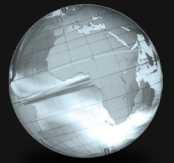


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Engineering Mechanics

Dynamics

FIFTEENTH EDITION IN SI UNITS

R. C. Hibbeler



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ENGINEERING MECHANICS

DYNAMICS

FIFTEENTH EDITION IN SI UNITS

R. C. HIBBELER

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To the Student

With the hope that this work will stimulate
an interest in Engineering Mechanics
and provide an acceptable guide to its understanding.

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The main purpose of this book is to provide the student with a clear and thorough presentation of the theory and application of engineering mechanics. To achieve this objective, this work has been shaped by the comments and suggestions of hundreds of reviewers in the teaching profession, as well as many of the author's students.

New to this Edition

Expanded Answer Section. The answer section in the back of the book now includes additional information related to the solution of select Fundamental Problems in order to offer the student some guidance in solving the problems.

Re-writing of Text Material. Some concepts have been clarified further in this edition, and throughout the book the accuracy has been enhanced, and important definitions are now in boldface throughout the text to highlight their importance.

New Photos. The relevance of knowing the subject matter is reflected by the real-world applications depicted in the over 14 new or updated photos placed throughout the book. These photos generally are used to explain how the relevant principles apply to real-world situations and how materials behave under load.

New Problems. There are approximately 30% new problems that have been added to this edition, which involve applications to many different fields of engineering.

New Videos. Three types of videos are available that are designed to enhance the most important material in the book. Lecture Videos serve to test the student's ability to understand the concepts, Example Problem Videos are intended to review these problems, and Fundamental Problem Videos guide the student in solving these problems that are in the book. They are available for selected sections in the chapters and marked with this icon. The videos appear on a companion website available for separate purchase at www.pearsonglobaleditions.com.



Hallmark Features

Besides the new features mentioned, other outstanding features that define the contents of the book include the following:

Organization and Approach. Each chapter is organized into well-defined sections that contain an explanation of specific topics, illustrative example problems, and a set of homework problems. The topics within each section are placed into subgroups defined by boldface titles. The purpose of this is to present a structured method for introducing each new definition or concept and to make the book convenient for later reference and review.

Chapter Contents. Each chapter begins with an illustration demonstrating a broad-range application of the material within the chapter. A bulleted list of the chapter contents is provided to give a general overview of the material that will be covered.

Emphasis on Free-Body Diagrams. Drawing a free-body diagram is particularly important when solving problems, and for this reason this step is strongly emphasized throughout the book. In particular, special sections and examples are devoted to show how to draw free-body diagrams. Specific homework problems have also been added to develop this practice.

Procedures for Analysis. A general procedure for analyzing any mechanics problem is presented at the end of the first chapter. Then this procedure is customized to relate to specific types of problems that are covered throughout the book. This unique feature provides the student with a logical and orderly method to follow when applying the theory. The example problems are solved using this outlined method in order to clarify its numerical application. Realize, however, that once the relevant principles have been mastered and enough confidence and judgment have been obtained, the student can then develop his or her own procedures for solving problems.

Important Points. This feature provides a review or summary of the most important concepts in a section and highlights the most significant points that should be known when applying the theory to solve problems.

Fundamental Problems. These problem sets are selectively located just after most of the example problems. They provide students with simple applications of the concepts, and therefore, the chance to develop their problem-solving skills before attempting to solve any of the standard problems that follow. In addition, they can be used for preparing for exams, and they can be used at a later time when preparing for the Fundamentals in Engineering Exam. The partial solutions are given in the back of the book.

Conceptual Understanding. Through the use of photographs placed throughout the book, the theory is applied in a simplified way in order to illustrate some of its more important conceptual features and instill the physical meaning of many of the terms used in the equations.

Homework Problems. Apart from the Fundamental and Conceptual type problems mentioned previously, other types of problems contained in the book include the following:

- **Free-Body Diagram Problems.** Some sections of the book contain introductory problems that only require drawing the free-body diagram for the specific problems within a problem set. These assignments will impress upon the student the importance of mastering this skill as a requirement for a complete solution of any equilibrium problem.
- **General Analysis and Design Problems.** The majority of problems in the book depict realistic situations encountered in engineering practice. Some of these problems come from actual products used in industry. It is hoped that this realism will both stimulate the student's interest in engineering mechanics and provide a means for developing the skill to reduce any such problem from its physical description to a model or symbolic representation to which the principles of mechanics may be applied.

