads to elevator components.

CHAPTER 3

NUMERICAL STUDIES ON ELEVATOR MODELS

3.1. Introduction

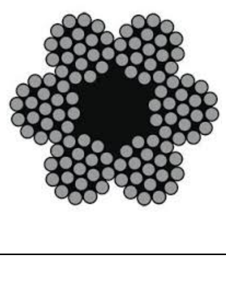
The different elevator models are considered here to simulate the motions of the car cabinet under acceleration and deceleration. The computer codes are developed in ANSYS by APDL. For the sake of brevity and simplicity, common numerical data used throughout the models are listed in Table 3.1 and Table 3.2.

Table 3.1. Common data used throughout the all models

I_s : mass moment of inertia of sheave (kg.m^2)	5.03
k_{cc} : stiffness of car cabinet spring for per item (N/m)	120210
k_s : stiffness of suspension spring per rope (N/m)	106667
m_{cc} : mass of car cabinet with eight passengers**(kg)	500+600
m_{cf} : mass of car frame (kg)	200
m_{cw} : mass of cw* (kg)	1000
m_s : mass of sheave (kg)	31
n : number of wire rope with fibre core	6

cw*: counterweight, passengers**: each one has 75 kg.

Table 3.2. Data for rope with fibre core (Bhandari, 2010)

Cross-section	Wire rope construction	6x19(12/6/1)
	Tensile designation (MPa)	1570
	d (mm)	10
	A = 0.38d^2 (mm^2)	38
	E (MPa)	83000
	μ (kg/m)	0.346

If A and E are cross-sectional area and Young' modulus of rope, respectively, the stiffness of a rope k_i corresponding the rope length L_i is found by

$$k_i = L_i /(AE) \tag{3.1}$$

The displacement, velocity, and acceleration of a region of rope almost contacted to traction sheave pointed in Figure 3.1 are shown in Figures 3.2-3.4, respectively.

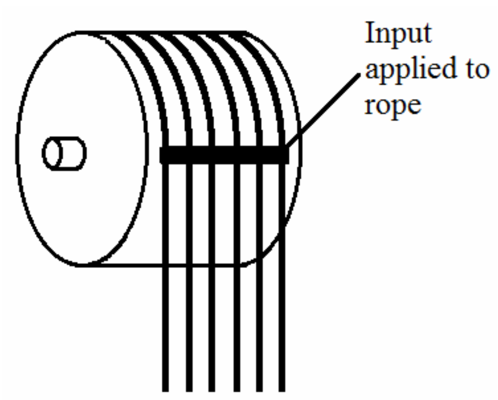


Figure 3.1. Input region of rope

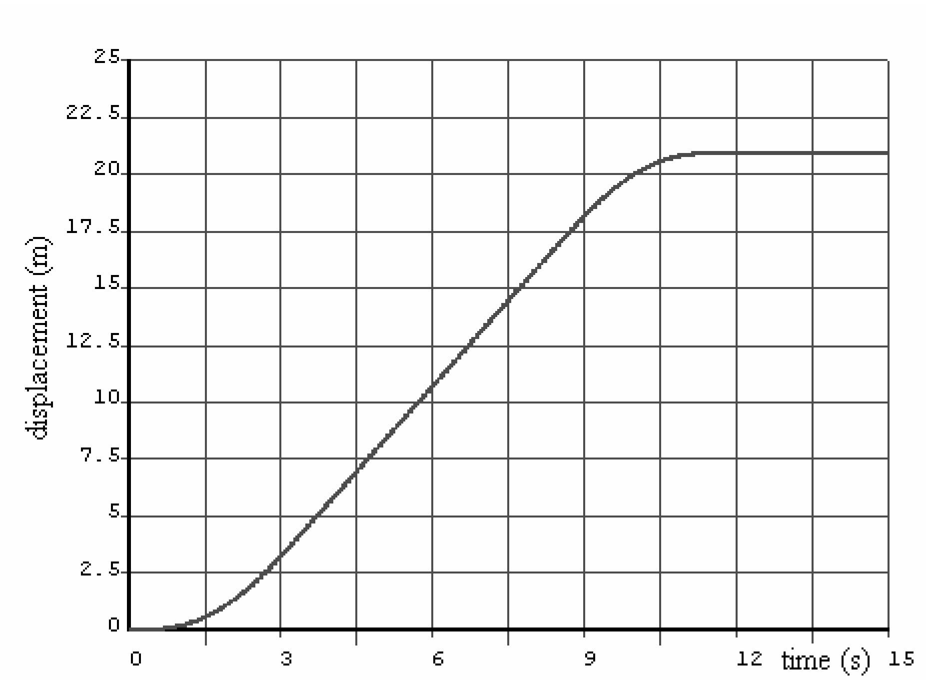


Figure 3.2. The displacement of a point of rope almost contacted to sheave

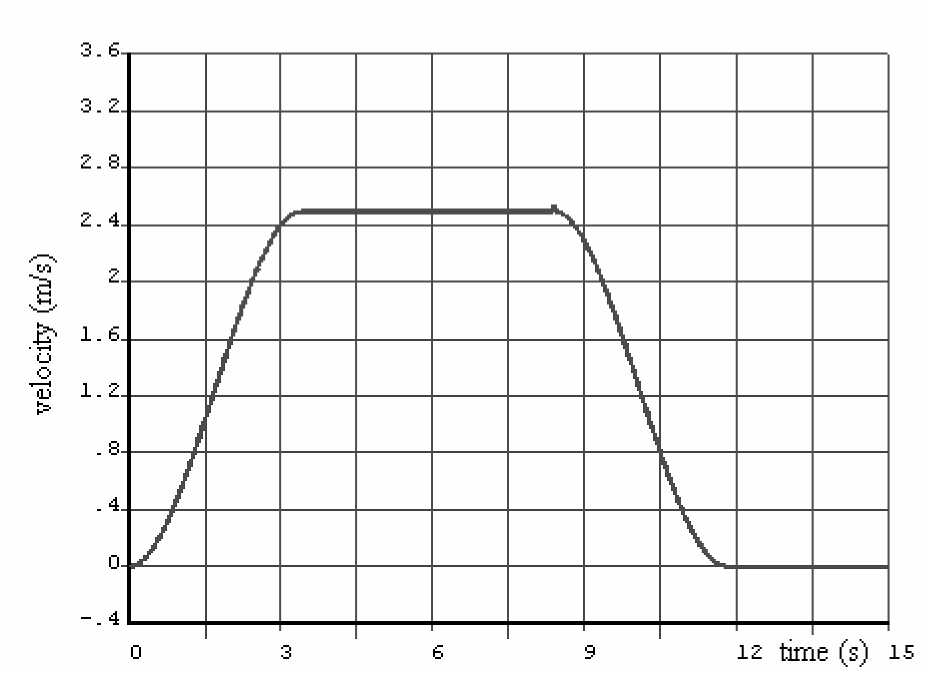


Figure 3.3. The velocity of a point of rope almost contacted to sheave

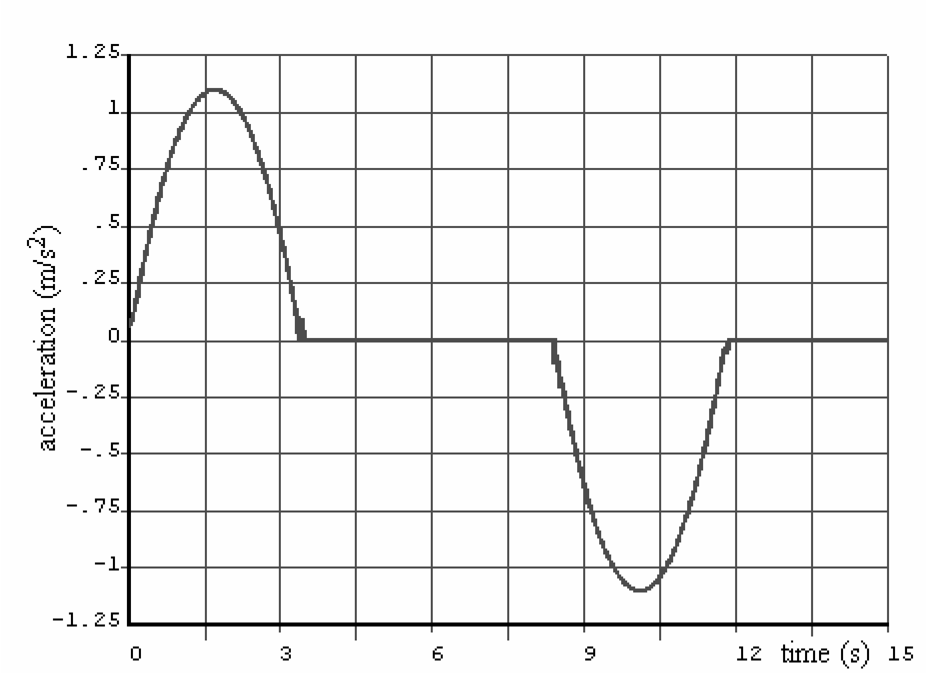


Figure 3.4. The acceleration of a point of rope almost contacted to sheave

When the plots are examined, it can be determined that the acceleration of input apllied to rope during the time interval related with the starting and stopping phase can be represented by second order polynomial functions. The critical times in that plot is 0, 3.4, 8.4, 11.8, and 15 seconds. Also, the absolute value of it is 1.11 m/s^2. Remaing numerical vaules are based on the aforementioned data.

