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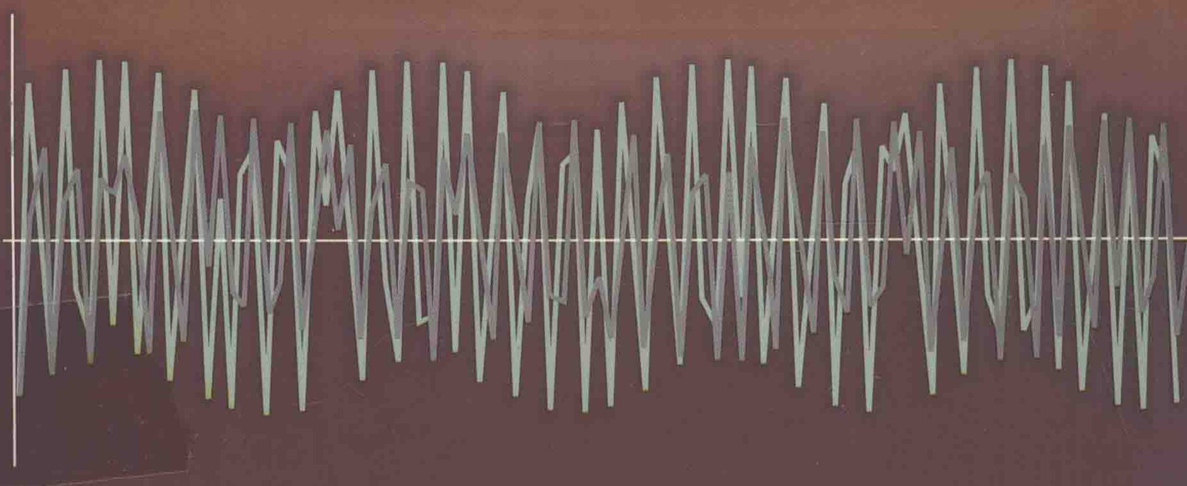
Mechanical Vibrations and Industrial Noise Control



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Mechanical Vibrations and Industrial Noise Control

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Delhi-110092
2014

₹ 525.00

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ISBN-978-81-203-4779-3

Published by Asoke K. Ghosh, PHI Learning Private Limited, Rimjhim House, 111, Patparganj Industrial Estate, Delhi-110092 and Printed by Mohan Makhijani at Rekha Printers Private Limited, New Delhi-110020.

Preface

This book is an outgrowth of my teaching experience. It is written for undergraduate students of mechanical engineering. Besides, it would also be useful to the postgraduate students of mechanical engineering. It comprehensively covers the topics prescribed in the syllabi of different universities/institutes. The course contents have been organized in such a way that the general requirements of the students are fulfilled. Having observed that the students face difficulty in understanding clearly the basic principles, fundamental concepts and theory without a proper explanation of the topics, a conscious effort has been made to stress the points where students generally make mistake. A lucid pattern, both in terms of language and content, has been adopted throughout the book.

The book is divided into 14 chapters. Chapter 1 is on introduction to vibration. Chapters 2–4 deal with undamped and damped free vibrations and harmonically excited vibration of single-degree-of-freedom systems. Chapter 5 discusses the vibration measuring instruments and support excitation. Chapters 6–7 describe the two- and multidegree-of-freedom systems. Chapter 8 explains the torsional vibrations. Chapters 9–10 are devoted to the vibration analysis of continuous system and approximate numerical methods of the multidegree-of-freedom systems. Chapters 11–13 cover the nonlinear and self-excited vibrations, random vibration and vibration under general forcing conditions. The last Chapter 14 discusses the characteristics, effects and control of industrial noise. Besides, an appendix on convolution integral is also given at the end.

The text is supported by a large number of solved examples to illustrate the concepts discussed. At the end of each chapter, practice questions are given to reinforce the student's understanding of the subject matter.

I am much indebted to my colleagues and professors of other engineering colleges of Kerala who gave valuable suggestions and insight in writing this book. My special thanks to Dr. A. Samson, Professor, College of Engineering, Trivandrum who gave valuable guidance in preparing this book. I am also thankful to Professor J. Benjamin (retired Professor of TKM Engineering College, Kollam) whose continuous encouragement and support helped me a lot in writing this manuscript. I am very much thankful to Mrs. K.V. Shiji, Head of Applied Science

Department and M.C. Jayan, Assistant Professor, Department of Mechanical Engineering, College of Engineering, Adoor who helped me for the preparation of the appendix.