Throughout the book, in any set of problems, an attempt has been made to arrange them in order of increasing difficulty except for the end of chapter review problems, which are presented in random order.

- **Computer Problems.** An effort has been made to include a few problems that may be solved using a numerical procedure executed on either a desktop computer or a programmable pocket calculator. The intent here is to broaden the student's capacity for using other forms of mathematical analysis without sacrificing the time needed to focus on the application of the principles of mechanics. Problems of this type, which either can or must be solved using numerical procedures, are identified by a "square" symbol (■) preceding the problem number.

The many homework problems in this edition, have been placed into two different categories. Problems that are simply indicated by a problem number have an answer and in some cases an additional numerical result given in the back of the book. An asterisk (*) before every fourth problem number indicates a problem without an answer.

Accuracy. As with the previous editions, apart from the author, the accuracy of the text and problem solutions has been thoroughly checked by Kai Beng Yap and Jun Hwa Lee, along with a team of specialists at EPAM, including Georgii Kolobov, Ekaterina Radchenko, and Artur Akberov.

Contents

The book is divided into 11 chapters, in which the principles are first applied to simple, then to more complicated situations.

The kinematics of a particle is discussed in Chapter 12, followed by a discussion of particle kinetics in Chapter 13 (Equation of Motion), Chapter 14 (Work and Energy), and Chapter 15 (Impulse and Momentum). The concepts of particle dynamics contained in these four chapters are then summarized in a “review” section, and the student is given the chance to identify and solve a variety of problems. A similar sequence of presentation is given for the planar motion of a rigid body: Chapter 16 (Planar Kinematics), Chapter 17 (Equations of Motion), Chapter 18 (Work and Energy), and Chapter 19 (Impulse and Momentum), followed by a summary and review set of problems for these chapters.

If time permits, some of the material involving three-dimensional rigid-body motion may be included in the course. The kinematics and kinetics of this motion are discussed in Chapters 20 and 21, respectively. Chapter 22 (Vibrations) may be included if the student has the necessary mathematical background. Sections of the book that are considered to be beyond the scope of the basic dynamics course are indicated by a star (★) and may be omitted. Note that this material also provides a suitable reference for basic principles when it is discussed in more advanced courses. Finally, Appendix A provides a list of mathematical formulas needed to solve the problems in the book, Appendix B provides a brief review of vector analysis, and Appendix C reviews application of the chain rule.

Alternative Coverage. At the discretion of the instructor, it is possible to cover Chapters 12 through 19 in the following order with no loss in continuity: Chapters 12 and 16 (Kinematics), Chapters 13 and 17 (Equations of Motion), Chapter 14 and 18 (Work and Energy), and Chapters 15 and 19 (Impulse and Momentum).

Acknowledgments

I have endeavored to write this book so that it will appeal to both the student and instructor. Through the years, many people have helped in its development, and I will always be grateful for their valued suggestions and comments. Specifically, I wish to thank all the individuals who have sent comments to me. These include J. Aurand, J. Ari-Gur, R. Boyd, O. Byer, E. Erisman, C. Heinke, H. Kuhlman, E. Most, S. Moustafa, H. Nazeri, D. Pox, J. Ross, D. Rowlison, R. Scott, K. Steurer.

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I would greatly appreciate hearing from you if at any time you have any comments, suggestions, or issues related to any matters regarding this edition.

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We would also like to thank Kai Beng Yap for his contributions to the previous Global Edition. He was a registered professional engineer working in Malaysia and had a BS degree in Civil Engineering from the University of Louisiana-Lafayette and an MS degree from Virginia Polytechnic Institute.

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Resources for Students

Videos Developed by the author, three different types of videos are now available to reinforce learning the basic theory and applying the principles. The first set provides a lecture review and a self-test of the material related to the theory and concepts presented in the book. The second set provides a self-test of the example problems and the basic procedures used for their solution. The third set provides an engagement for solving the Fundamental Problems throughout the book. They are available for selected sections in the chapters and marked with a video icon. The videos can be accessed in the Pearson eText or from a website available for purchase separately at www.pearsonglobaleditions.com.