3.2. Elevators with Roping Ratio 1:1

The architectural plan of an elevator with roping ratio 1:1 is shown in Figure 3.5. This plan is used to determine the rope length in various floors in order to calculate the required stiffness properties. The rope lengths L_i for different positions of an elevator car are illustrated in Figure 3.6 and given in Table 3.3.

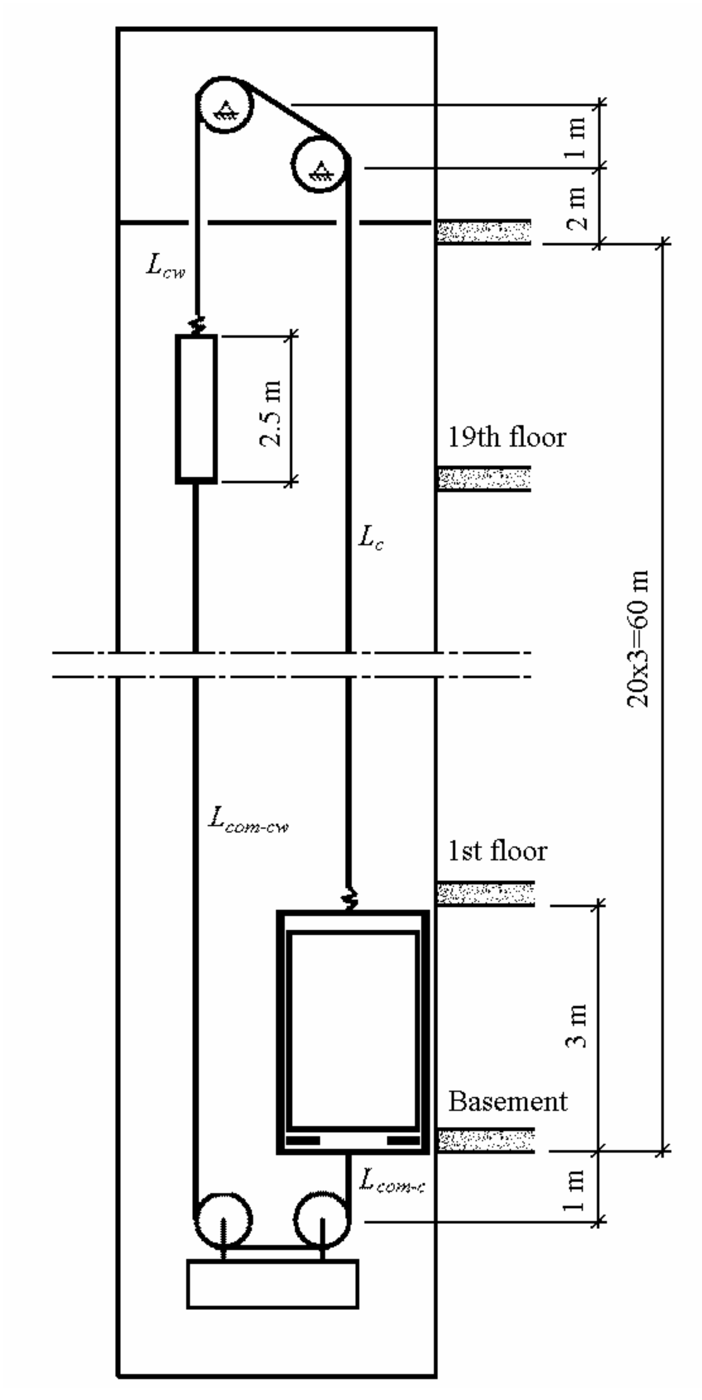


Figure 3.5. The elevator model with roping ratio 1:1 in hoistway

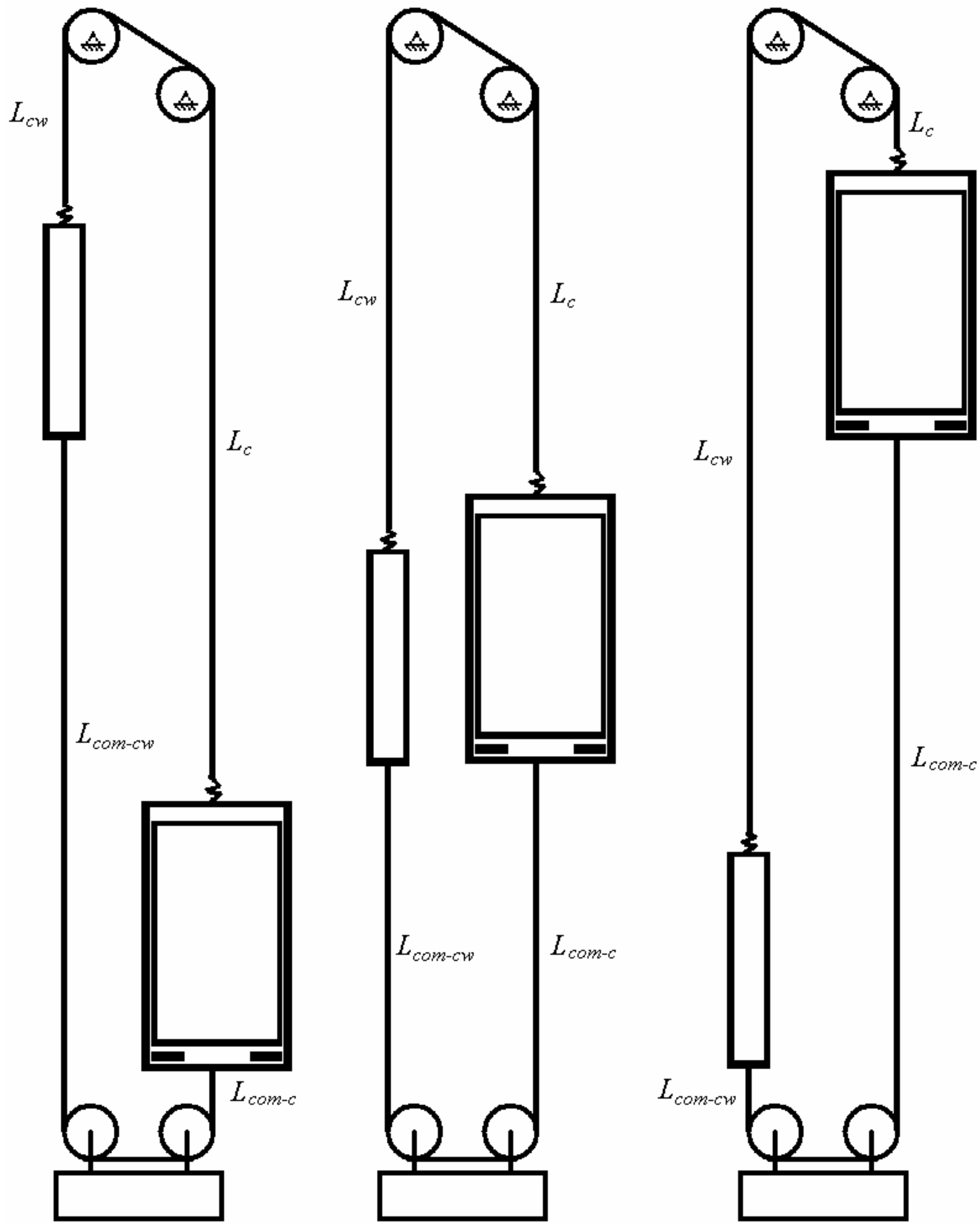


Figure 3.6. The rope lengths of elevator model while car in different positions

Table 3.3.The rope lengths while car in different positions (m)

Position of car	L_c	L_{cw}	L_{com-c}	L_{com-cw}
First floor	59	3.5	1	58
Tenth floor	29	33.5	31	31
Nineteenth floor	2	60.5	58	1

In order to develop the computer codes for different elevator models by using APDL in ANSYS, spring-mass systems are illustrated in Figure 3.7. In the present study, main interest is focused to the motion of car cabinet. Therefore, only the car side of the elevator system is considered. As an input to system, the displacement function which is plotted in Figure 3.2 is used.

