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# **Engineering Mechanics**

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**Statics and Dynamics**

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Kopykitab

**ENGINEERING MECHANICS: Statics and Dynamics**

C. Lakshmana Rao, J. Lakshminarasimhan, Raju Sethuraman, and Srinivasan M. Sivakumar

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# Contents

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(Note: Topics marked with asterisk (\*) are advanced topics.)

Preface

ix

## Part I STATICS

<b>1. Equilibrium of Particles and Rigid Bodies</b>	<b>1–28</b>
1.1 Introduction to Engineering Mechanics 3	
1.1.1 Engineering Design 3	
1.1.2 Mechanics in Engineering—An Overview 4	
1.2 Notion of Equilibrium—Newton’s Laws Revisited 5	
1.2.1 Newton’s Laws of Motion 5	
1.3 Types of Forces Acting on a Body 6	
1.4 Equations of Equilibrium of a Rigid Body 7	
1.5 Degrees of Freedom for a System of Rigid Bodies 11	
1.6 Constraints on Rigid Bodies and the Corresponding Reactions: Free-Body Diagram 13	
1.7 Free-Body Diagrams for Planar Systems of Rigid Bodies 16	
1.8 Application of Equilibrium Equations 19	
1.9 Summary 24	
Problems 25	
<b>2. Equilibrium of Structural Systems</b>	<b>29–89</b>
2.1 Introduction 29	
2.2 Classification of Structures 30	
2.2.1 Axial Force Members 33	
2.2.2 Trusses 37	
2.2.3 Methods of Analysis of a Determinate Truss System 42	
2.2.4 Beams 59	
2.2.5 Frames* 70	
2.2.6 Shafts 77	
2.2.7 Mechanical Levers 79	
2.2.8 Cables* 80	
2.3 Summary 85	
Problems 86	
<b>3. Energy Methods in Engineering Mechanics</b>	<b>90–110</b>
3.1 Introduction 90	
3.2 Principle of Virtual Work 91	

3.2.1	Virtual Work Statement for a Single Particle	93
3.2.2	Virtual Work Statement for a Rigid Body	93
3.2.3	Virtual Work Statement for Connected Rigid Bodies	96
3.3	Applications of Principle of Virtual Work (PVW)	101
3.4	Castigliano's Theorem*	102
3.4.1	Strain Energy in an Elastic Body	103
3.5	Summary	106
	Problems	107
<b>4.</b>	<b>Frictional Forces in Engineering Systems</b>	<b>111–128</b>
4.1	Introduction	111
4.2	Belt Friction	114
4.2.1	Equilibrium of a Belt	115
4.3	Bearing Friction	117
4.4	Wedges*	119
4.5	Rolling Friction*	123
4.6	Summary	125
	Problems	126
<b>Part II DYNAMICS</b>		
<b>5.</b>	<b>Dynamics of Particles</b>	<b>129–155</b>
5.1	Introduction	131
5.2	Basic Relations between Kinematic Quantities	131
5.3	Kinematics in Inertial Frame of Reference	132
5.3.1	Rectangular Coordinates	132
5.4	Kinematics in Moving Frame of Reference	132
5.4.1	Plane Motion in Path Coordinate System	132
5.4.2	Planar Motion Using Polar Coordinates	134
5.5	Central Force Motion*	135
5.5.1	Trajectory of a Particle Subjected to Central Force Motion	135
5.5.2	Energy Associated with Elliptical Orbit	140
5.6	Two-body Problem*	144
5.7	Lagrangian Dynamics*	145
5.7.1	Generalized Coordinates and Generalized Forces	145
5.7.2	Derivation of Lagrangian Equation	146
5.7.3	Generalization to a System of $p$ Particles	148
5.7.4	Systems with Conservative Force	148
5.7.5	Partly Conservative and Partly Non-conservative Systems	149
5.8	Summary	151
	Problems	152
<b>6.</b>	<b>Plane Kinematics of Rigid Bodies</b>	<b>156–174</b>
6.1	Introduction	156
6.2	Decomposition of the Total Motion	157
6.3	Plane Rotation about a Fixed Axis	157
6.3.1	Instantaneous Centre of Rotation	160