CONTENTS



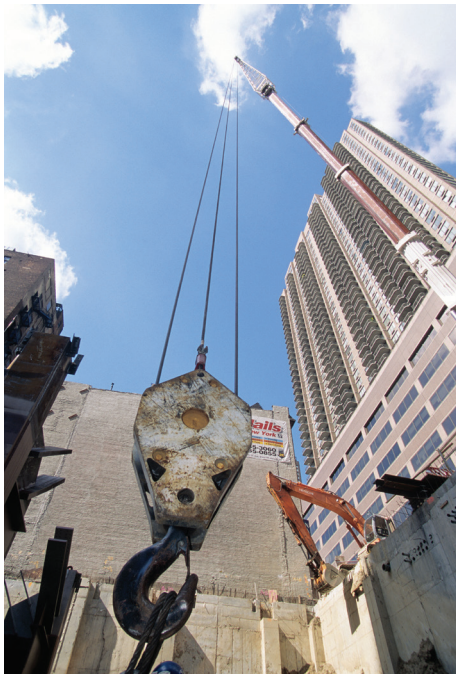
12 Kinematics of a Particle 23

- Chapter Objectives 23
- 12.1 Introduction 23
- 12.2 Rectilinear Kinematics: Continuous Motion 25
- 12.3 Rectilinear Kinematics: Erratic Motion 39
- 12.4 General Curvilinear Motion 52
- 12.5 Curvilinear Motion: Rectangular Components 54
- 12.6 Motion of a Projectile 59
- 12.7 Curvilinear Motion: Normal and Tangential Components 73
- *12.8 Curvilinear Motion: Cylindrical Components 87
- 12.9 Absolute Dependent Motion Analysis of Two Particles 101
- 12.10 Relative Motion of Two Particles Using Translating Axes 113



13 Kinetics of a Particle: Force and Acceleration 129

- Chapter Objectives 129
- 13.1 Newton's Second Law of Motion 129
- 13.2 The Equation of Motion 132
- 13.3 Equation of Motion for a System of Particles 134
- 13.4 Equations of Motion: Rectangular Coordinates 136
- 13.5 Equations of Motion: Normal and Tangential Coordinates 154
- *13.6 Equations of Motion: Cylindrical Coordinates 168
- *13.7 Central-Force Motion and Space Mechanics 180



14

Kinetics of a Particle: Work and Energy 195

- Chapter Objectives 195
- 14.1 The Work of a Force 195
- 14.2 Principle of Work and Energy 200
- 14.3 Principle of Work and Energy for a System of Particles 202
- 14.4 Power and Efficiency 219
- 14.5 Conservative Forces and Potential Energy 228
- 14.6 Conservation of Energy 232



15

Kinetics of a Particle: Impulse and Momentum 251

- Chapter Objectives 251
- 15.1 Principle of Linear Impulse and Momentum 251
- 15.2 Principle of Linear Impulse and Momentum for a System of Particles 254
- 15.3 Conservation of Linear Momentum for a System of Particles 267
- 15.4 Impact 279
- 15.5 Angular Momentum 294
- 15.6 Relation Between the Moment of a Force and Angular Momentum 295
- 15.7 Principle of Angular Impulse and Momentum 298
- 15.8 Bodies Subjected to a Mass Flow 309
- 15.9 Steady Flow of a Fluid Stream 311
- 15.10 Bodies that Lose or Gain Mass 315



16 Planar Kinematics of a Rigid Body 329

- Chapter Objectives 329
- 16.1 Planar Rigid-Body Motion 329
 - 16.2 Translation 331
 - 16.3 Rotation about a Fixed Axis 332
 - *16.4 Absolute Motion Analysis 348
 - 16.5 Relative-Motion Analysis: Velocity 356
 - 16.6 Instantaneous Center of Zero Velocity 369
 - 16.7 Relative-Motion Analysis:
Acceleration 381
 - *16.8 Relative-Motion Analysis using Rotating
Axes 395



17 Planar Kinetics of a Rigid Body: Force and Acceleration 413

- Chapter Objectives 413
- 17.1 Mass Moment of Inertia 413
 - 17.2 Planar Kinetic Equations of Motion 427
 - 17.3 Equations of Motion: Translation 430
 - 17.4 Equations of Motion: Rotation About a
Fixed Axis 443
 - 17.5 Equations of Motion: General Plane
Motion 457



18 Planar Kinetics of a Rigid Body: Work and Energy 473

- Chapter Objectives 473
- 18.1 Kinetic Energy 473
- 18.2 The Work of a Force 476
- 18.3 The Work of a Couple Moment 478
- 18.4 Principle of Work and Energy 480
- 18.5 Conservation of Energy 495