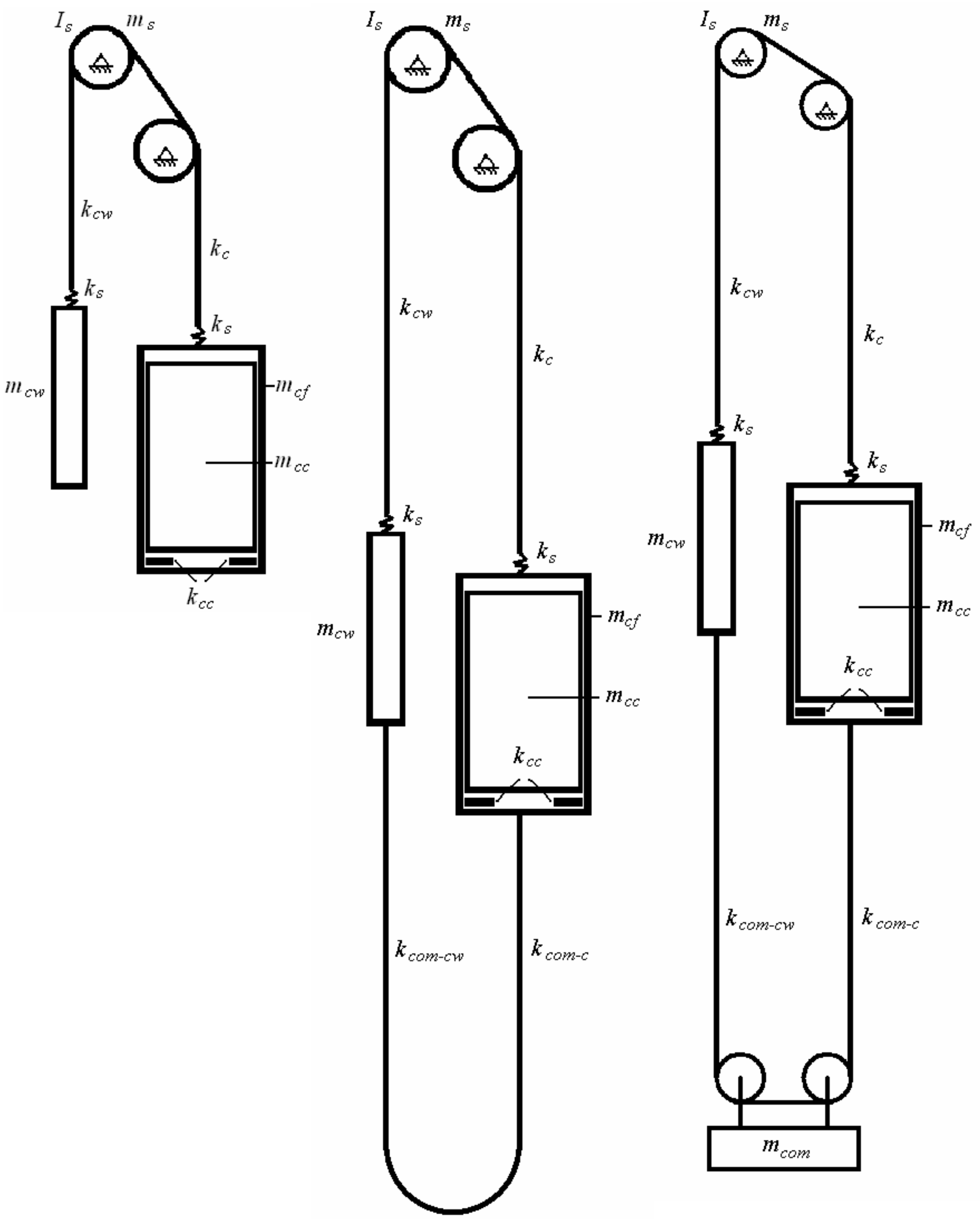


Figure 3.7. The elevator models with roping ration 1:1 and parameters

In this section, numerical results obtained for the general model shown in the right side of the Figure 3.7 is presented. As seen from the Figure 3.7 that, general model has compensation rope and mass. The first natural frequencies of the system when the elevator car at different floors are given in Table 3.4.

Table 3.4. The first natural frequencies of the system with 1:1 roping ratio

Position of car	f (Hz)
First floor	1.8331101
Tenth floor	2.095055
Nineteenth floor	2.466842

When elevator car starts movement from the first floor shown in Figure 3.5, the displacement of car components due to the input plotted in Figure 3.2 is found from the developed APDL code in ANSYS and shown in Figure 3.8. Due to the passengers in the car cabinet, acceleration of car is critical. Therefore, acceleration of car cabinet for the same time interval is plotted in Figure 3.9. Figure 3.9 can be compared with Figure 3.4 which is the acceleration of the input applied to rope region very close to traction sheave.

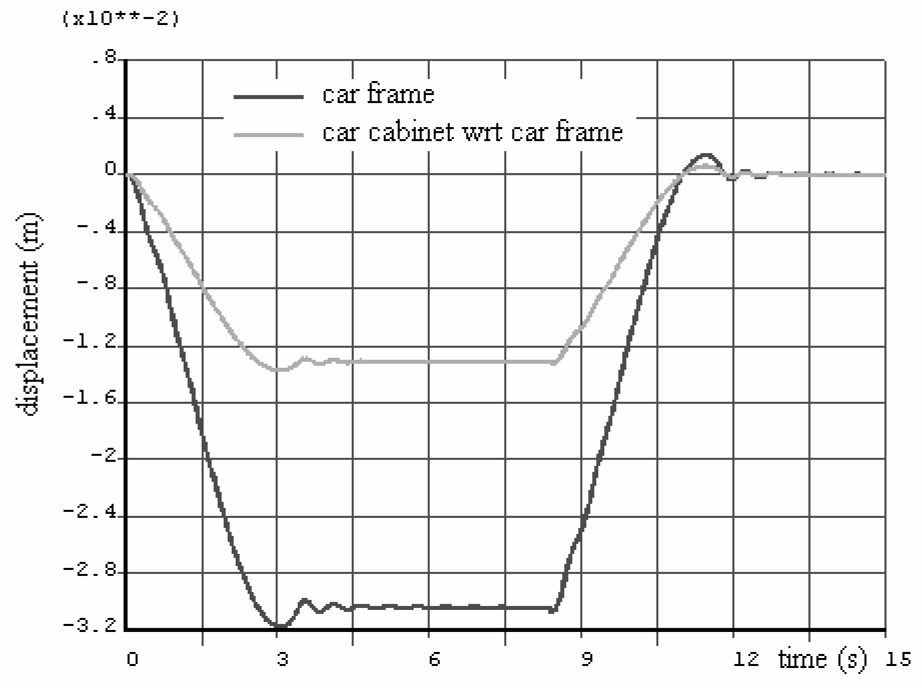


Figure 3.8. Displacement of car components when car starts from first floor

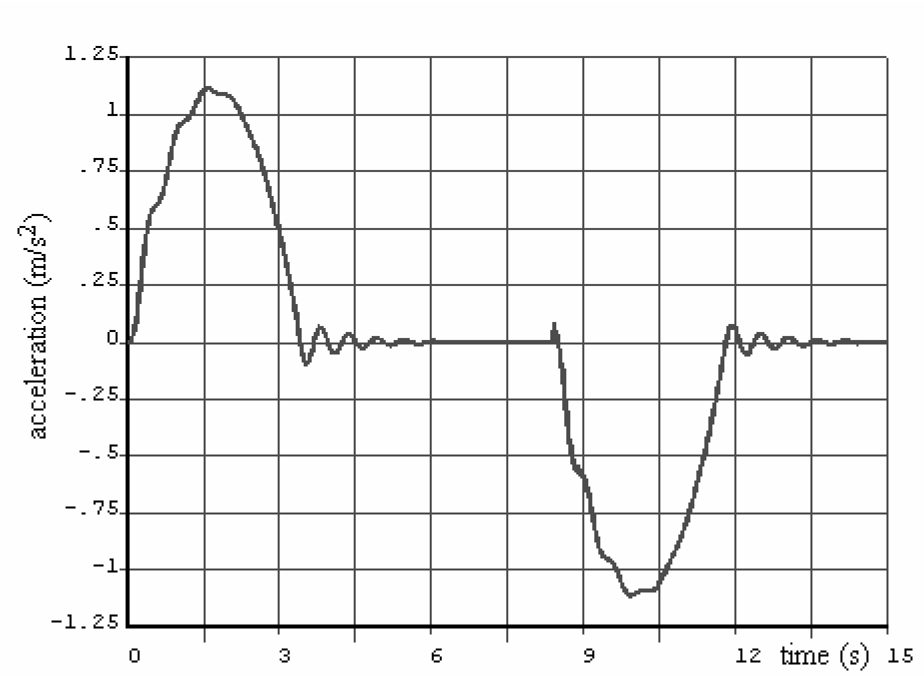


Figure 3.9. Acceleration of car cabinet when car starts from first floor

On the other hand, compensation mass is also effective on the eliminating unwanted motion of the compensation rope due to the acceleration of the system. Because of this reason, displacement of compensation mass when car starts movement from first floor is found and plotted in Figure 3.10.