6.4	Motion of a Particle Relative to Rotating Axes	161
6.4.1	Relative Velocity	161
6.4.2	Absolute Velocity	162
6.4.3	Absolute Acceleration	162
6.5	Summary	169
	<i>Problems</i>	170
<b>7.</b>	<b>Kinetics of Rigid Bodies</b>	<b>175–199</b>
7.1	Introduction	175
7.2	Basic Terms and Theorems for Rigid Body Dynamics	175
7.2.1	Radius of Gyration	176
7.2.2	Transfer of Axis	176
7.2.3	Products of Inertia	178
7.2.4	Moment of Inertia of a Rigid Body about any Prescribed Axis	178
7.3	Angular Momentum of Rigid Bodies	179
7.3.1	Momentum Equations	181
7.4	Energy Relations in Rigid Bodies	183
7.4.1	Kinetic Energy	183
7.4.2	Potential Energy	184
7.4.3	Total Work	185
7.4.4	Power	185
7.5	Impulse-Momentum Equations*	185
7.6	Gyroscopic Motion—Steady Precession*	186
7.6.1	Principles of Gyroscopic Motion	186
7.6.2	Steady Precession of a Symmetric Top	188
7.6.3	A Complete Analysis of a Spinning Object	189
7.7	Summary	195
	<i>Problems</i>	196
<b>8.</b>	<b>Mechanical Vibrations</b>	<b>200–223</b>
8.1	Introduction	200
8.2	Analysis of a Single Degree of Freedom (SDOF) System	201
8.3	Undamped Free Vibrations	202
8.3.1	Perturbations about Static Equilibrium Position	203
8.4	Damped-free Vibrations	204
8.5	Forced Vibrations of Rigid Bodies	209
8.5.1	Response to Sinusoidal Loading	210
8.5.2	Undamped Forced Vibration for Sinusoidal Loading	210
8.5.3	Damped Forced Vibration with Sinusoidal Loading*	211
8.6	Forced Vibrations due to Base Motion*	214
8.7	Summary	217
	<i>Problems</i>	218
	<b>Appendix</b>	<b>225–234</b>
	<b>Answers to Problems</b>	<b>235–240</b>
	<b>Bibliography</b>	<b>241</b>
	<b>Index</b>	<b>243–247</b>

# Preface

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*Mechanics* is formally taught to all physical science and engineering students as part of their physics curriculum. Newton's laws and their application to particles as well as rigid bodies are briefly introduced in physics and the concepts are normally illustrated by application to simple masses, bars or springs. An extension of mechanics in the form of *Engineering Mechanics* is taught to the first year undergraduate students in all engineering colleges.

There seems to be a particular vision while introducing *Engineering Mechanics* as a core course for undergraduate engineering students. This vision is based on a thinking that a background to the application of principles of mechanics to practical engineering problems is necessary for any engineer. They are all concerned with designing—the civil engineer with buildings, the mechanical engineer with machines, the aerospace engineer with aeroplanes, and the electrical engineer with microcircuits housed in a protected casing. Very often, this vision gets challenged and gets replaced with an alternate vision which states that the basic mechanics as introduced in physics is more than sufficient for many engineering students, especially those who make a career only by writing programs.

The predominance of the second vision in favour of the first vision has resulted in the subject of *Engineering Mechanics* being reduced from a two-semester course to a one-semester course in most universities. While there seems to be a strong basis for all engineers from not being exposed to the details of *Engineering Mechanics*, it is also likely that those topics that got chopped off from a regular curriculum of *Engineering Mechanics* will regain prominence at some later date, especially for the core mechanics based engineering disciplines such as civil engineering, mechanical engineering, aerospace engineering, naval architecture, and chemical engineering. Such topics may be covered in these branches as advanced topics as part of a second course in Engineering Mechanics.

The reader may justifiably ask: why yet another book when there are many books on the subject available in the market and what is new in the present book? With regard to the fundamental principles behind *Engineering Mechanics*, we admit that we are not inventing new laws of physics that will require a special mention. We humbly join the voice with *Shantideva*, a Buddhist Acharya who, in his book *The Way of the Bodhisatva*, asserted:

*What I have to say has been said before.  
And I am destitute of learning and of skills with words.  
I therefore have no thought that this might be of benefit to others;  
I wrote it only to sustain my understanding.*

However, as teachers who have taught the subject of *Engineering Mechanics* for several years to undergraduate students, we did notice some deficiencies in the approach taken to the subject by other authors. We believe that our teaching and experience as engineers have given us sufficient

insight that will help us to readdress these deficiencies, even without losing the overall focus on the subject.

We now attempt to articulate the prominent features of the book.