19 Planar Kinetics of a Rigid Body: Impulse and Momentum 515

- Chapter Objectives 515
- 19.1 Linear and Angular Momentum 515
- 19.2 Principle of Impulse and Momentum 521
- 19.3 Conservation of Momentum 536
- *19.4 Eccentric Impact 540



20 Three-Dimensional Kinematics of a Rigid Body 555

- Chapter Objectives 555
- 20.1 Rotation About a Fixed Point 555
 - *20.2 The Time Derivative of a Vector Measured from a Fixed or Translating-Rotating System 558
 - 20.3 General Motion 563
 - *20.4 Relative-Motion Analysis Using Translating and Rotating Axes 572



21 Three-Dimensional Kinetics of a Rigid Body 585

- Chapter Objectives 585
- *21.1 Moments and Products of Inertia 585
 - 21.2 Angular Momentum 595
 - 21.3 Kinetic Energy 598
 - *21.4 Equations of Motion 606
 - *21.5 Gyroscopic Motion 620
 - 21.6 Torque-Free Motion 626



22 Vibrations 637

Chapter Objectives 637

- 22.1 Undamped Free Vibration 637
- *22.2 Energy Methods 651
- *22.3 Undamped Forced Vibration 657
- *22.4 Viscous Damped Free Vibration 661
- *22.5 Viscous Damped Forced Vibration 664
- *22.6 Electrical Circuit Analogs 667

Appendices

- A. Mathematical Expressions 676
- B. Vector Analysis 679
- C. The Chain Rule 685

Fundamental Problems Solutions and Answers 689

Review Problem Answers 711

Answers to Selected Problems 713

Index 727

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ENGINEERING MECHANICS

DYNAMICS

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CHAPTER 12



Although these jet planes are rather large, from a distance their motion can be analyzed as if each were a particle.



Lecture Summary and Quiz, Example, and Problem-solving videos are available where this icon appears.

KINEMATICS OF A PARTICLE

CHAPTER OBJECTIVES

- To introduce the concepts of position, displacement, velocity, and acceleration.
- To study particle motion along a straight line and represent this motion graphically.
- To investigate particle motion along a curved path using different coordinate systems.
- To present an analysis of dependent motion of two particles.
- To examine the principles of relative motion of two particles using translating axes.

12.1 INTRODUCTION

Engineering mechanics is the study of the state of rest or motion of bodies subjected to the action of forces. It is divided into two areas, namely, statics and dynamics. **Statics** is concerned with the equilibrium of a body that is either at rest or moves with constant velocity. Here we will consider **dynamics**, which deals with the accelerated motion of a body. This subject will be presented in two parts: *kinematics*, which treats only the geometric aspects of the motion, and *kinetics*, which is the analysis of the forces causing the motion. To develop these principles, the dynamics of a particle will be discussed first, followed by topics in rigid-body dynamics in two and then three dimensions.

Historically, the principles of dynamics developed when it was possible to make an accurate measurement of time. Galileo Galilei (1564–1642) was one of the first major contributors to this field. His work consisted of experiments using pendulums and falling bodies. The most significant contributions to dynamics, however, were made by Isaac Newton (1642–1727), who is noted for his formulation of the three fundamental laws of motion and the law of universal gravitational attraction. Shortly after these laws were postulated, important techniques for their application were developed by Euler, D’Alembert, Lagrange, and others.

There are many problems in engineering whose solutions require application of the principles of dynamics. For example, bridges and frames are subjected to moving loads and natural forces caused by wind and earthquakes. The structural design of any vehicle, such as an automobile or airplane, requires consideration of the motion to which it is subjected. This is also true for many mechanical devices, such as motors, pumps, movable tools, industrial manipulators, and machinery. Furthermore, predictions of the motions of artificial satellites, projectiles, and spacecraft are based on the theory of dynamics. With further advances in technology, there will be an even greater need for knowing how to apply the principles of this subject.