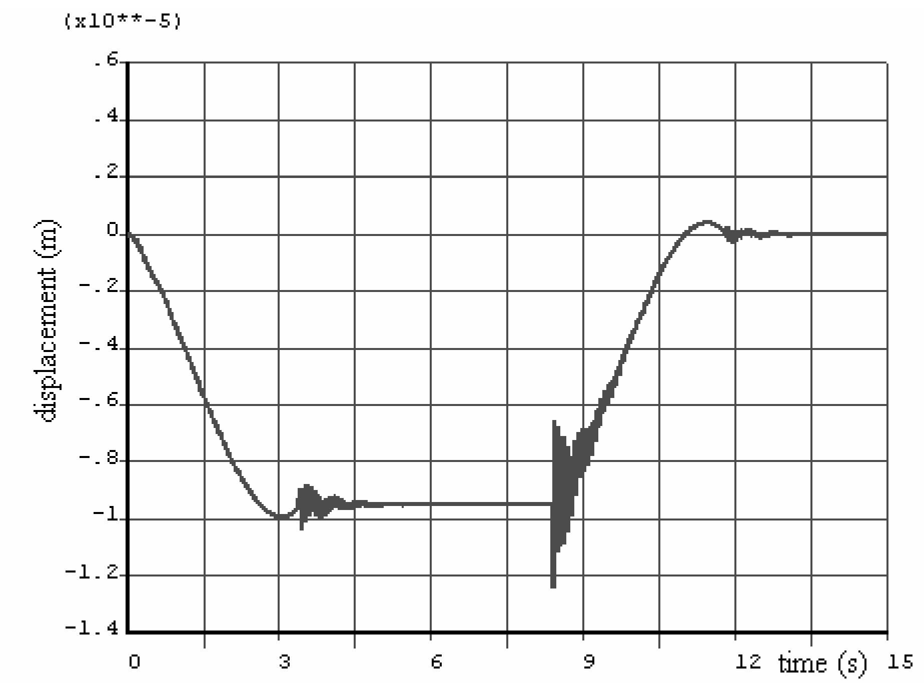


Figure 3.10. Displacement of compensation mass when car starts from first floor

Similar to studies based on the movement of the elevator car from first floor, two more cases are accomplished. They are related with the movement of elevator car from tenth and nineteenth floors. Figures 3.11-3.13 shows the results for tenth floor. Also, Figures 3.14-3.16 shows the results for nineteenth floor.

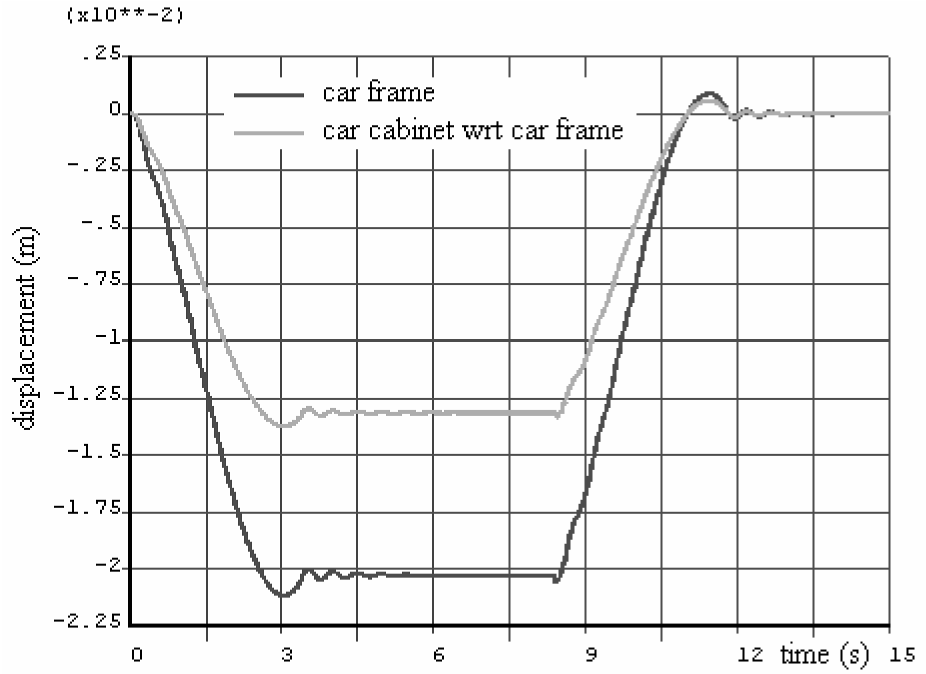


Figure 3.11. Displacement of car components when car starts from tenth floor

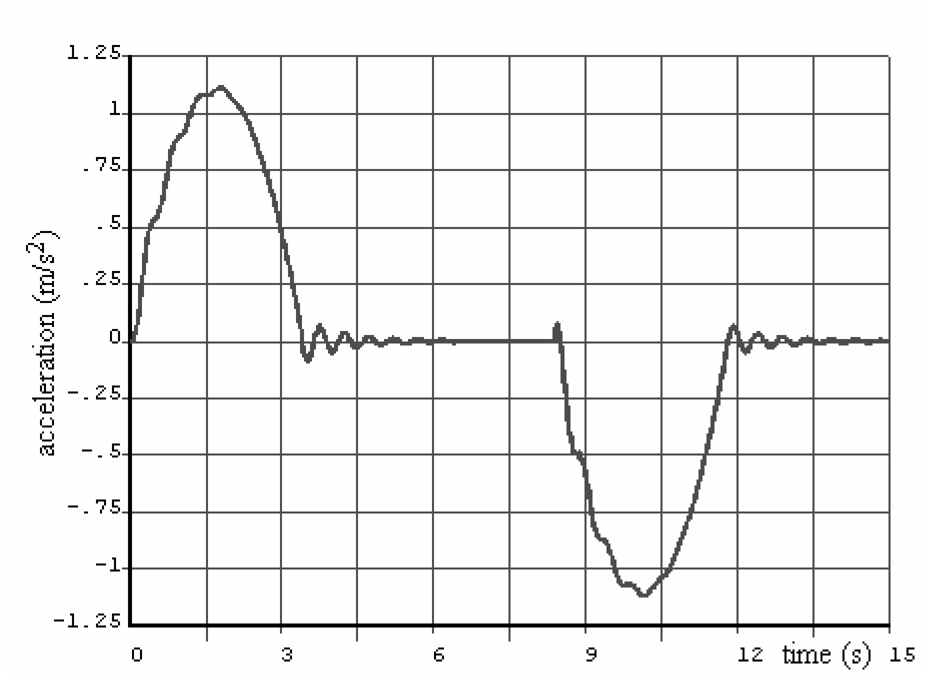


Figure 3.12. Acceleration of car cabinet when car starts from tenth floor

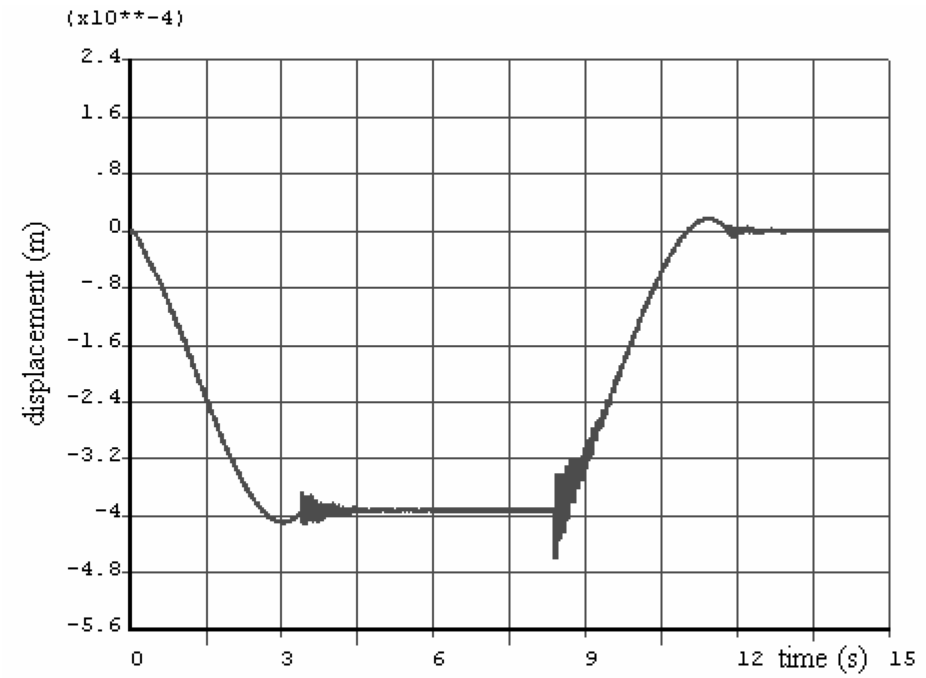


Figure 3.13. Displacement of compensation mass when car starts from tenth floor

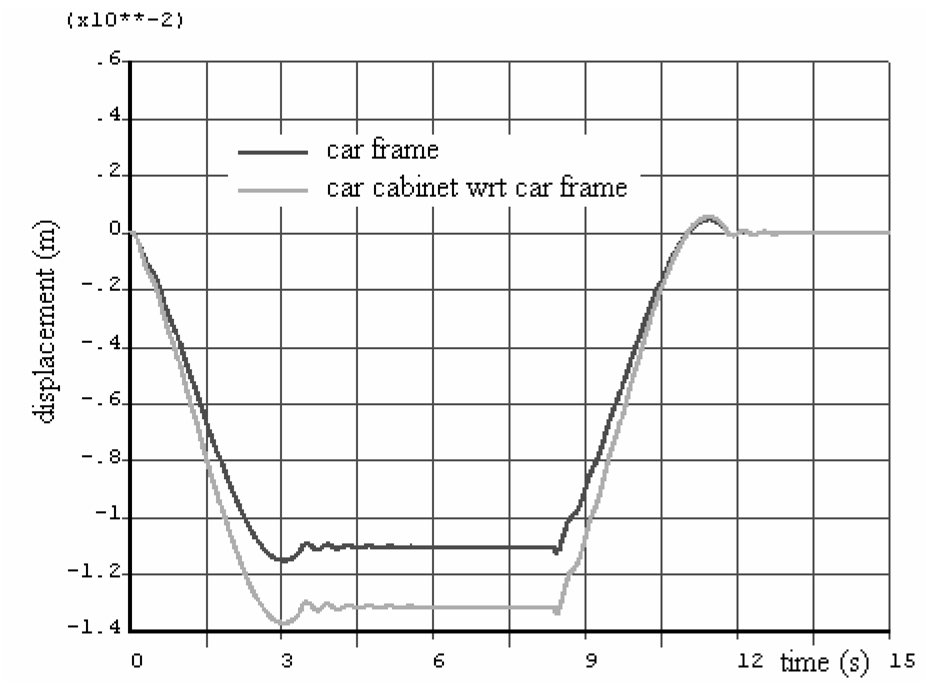


Figure 3.14. Displacement of car components when car starts from nineteenth floor