- Since the engineering applications of mechanics should focus on the equilibrium and motion of rigid bodies, our emphasis in the entire book is to develop the mechanics of rigid bodies. We assume that the student has sufficient background on mechanics of particles from his/her exposure to physics as well as vector calculus from a study of mathematics. Hence, the application of mechanics to particles or to a system of particles is mentioned as an introduction to rigid bodies, but has not been elaborated in detail.
- The book takes care to give an overall picture of the mechanical loads as well as their effects, in the form of displacements. This overall picture, we felt, was necessary in an introductory course. For example, we believe that mention of shear force and bending moment diagrams, without addressing their usage will be incomplete. Therefore, we have attempted to give the total vision with regard to the application of a concept to the best of our ability.
- Special care has been taken to develop the concept of *free body diagram* and *degrees of freedom* for a structure in Chapters 1 and 2. This was found necessary since the concept of degree of freedom is an important concept in engineering, which is not understood with ease by a first year undergraduate student who has no exposure to engineering.
- Again, the *Principle of virtual work* is an important concept that is used in engineering, especially in analysis tools like *Finite Element Methods*. We have developed this concept from first principles and have shown the similarity between the application of this concept to a rigid body assembly and a deformable solid. The illustration of the application of energy principles for indeterminate analysis through *Castigliano's theorem* is an added feature of the book.
- While developing the equations of motion of particles in various coordinate systems, we took special care to introduce energy principles as an alternate means of formulating the same equations. Hence, we have introduced *Lagrange's equation* as an approach that can be used to derive equations of motion for multidegree of freedom systems.
- Worked-out examples on various topics have been carefully chosen to explain the engineering application of the concepts used in the example. Detailed explanations are added about the various thought processes that go behind the solution of problems, which include simple decisions like choice of coordinate frame and the implications of the same.
- Chapter 8 on mechanical vibrations is specially oriented towards the application of the concepts of vibrations to rigid body assemblies that are normally encountered in engineering. This chapter illustrates the solutions of equations of motion which were developed earlier in the book. Further, the concepts that are developed in this chapter are fundamental to any branch of engineering. Hence, we suggest that this topic be taught with some care and should never be omitted from any syllabus on *Engineering Mechanics*.

Our aim in bringing out this text is to give a new orientation to the treatment of the subject. We took a deliberate decision to restrict our attention to about ten exercise problems in each chapter. We believe that innovating a good exercise problem is as much a challenging and creative task as writing about the principles that are behind the problem. We hope that we will get an opportunity to introduce many more innovative and challenging exercise problems in further editions of the book.

In this text, we attempt to give a broad perspective of engineering mechanics, where all the important topics are explained and developed in a systematic and consistent manner. Part I (Chapters 1–4) deals with equilibrium of structures, which is broadly defined as *Statics*, while Part II (Chapters 5–8) covers motion of rigid bodies, which is popularly known as *Dynamics*. In Chapter 1, the principles of statics equilibrium of particles and rigid bodies are stated, and the same concepts are applied to specific structural systems in Chapter 2. Chapter 3 explores the use of energy relations in establishing equilibrium of rigid body systems, while Chapter 4 attempts to quantify the frictional forces that are operating in a system of rigid bodies during incipient motion. Chapter 5 derives simple relations that govern the kinematics of particles, while Chapter 6 applies the same concepts to rigid bodies and their assemblies. Chapter 7 attempts to quantify the forces that cause motion and establishes the relation between these forces and their effects, i.e. motion. Chapter 8 illustrates the solution of equations of motion for a very practical day-to-day application of mechanical vibrations.

The book has been written so that it can be used both as a textbook for a four-credit, one-semester course on engineering mechanics as well as a textbook for advanced engineering mechanics. In order to help teachers in formulating their course contents, we have indicated the advanced topics in the table of contents with an asterisk. These topics may be omitted when using this book as a textbook for teaching engineering mechanics as a four-credit course (with tutorials) over one semester. It is our belief that all the unasterisked topics should be covered, and can be covered, over one semester to first year undergraduate students so that they get an overall view of the subject. Our belief is based on our own success in implementing such a curriculum at Indian Institute of Technology Madras.

We wish to acknowledge the excellent system and the conducive environment at IIT Madras that encouraged us in writing this text. The book could not have seen the light of the day but for the timely help rendered by our students Maj. K.N. Singh, Maj. D. Pereira, G. Baskaran, Sakey Shamu, J. Kumar, P. Velu, and S. Satyanarayanan who helped us in preparing the draft of the drawings. Special thanks are due to our students Ms D. Rekha Rani, A. Rajagopal, R. Gangadharan and M. Kishore Kumar who helped us in editing the text and bringing the various chapters to a standard format. We would like to acknowledge the services of P. Parthiban, who typed the original manuscript and the excellent work done by P. Unnamalai and A. Yuvaraj in taking out several drafts of the manuscript. We would also like to place on record the patience and perseverance of all our family members who helped us in various ways during the writing of this book.