Though much care has been taken to present an error-free text, however, any further comments and suggestions for improvement of the book would be appreciated.

Lasithan L.G.

Contents

1

Introduction to Vibration

A motion which repeats itself after a certain interval of time may be called a vibration. It is the motion of a particle or a body or a system of connected bodies displaced from a position of equilibrium. Vibration occurs when a system is displaced from a position of stable equilibrium. The system tends to return to this equilibrium position under the action of restoring forces. A system is a combination of elements intended to act together to accomplish an objective. It is of two types:

1. Static system
2. Dynamic system

A static system contains only static elements, i.e. there is no moving element, while a dynamic system contains at least one dynamic element. Vibration is associated with dynamic systems. A physical system undergoing a time-varying change or dissipation of energy among or within its elementary storage or dissipative devices is said to be in a dynamic state. A dynamic system composed of a finite number of storage elements is said to be a discrete system, while a system containing elements, which are dense in physical space, is called continuous. The analytical description of the dynamics of the discrete case is a set of ordinary differential equations, while for the continuous case it is a set of partial differential equations. The analytical formulation of a dynamic system depends on the kinematic or geometric constraints and the physical laws governing the behaviour of the system.

The root causes of vibration are:

- External excitations
- Unbalanced forces in the machine
- Dry friction between two mating surfaces
- Earthquakes
- Winds

The effect of vibration are excessive stresses, undesirable noise, looseness of part and partial or complete failure of parts. In spite of these harmful effects, the vibration phenomenon does some uses also, e.g. in musical instruments, vibrating screens, shakers, stress relieving, etc.

Elimination or reduction of the undesirable vibrations can be obtained by one or more of the following methods:

- Removing the causes of vibrations
- Putting the screens if noise is the objection
- Placing the machinery on proper type of isolators
- Shock absorbers
- Dynamic vibration absorbers

1.1 DEFINITIONS AND TERMINOLOGY

The following terms are used in the text.

Periodic Motion

A motion which repeats itself after an equal interval of time.

Time Period

Time taken to complete one cycle is the time period. Generally, time is measured in seconds. It is denoted by T or t_p.

Frequency

Frequency is the number of cycles per unit time. Generally, the unit time is taken as one second, and, hence, frequency is the cycles per second (cps).

$$1 \text{ cps} = 1 \text{ Hz}.$$

Cycle

Cycle is the motion completed during one time period.

Amplitude

Amplitude is the distance between the mean position and the extreme position of a vibrating body. It is the maximum displacement of a vibrating body from the mean position, as shown in Figure 1.1.

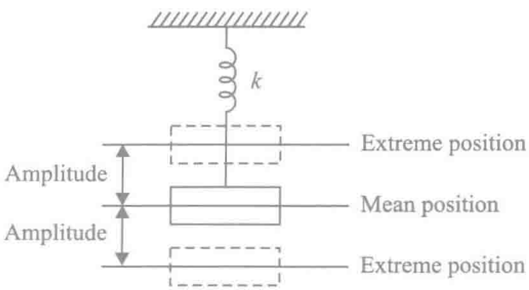

Figure 1.1 Amplitude.

Natural Frequency

When no external force acts on a body after giving it an initial displacement, then the body is said to be under free or natural vibration. The frequency of free vibration is called natural frequency. It is expressed in rad/s or hertz (Hz).

Resonance

When the frequency of excitation is equal to the natural frequency of a system, a state of resonance is said to have been reached. At resonance, the amplitude of vibration is excessively large.

Degrees of Freedom

The number of independent coordinates required to describe the motion of a system is called degrees of freedom (DF). A system is said to be *n*-degree-of-freedom system, if it needs *n* independent coordinates to specify completely the configuration of the system at any instant.

The simple pendulum shown in Figure 1.2 represents a single-degree-of-freedom system.

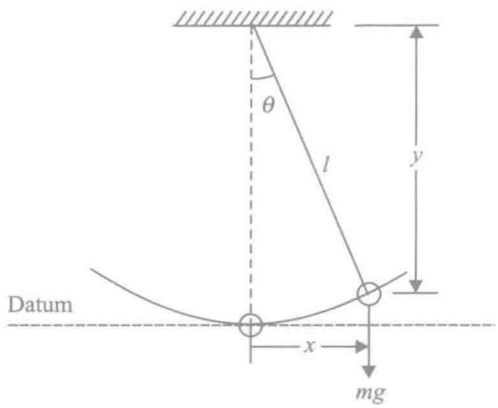

Figure 1.2 Simple pendulum.