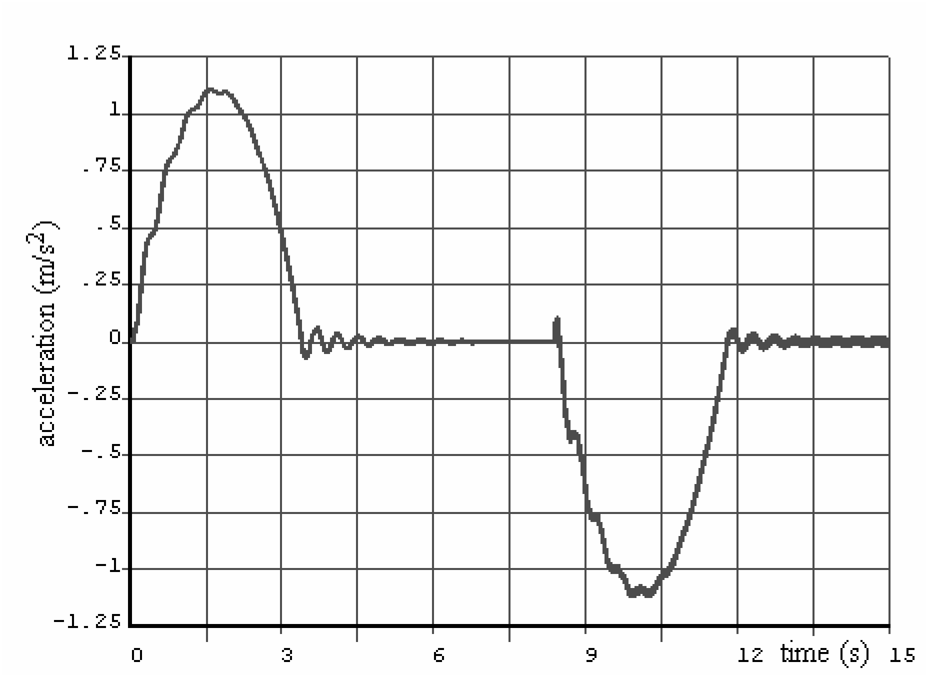


Figure 3.15. Acceleration of car cabinet when car starts from nineteenth floor

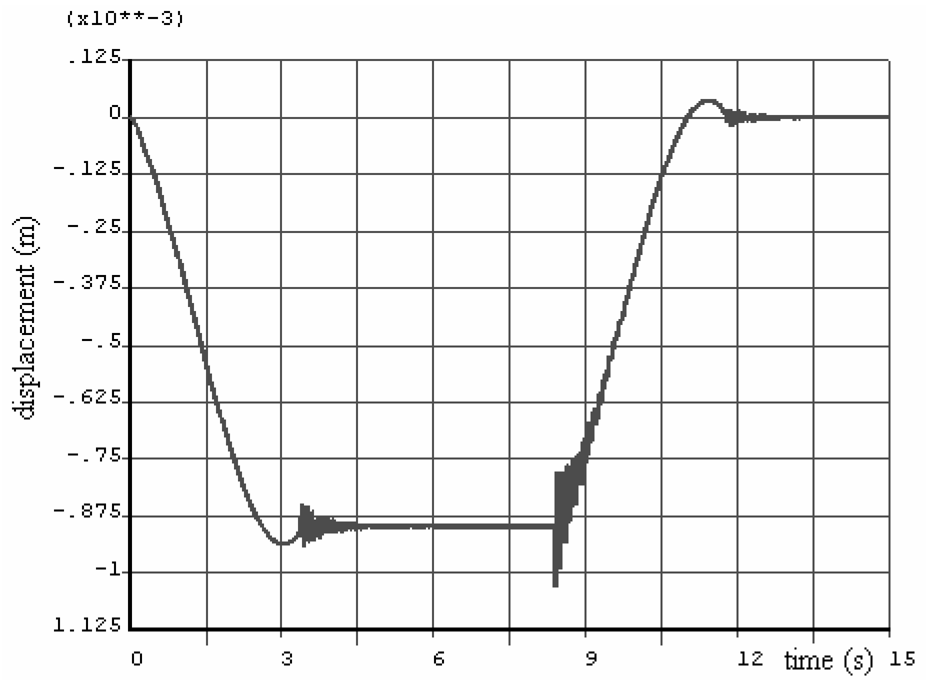


Figure 3.16. Displacement of compensation mass when car starts from nineteenth floor

3.3. Elevators with Roping Ratio 2:1

The architectural plan of an elevator with roping ratio 2:1 is shown in Figure 3.17. This plan is used to determine the rope length in various floors in order to calculate the required stiffness properties. The rope lengths L_i for different positions of an elevator car are given in Table 3.5.

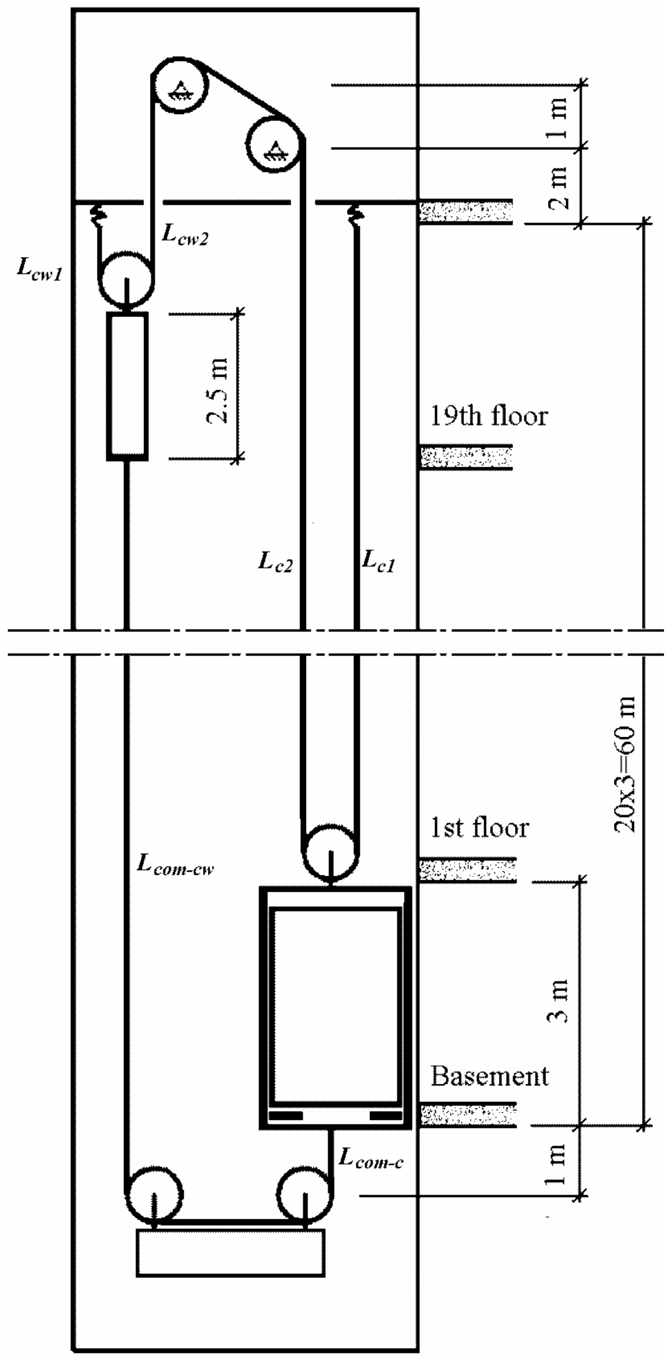


Figure 3.17. The elevator model with roping ratio 2:1 in hoistway

Table 3.5.The rope lengths while car in different positions (m)

Position of car	L_{c1}	L_{c2}	L_{cw1}	L_{cw2}	$L_{com\text{-}c}$	$L_{com\text{-}cw}$
First floor	57	59	0.5	3.5	1	58
Tenth floor	27	29	30.5	33.5	31	31
Nineteenth floor	1	2	57.5	60.5	58	1

The spring-mass systems for 2:1 roping ratio are illustrated in Figures 3.18 and 3.19. The same approach presented in Section 3.2 is used here again.