**C. Lakshmana Rao**  
**J. Lakshminarasimhan**  
**Raju Sethuraman**  
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Part I

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STATICS

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# 1

## Equilibrium of Particles and Rigid Bodies

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... *Sidhyasidhyoh Samo Bhootvaa Samatvam Yoga Uchyate.*

Being equal with respect to achievement and non-achievement, an attitude of equanimity is the discipline of (*karma*) *yoga*.

—*Bhagavadgita*

### 1.1 Introduction to Engineering Mechanics

*Engineering Mechanics* can broadly be defined as the body of knowledge that deals with the application of *mechanics* in *engineering*. We all know that mechanics is a subject in physics that deals with the motion of bodies and the forces that cause these motions. The principles of mechanics as outlined in physics text books are universal and invariant and must be applicable to any problem in engineering as well. Hence, we may wonder as to whether there is any necessity at all to deal with engineering mechanics as a separate subject in engineering education. To address the above question, it is essential that we familiarize ourselves with the science and the art of *Engineering* as it exists in practice.

#### 1.1.1 Engineering Design

*Engineering* can, in general, be defined as the practice of making structures or devices that will meet certain desired performance requirements. The creation of such devices involves the following steps:

1. Definition of performance requirements.
2. Postulation of available means and methods that will help us achieve the performance requirement.
3. Assembly or fabrication of the postulated means using well defined procedures.
4. Testing of the assembly to check if it meets the originally defined performance requirement.

Steps 1 and 2 are broadly defined as *engineering design*. Step 3 is associated with *construction* or *manufacturing*, and Step 4 is generally known as *performance appraisal*.

We can illustrate the steps in engineering through a simple example. We can, for example, state that a young person needs a method by which he/she could travel a distance of about four kilometres within 15 minutes, without causing any environmental pollution. A mechanism that can suit this requirement and is used by the masses is the simple bicycle. An experiment can be performed by a person to see if his existing bicycle can suit the given requirement, or if any special gadget like a speed enhancing gear needs to be attached to his bicycle. Of course, the person needs to do some calculations to see as to how he/she must give the required specifications of the attachment that will give the desired increase in speed.

There is thus an important phase of engineering design, where we need to predict the performance of a device. In the above example, we have to estimate the time for motion of a rider of an estimated weight, between two points of travel. Further, the motion of the rider is related to the thrust exerted by him/her on a pedal which will control the motion of the chain, which in turn further rotates the rear wheel, etc. The motion of each of these components is predictable using simple laws of motion, which we learn from elementary physics, provided we make appropriate assumptions regarding the behaviour of these bodies. For example, a simple assumption made in the analysis of the motion of components of a bicycle is that all the components are rigid bodies which do not undergo any deformation. Engineering mechanics deals with the analysis of physical systems. Such an analysis is done by using the principles of mechanics based on simple assumptions so as to obtain reasonably accurate predictions of forces or motion. Hence, we see that it is a subject that will train us to apply the familiar laws of physics to obtain the details of components and devices that we encounter in engineering.

From the foregoing discussion, we see that *Engineering Mechanics* provides the necessary tools to make performance predictions in mechanical systems. It uses realistic estimates of mechanical loads acting on a system makes simplified assumptions regarding the material and system behaviour and provides reasonable estimates of system responses—which are in the form of forces, displacements, velocities, etc.—in a mechanical system. The object is of general interest to all engineers who build or use physical components. It is of special interest to engineers who deal with mechanical loads on a day-to-day basis, such as aerospace engineers, mechanical engineers, chemical engineers, civil engineers, and naval architects.

### **1.1.2 Mechanics in Engineering—An Overview**

Most of the objects of utility that we see around in our day-to-day life can be broadly classified as *structures* and *mechanisms*. *Structures* are built assemblies which are usually relatively *immobile* and support other moving objects within their framework. Typical examples of structures are buildings, bridges, automobile frames, bookshelves, and electronic casings. A *mechanism* is an assembly of small components which are in contact with each other, and are in a state of *motion*. Examples of mechanisms are crank shaft, rotating shafts, gears, pulleys, moving car and belt drives. Engineering structures and components are designed to serve certain functional uses in day-to-day life. These functional uses may depend on the ability of the components to endure the influence of external environment for a reasonable period of time. The external environment acting on a component may be in the form of mechanical loads, thermal loads, electromagnetic interactions, chemical interactions, etc. The component responds to these external agencies through motion, generally in the form of change in the geometry of the component.