The motion of the simple pendulum can be stated either in terms of the angle θ or in terms of the cartesian coordinates x and y. If the coordinates x and y are used to describe the motion, it must be recognized that these coordinates are not independent. They are related to each other through the relation $x^2 + y^2 = l^2$, where l is the constant length of the pendulum. Thus any one coordinate can describe the motion of the pendulum. In this example we find that the choice of angle θ as the independent coordinate will be more convenient than the choice of x or y. For the spring mass system shown in Figure 1.3, the linear coordinate x can be used to specify the motion. For the torsional system shown in Figure 1.4, the angular coordinate θ can be used to describe the motion.

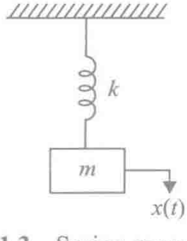

Figure 1.3 Spring mass system.

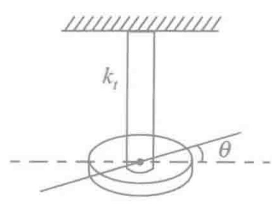

Figure 1.4 Torsional system.

Some examples of two and three degrees of freedom systems are shown in Figures 1.5 and 1.6.

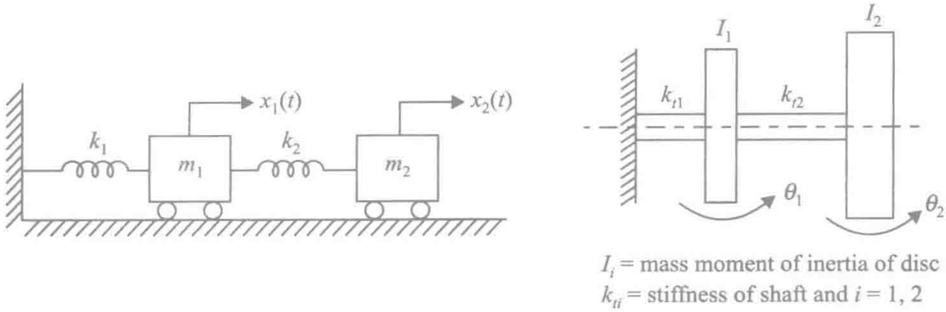

Figure 1.5 Two degrees of freedom systems.

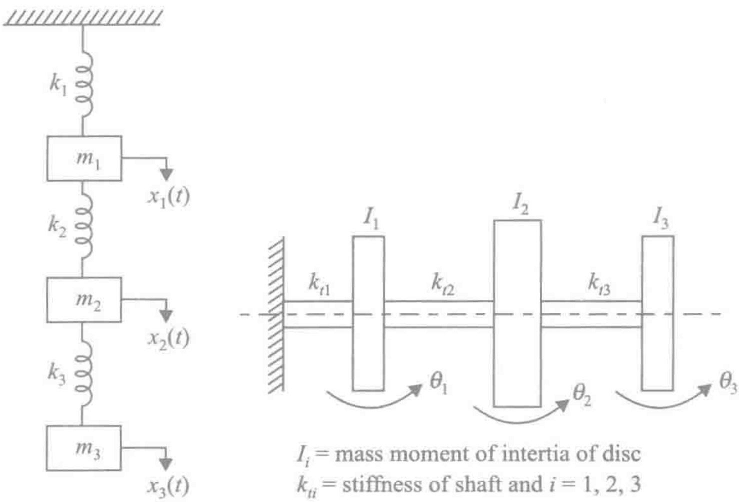

Figure 1.6 Three degrees of freedom systems.

Figure 1.5 shows a two-mass, two spring system and a torsional system that is described by the two linear coordinates x_1 and x_2 and angular coordinates θ_1 and θ_2.

Figure 1.6 shows a three-mass, three-spring system and a torsional system that is described by the three linear coordinates x_1, x_2 and x_3 and angular coordinates θ_1, θ_2 and θ_3.

On the other hand, a spring supported rigid mass which can move in the direction of the spring and can also have angular motion in one plane has two degrees of freedom (Figure 1.7).

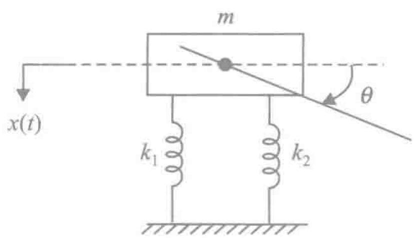

Figure 1.7 A spring-supported rigid mass with two degrees of freedom.