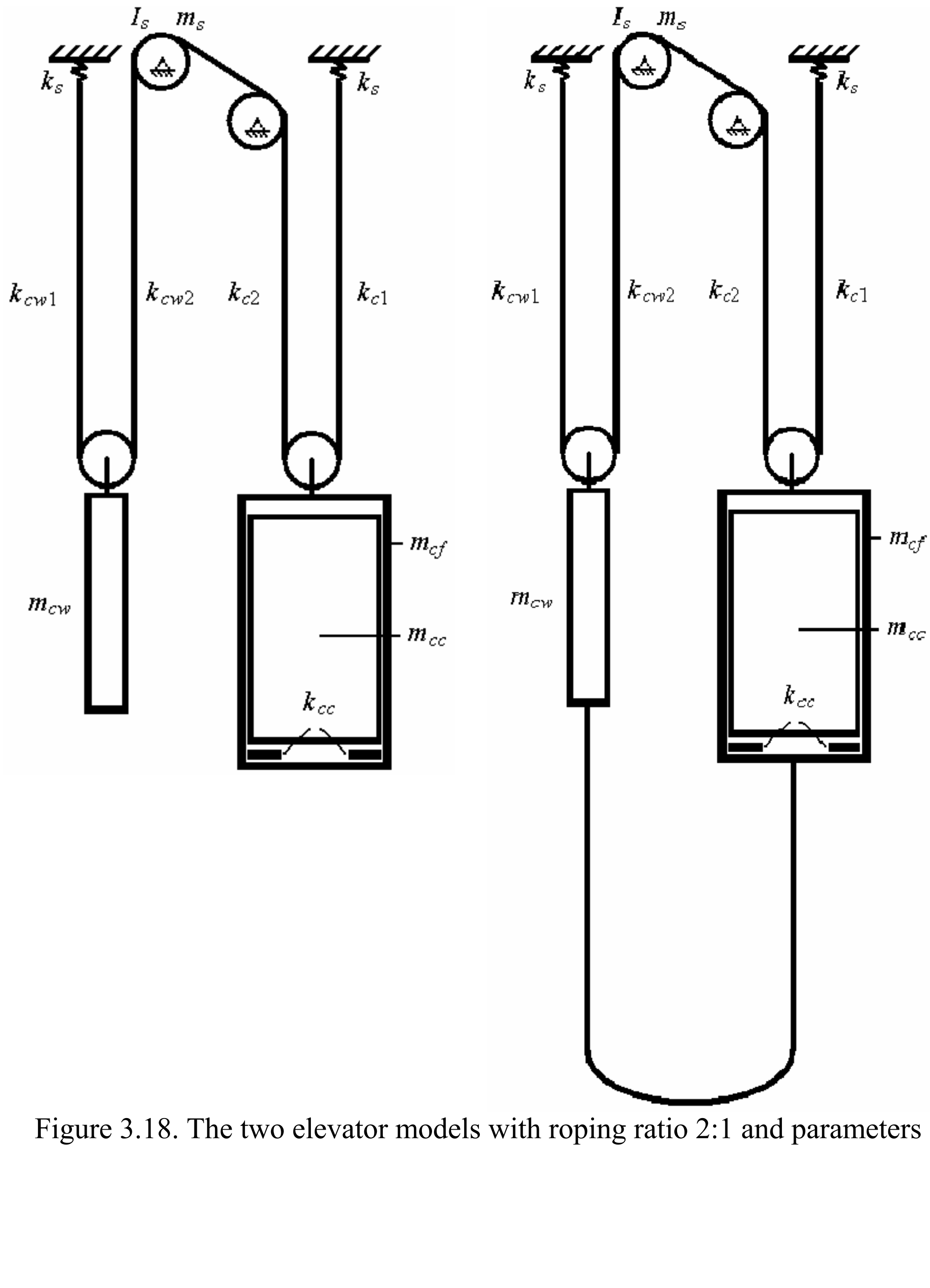


Figure 3.18. The two elevator models with roping ratio 2:1 and parameters

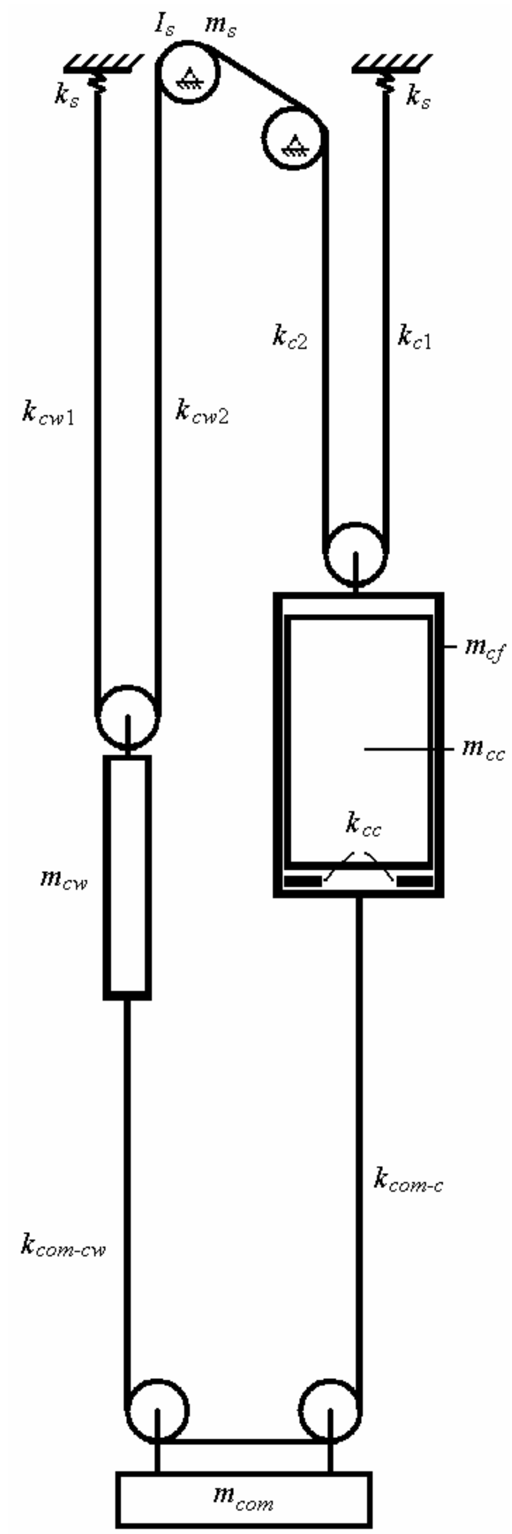


Figure 3.19. The general elevator models with roping ratio 2:1 and parameters

The first natural frequency of the system when the elevator car at different floors are given in Table 3.6. The results related with the movement of elevator car movement from first, tenth, and nineteenth floors are given in Figures 3.20-3.28.

Table 3.6. The first natural frequencies of the system with 2:1 roping ratio

Position of car	First floor	Tenth floor	Nineteenth floor
f (Hz)	2.411780	2.722962	3.250752