A geometric change, usually a very small change caused on the particles of a body, is technically termed as *deformation* experienced by the body. While deformations are inevitable consequences of external interaction of the component, very often in engineering, deformations are

reversible. A reversible deformation may be defined as a deformation that ceases to exist when the external agents causing deformation are removed. The ability to sustain reversible deformations at the material level is one of the characteristics of a solid that distinguishes it from fluids.

An integrated study of response of a component when subjected to external agents must account for the deformations that are experienced by each and every particle of the body. A rigorous treatment of this nature is done in courses like *continuum mechanics*. Analysis with certain simplifying assumptions on the deformations of the body when subjected mainly to mechanical and thermal loads is done in courses such as *mechanics of materials*, also popularly known as *strength of materials*. The mechanical loads transmitted to a component within an assembly, however, can be estimated in many cases, without considering the deformations of either the component of the assembly or the deformations within a component. When these deformations are ignored in any analysis, the component or the body is considered as a *rigid body*. This also means that the geometry of the *rigid body* remains unchanged under the action of the external agencies. Treatment of components as rigid bodies is a useful tool in mechanics and is primarily used in identifying the mechanical loads that are imposed in individual members in an assembly. For example, we can identify the loads that are imposed on individual members of a truss or a framed structure, without actually considering the deformations that the assembly or the individual components are actually experiencing. In other words, very useful information can be extracted purely by invoking the static equilibrium of such structures. The focus of this book will primarily be on the treatment of components as rigid bodies. Elementary deformations of the bodies will be invoked occasionally, especially when one considers deformations of structural elements like beams and cables. The interaction of forces and deformations in the form of energy associated with the structure will also be considered later in Chapter 4 so that the reader gets a total picture of the fundamental issues associated with the analysis of components.

## 1.2 Notion of Equilibrium—Newton's Laws Revisited

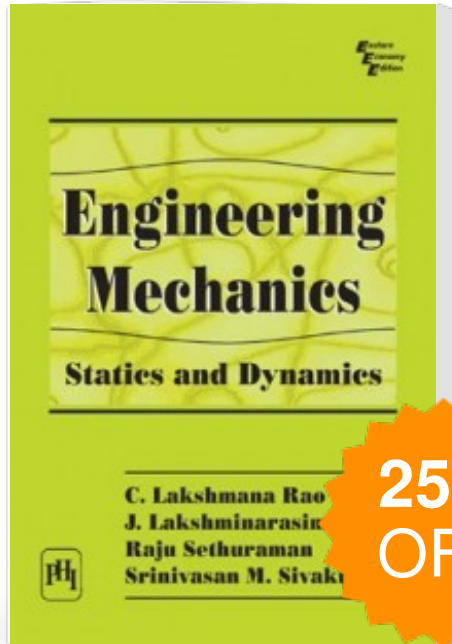
Mechanics of rigid bodies can be derived as a natural outcome of the application of Newton's laws of motion, which are familiar to all readers from high school physics. We will now redefine Newton's laws in a language that is useful for addressing issues which are of importance in engineering mechanics. We will also try to extract as much information out of these laws as possible.

### 1.2.1 Newton's Laws of Motion

Sir Isaac Newton, in his classical work *Principia*, written in 1686, introduced some important concepts that proved to be useful in formalizing the agents causing motion of any body. He proposed three laws, which are primarily applied to particles. Newton was the first to propose that uniform motion was possible when there is no net force acting on a particle. His laws were responsible for the identification of the role of inertia and mass of a body, while it undergoes motion. He formalized the relationship between agents causing motion, viz. forces, and their effects (accelerations). Newton was perhaps the first to recognize the role of 'hidden forces' that invariably exist whenever there is an interaction between two bodies.

Newton developed his concepts on bodies which are idealized as points in space. These concepts were later formalized for rigid bodies, where different particles can have different motions. The total motion of a particle in a rigid body is idealized as a translation of a reference point  $a$  and a rotation with respect to the reference point. In this section we examine how Newton's laws can be applied to rigid bodies.

# Engineering Mechanics Statics And Dynamics



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