Problem Solving. Dynamics is considered to be more involved than statics since both the forces applied to a body and its motion must be taken into account. Also, many applications require using calculus, rather than just algebra and trigonometry. In any case, the most effective way of learning the principles of dynamics is *to solve problems*. To be successful at this, it is necessary to present the work in a logical and orderly manner as suggested by the following sequence of steps:

1. Read the problem carefully and try to correlate the actual physical situation with the theory you have studied.
2. Draw any necessary diagrams and tabulate the problem data.
3. Establish a coordinate system and apply the relevant principles, generally in mathematical form.
4. Solve the necessary equations using a consistent set of units, and report the answer with no more than three significant figures, which is generally the accuracy of the given data.
5. Study the answer using technical judgment and common sense to determine whether or not it seems reasonable.

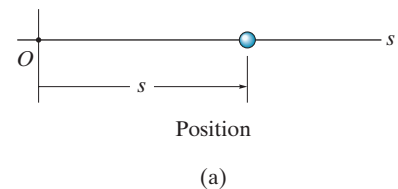
In applying this general procedure, do the work as neatly as possible. Being neat generally stimulates clear and orderly thinking, and vice versa. If you are having trouble developing your problem-solving skills, consider watching the videos available at www.pearson.com/hibbeler.

12.2 RECTILINEAR KINEMATICS: CONTINUOUS MOTION

We will begin our study of dynamics by discussing the kinematics of a particle that moves along a straight path. Recall that a *particle* has a mass but negligible size and shape, so we will limit application to those objects that have dimensions that are of no consequence in the analysis of the motion. For example, a rocket, projectile, or a vehicle can be considered as a particle, as long as its motion is characterized by the motion of its mass center, and any rotation of the body is neglected.

Rectilinear Kinematics. The kinematics of a particle is characterized by specifying, at any given instant, the particle's position, velocity, and acceleration.

Position. The rectilinear or straight-line path of a particle will be defined using a single coordinate axis s , Fig. 12-1*a*. The origin O on the path is a fixed point, and from this point the *position coordinate* s is used to specify the location of the particle at any given instant. The magnitude of s is the distance from O to the particle, usually measured in meters (m), and the sense of direction is defined by the algebraic sign of s . Although the choice is arbitrary, here s will be positive when the particle is located to the right of the origin, and it will be negative if the particle is located to the left of O . Position is actually a vector quantity since it has both magnitude and direction; however, it is being represented by the algebraic scalar s , rather than in boldface \mathbf{s} , since the direction always remains along the coordinate axis.



Displacement. The *displacement* of the particle is defined as the *change in its position*. For example, if the particle moves from one point to another, Fig. 12-1*b*, the displacement is

$$\Delta s = s' - s$$

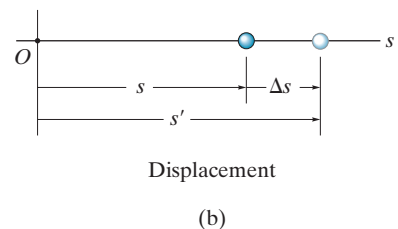


Fig. 12-1

In this case Δs is *positive* since the particle's final position is to the *right* of its initial position, i.e., $s' > s$. Displacement is also a *vector quantity*, and it should be distinguished from the distance the particle travels. Specifically, the *distance traveled* is a *positive scalar* that represents the total length of path over which the particle travels.

Velocity. If the particle moves through a displacement Δs during the time interval Δt , the **average velocity** of the particle is

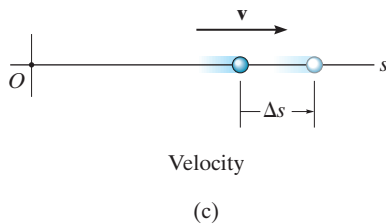
$$v_{\text{avg}} = \frac{\Delta s}{\Delta t}$$

If we take smaller and smaller values of Δt , the magnitude of Δs becomes smaller and smaller. Consequently, the **instantaneous velocity** is a vector defined as $v = \lim_{\Delta t \rightarrow 0} (\Delta s / \Delta t)$, or

(\pm)

$$v = \frac{ds}{dt}$$

(12-1)



Since Δt or dt is always positive, the sign used to define the *sense* of the velocity is the same as that of Δs or ds . For example, if the particle is moving to the *right*, Fig. 12-1c, the velocity is *positive*; whereas if it is moving to the *left*, the velocity is *negative*. (This is emphasized here by the arrow written at the left of Eq. 12-1.) The *magnitude* of the velocity is known as the **speed**, and it is generally expressed in units of m/s.