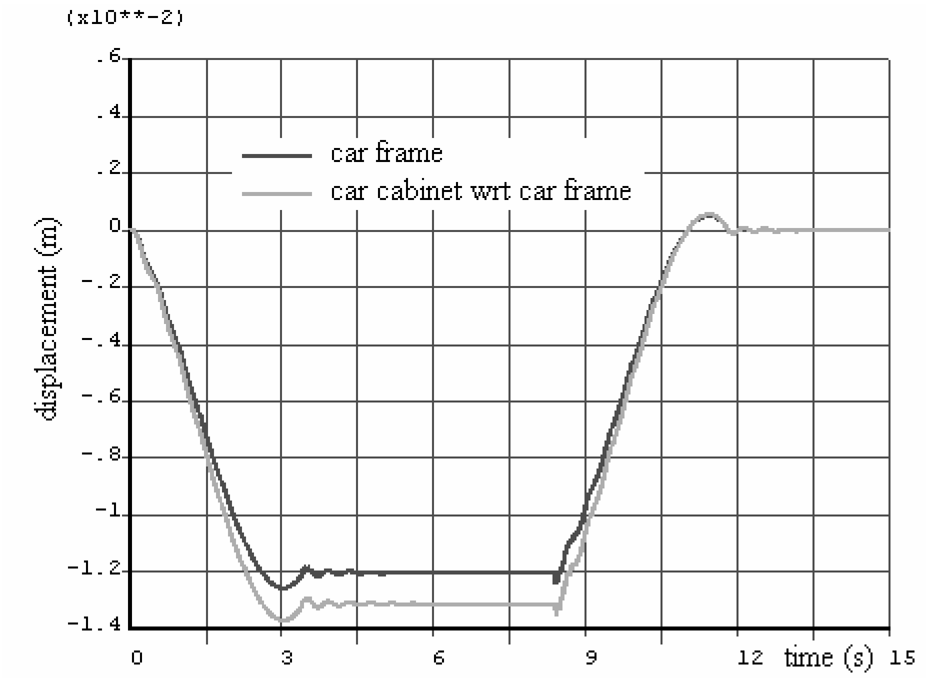


Figure 3.20. Displacement of car components when car starts from first floor

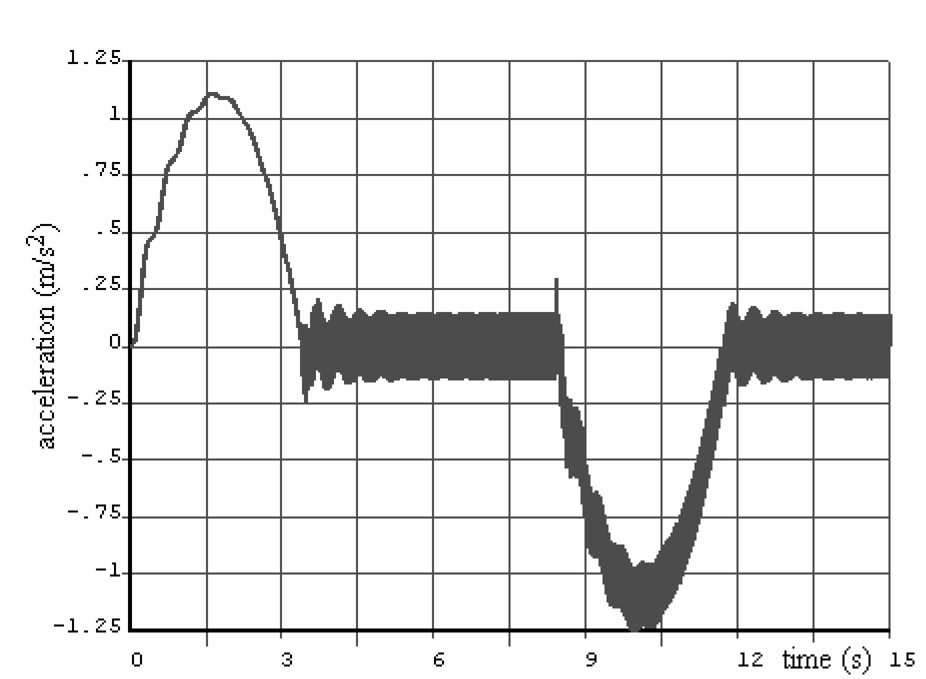


Figure 3.21. Acceleration of car cabinet when car starts from first floor

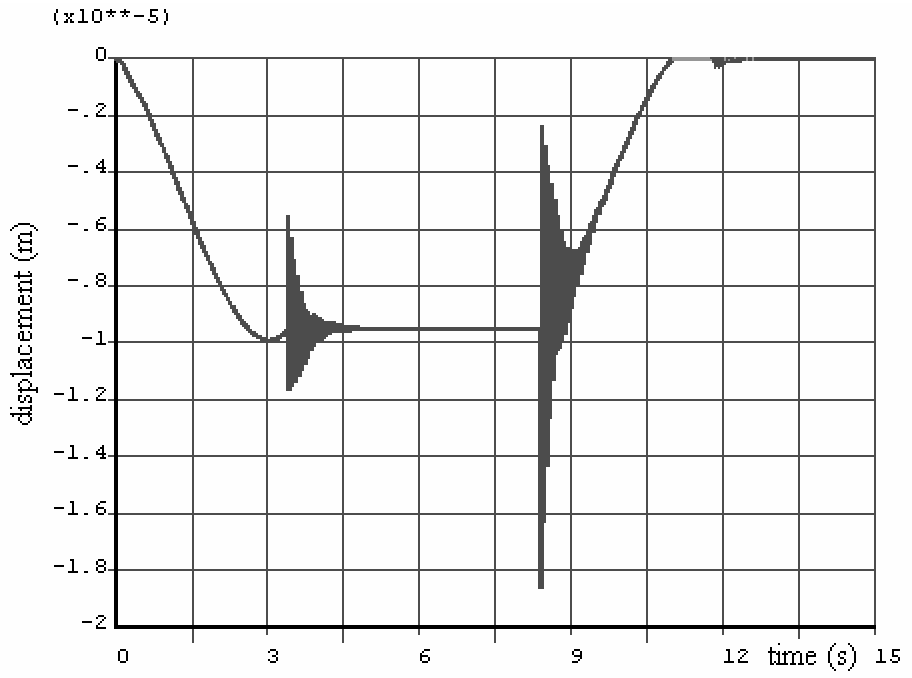


Figure 3.22. Displacement of compensation mass when car starts from first floor

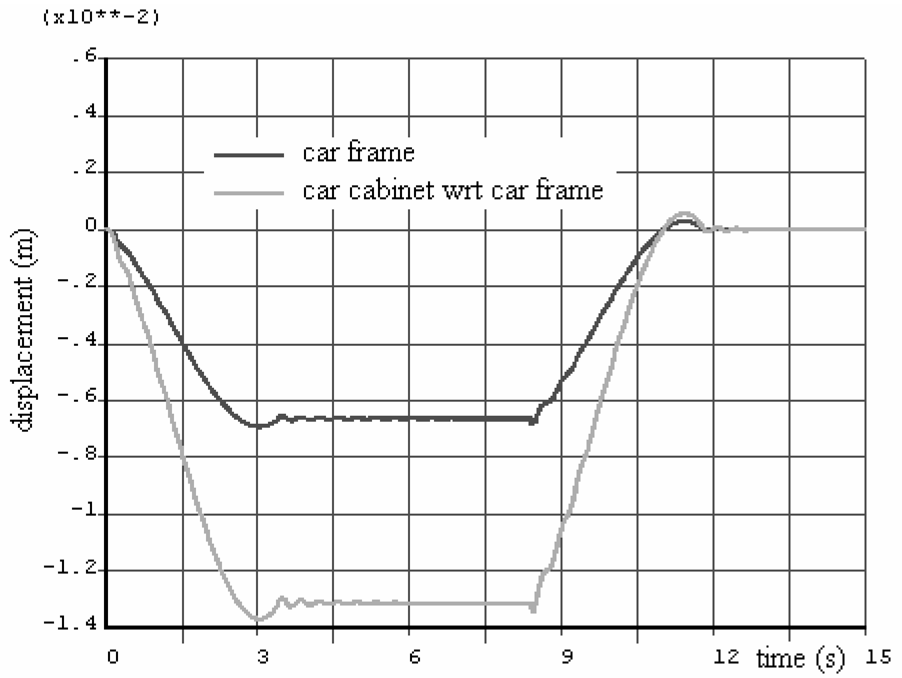


Figure 3.23. Displacement of car components when car starts from tenth floor

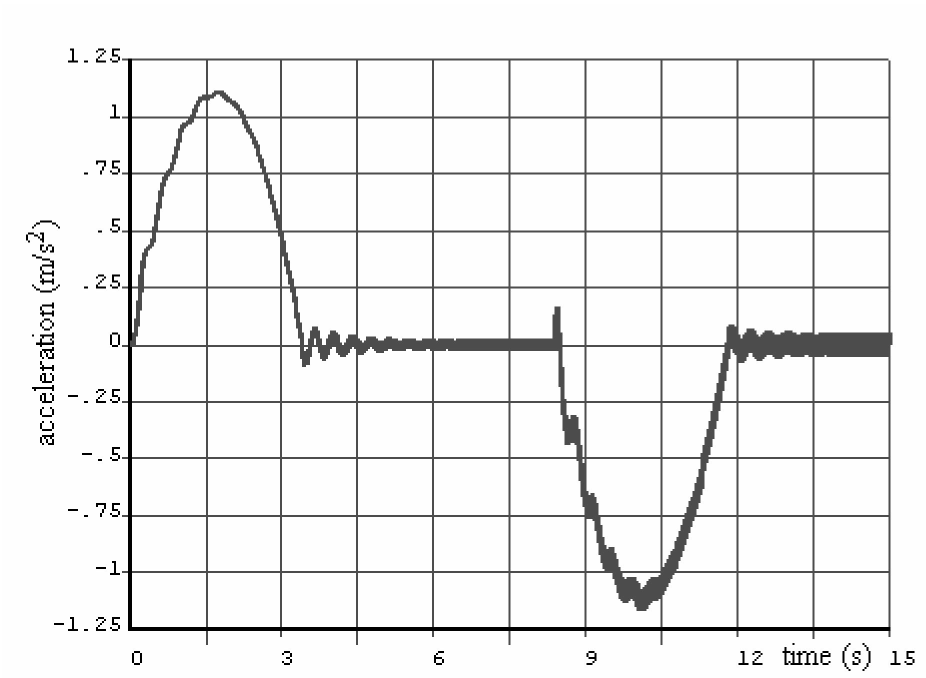


Figure 3.24. Acceleration of car cabinet when car starts from tenth floor

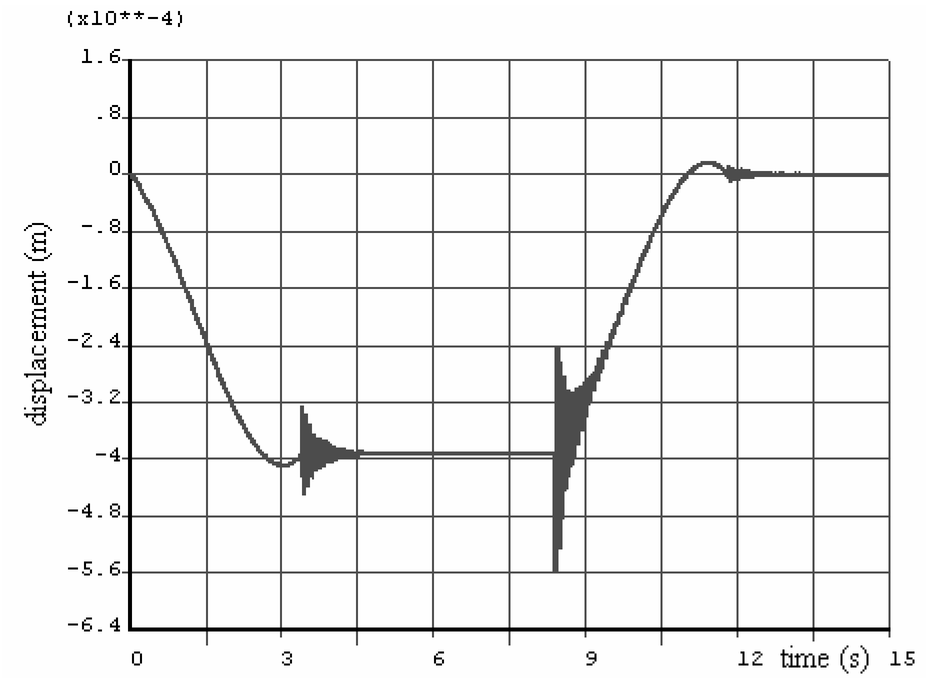


Figure 3.25. Displacement of compensation mass when car starts from tenth floor

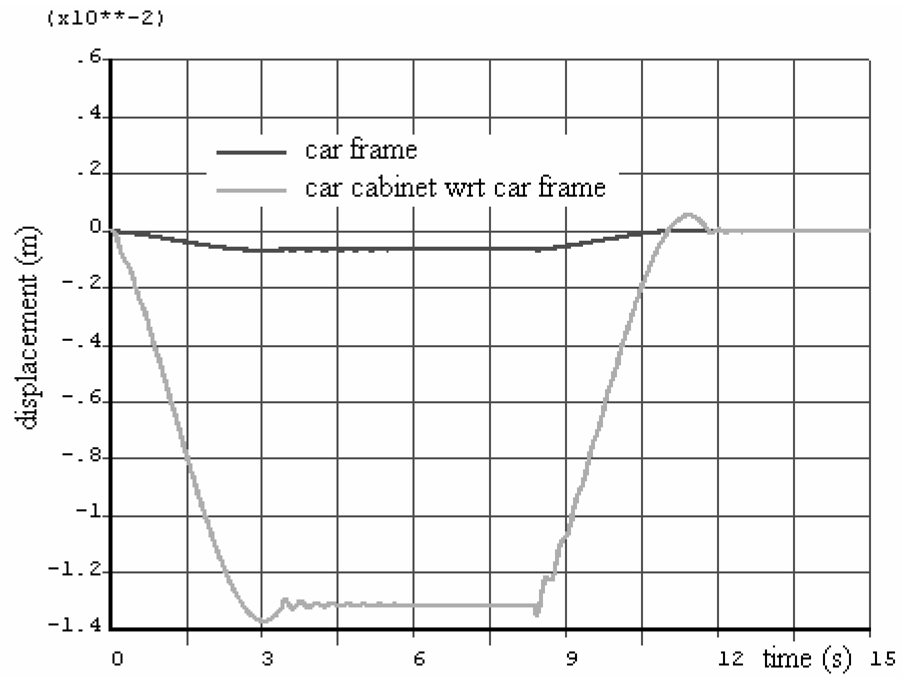


Figure 3.26. Displacement of car components when car starts from nineteenth floor

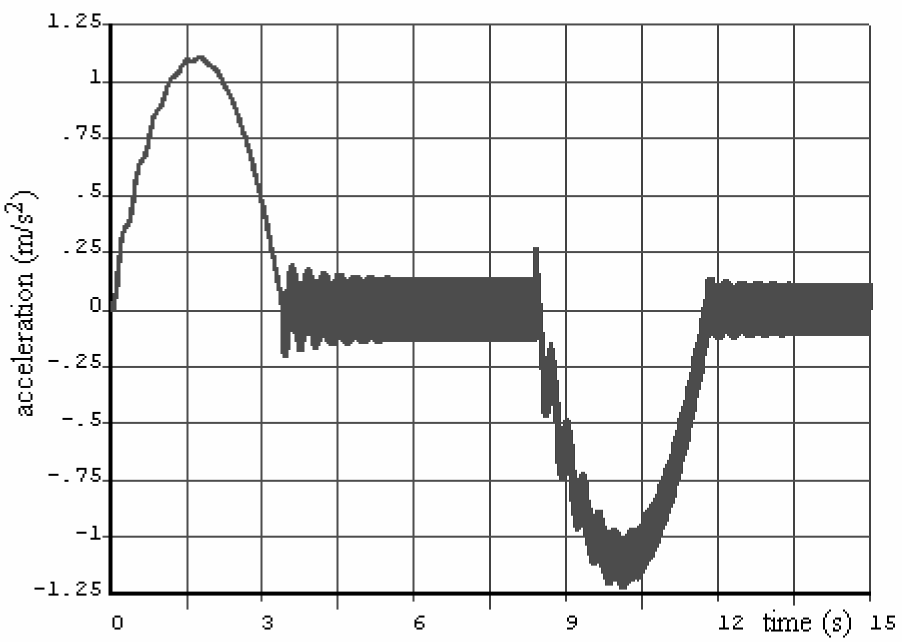


Figure 3.27. Acceleration of car cabinet when car starts from nineteenth floor

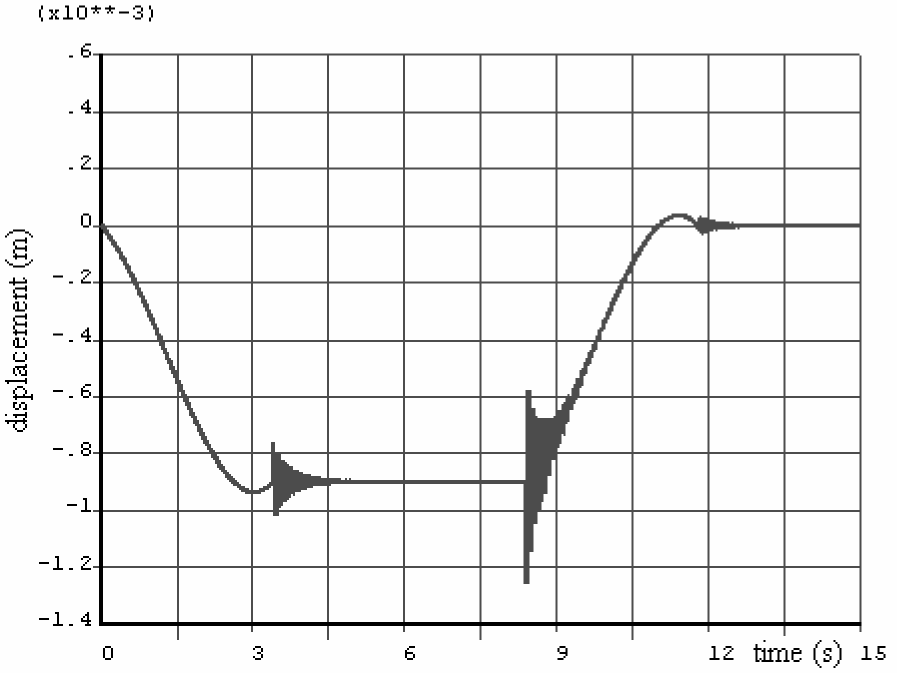


Figure 3.28. Displacement of compensation mass when car starts from nineteenth floor

3.4. Discussions of Results

First natural frequency for 1:1 roping ratio is increased from 1.833 Hz to 2.467 Hz during the travel from first to nineteenth floor. Similarly, for 2:1 roping ratio it is increased from 2.412 Hz to 3.251 Hz.

When the plots given for 1:1 roping ratio are analyzed for the car cabinet maximum displacement with respect to car frame during the travel from first to nineteenth floor, it is increased from 0.01035 m to 0.0138 m. Similarly, for 2:1 roping ratio it is increased from 0.0136 m to 0.0139 m.

On the other hand, the acceleration of car cabinet with respect to input acceleration applied to rope at the traction sheave is about 0.08 m/s^2 for all types of elevator model considered. The jerk of input reduces linearly from 1.29 m/s^3 to -1.29 m/s^3 during the first 3.4 seconds. If human body resonance frequencies are compared with the present results, no critical situation is exist.

CHAPTER 4

CONCLUSIONS

In this study, the car-passenger subsystem modeled by Herrera et al (2010) and the most common type analyzed by Chen et al (2014) are combined to see the rope effect on the riding comfort. Three elevator models with 1:1 and 2:1 roping ratio have been investigated by using APDL code which is developed in ANSYS. Each model has been considered at various floors so effect of rope length has been investigated. This study is focused on starting, traveling, and stopping durations. Displacements of elevator components, especially car cabinet, are determined. Also, accelerations of car cabinet are examined. Therefore, for the considered models base on the selected data, time responses due to the displacement excitation applied to rope are obtained.

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