For the three degrees of freedom system shown in Figure 1.8, $\theta_i (i = 1, 2, 3)$ specifies the position of the masses $m_i (i = 1, 2, 3)$.

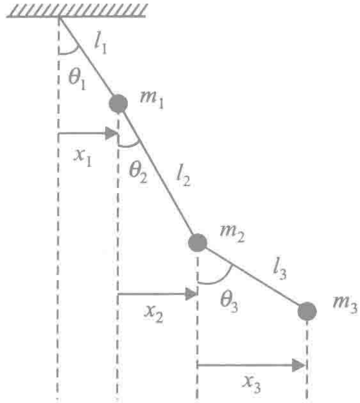

Figure 1.8 Tripple pendulum (a three degrees of freedom system).

Discrete and Continuous Systems

A large number of practical systems can be described using a finite number of degrees of freedom, such as the simple systems shown in Figures 1.2–1.8. Some systems, especially those involving continuous elastic members, have an infinite number of degrees of freedom. As a simple example, consider the cantilever beam shown in Figure 1.9.

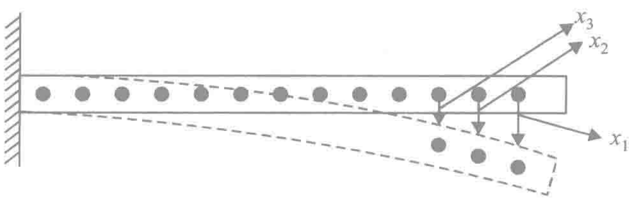

Figure 1.9 A cantilever beam (an infinite number of degrees of freedom system).

Since the beam has an infinite number of mass points, we need an infinite number of coordinates to specify its deflected configuration. The infinite number of coordinates define its elastic deflection curve. Thus, the cantilever beam is a continuous system having infinite number of degrees of freedom.

A flexible beam between two supports has an infinite number of degrees of freedom (Figure 1.10).

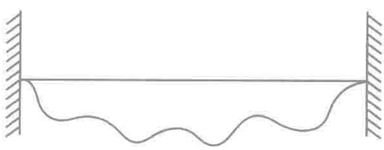

Figure 1.10 A flexible beam with infinite degrees of freedom.

Most structural and machine systems have deformable (elastic) members and, therefore, have an infinite number of degrees of freedom. Systems with a finite number of degrees of freedom are called discrete or lumped parameter systems, and those with an infinite number of degrees of freedom are called continuous or distributed systems. Details about continuous systems will be given in Chapter 9.

1.2 CLASSIFICATION OF VIBRATIONS AND VIBRATING SYSTEMS

System vibrations can be classified into three categories:

1. Free vibration
2. Forced vibration
3. Self-excited vibration.

Free vibration of a system occurs in the absence of any force where damping may or may not be present. In the absence of damping, the total mechanical energy due to the initial conditions is conserved, and the system can vibrate forever because of the continuous exchange between the kinetic and potential energy.

An external force that acts on the system causes the forced vibration. In this case, the exciting force continuously supplies energy to the system to compensate the energy dissipated by damping. Forced vibration may either be deterministic or random.

Self-excited vibration is periodic and deterministic. Under certain conditions, the equilibrium state in such a vibration system becomes unstable, and any disturbances cause the perturbations to grow until some effect limits any further growth. In the self-excited vibrations, the vibrations create periodic force that excites the vibrations themselves. If the system is prevented from vibrating, then the exciting force disappears. In contrast, in the case of forced vibrations, the exciting force is independent of the vibrations and can persist even when the system is prevented from vibrating. More details about self-excited vibrations will be given in Chapter 11.

1.2.1 Free and Forced Vibrations

If an external energy source is applied to initiate the vibrations and then removed, the resulting vibrations are called the free vibrations. In the absence of non-conservative forces, free vibrations sustain themselves and are periodic. The oscillations of a simple pendulum is an example of free vibration. Free vibrations decay when a non-conservative force is present.

If the vibrations occur during the presence of an external energy source, the vibrations are called the forced vibrations. The behaviour of a system under forced vibrations is dependent on the type of excitation. If the excitation is periodic, then the vibrations of a linear system are also periodic.

1.2.2 Linear and Nonlinear Vibrations

If the behaviour of all basic elements of a vibrating system namely the spring, the mass and the damper is linear [see Figure 1.15], then the resulting vibration is known as the linear vibration.