Occasionally, the term “average speed” is used. The **average speed** is always a positive scalar and is defined as the total distance traveled by a particle, s_T , divided by the elapsed time Δt ; i.e.,

$$(v_{\text{avg}})_{\text{sp}} = \frac{s_T}{\Delta t}$$

For example, the particle in Fig. 12-1d travels along the path of length s_T in time Δt , so its average speed is $(v_{\text{avg}})_{\text{sp}} = s_T / \Delta t$, but its average velocity is $v_{\text{avg}} = -\Delta s / \Delta t$.

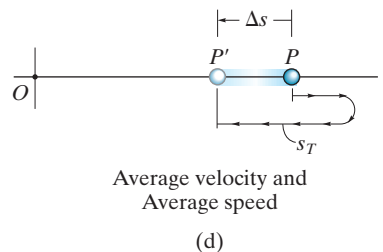


Fig. 12-1 (cont.)

Acceleration. If the velocity of the particle is known at two points, then the **average acceleration** of the particle during the time interval Δt is defined as

$$a_{\text{avg}} = \frac{\Delta v}{\Delta t}$$

Here Δv represents the difference in the velocity during the time interval Δt , i.e., $\Delta v = v' - v$, Fig. 12-1e.

The **instantaneous acceleration** at time t is a *vector* that is found by taking smaller and smaller values of Δt and corresponding smaller and smaller values of Δv , so that $a = \lim_{\Delta t \rightarrow 0} (\Delta v / \Delta t)$, or

$$(\pm) \quad \boxed{a = \frac{dv}{dt}} \quad (12-2)$$

Substituting Eq. 12-1 into this result, we can also write

$$(\pm) \quad a = \frac{d^2s}{dt^2}$$

Both the average and instantaneous acceleration can be either positive or negative. In particular, when the particle is *slowing down*, or its speed is decreasing, the particle is said to be **decelerating**. In this case, v' in Fig. 12-1f is *less* than v , and so $\Delta v = v' - v$ will be negative. Consequently, a will also be negative, and therefore it will act to the *left*, in the *opposite sense* to v . Also, notice that if the particle is originally at rest, then it can have an acceleration if a moment later it has a velocity v' . Units commonly used to express the magnitude of acceleration are m/s^2 .

Finally, an important differential relation involving the displacement, velocity, and acceleration along the path may be obtained by eliminating the time differential dt between Eqs. 12-1 and 12-2. We have

$$dt = \frac{ds}{v} = \frac{dv}{a}$$

or

$$(\pm) \quad \boxed{a ds = v dv} \quad (12-3)$$

Although we have now produced three important kinematic equations, realize that the above equation is not independent of Eqs. 12-1 and 12-2.

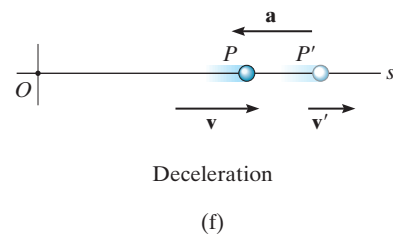
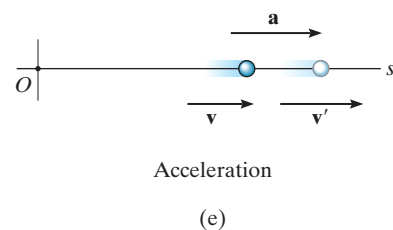


Fig. 12-1 (cont.)

Constant Acceleration, $a = a_c$. When the acceleration is constant, each of the three kinematic equations $a_c = dv/dt$, $v = ds/dt$, and $a_c ds = v dv$ can be integrated to obtain formulas that relate a_c , v , s , and t .

Velocity as a Function of Time. Integrating $a_c = dv/dt$, assuming that initially $v = v_0$ when $t = 0$, we get

$$\int_{v_0}^v dv = \int_0^t a_c dt$$

(\pm)

$$v = v_0 + a_c t$$

Constant Acceleration

(12-4)

Position as a Function of Time. Integrating $v = ds/dt = v_0 + a_c t$, assuming that initially $s = s_0$ when $t = 0$, yields

$$\int_{s_0}^s ds = \int_0^t (v_0 + a_c t) dt$$

(\pm)

$$s = s_0 + v_0 t + \frac{1}{2} a_c t^2$$

Constant Acceleration

(12-5)

Velocity as a Function of Position. If we solve for t in Eq. 12-4 and substitute it into Eq. 12-5, or integrate $v dv = a_c ds$, assuming that initially $v = v_0$ at $s = s_0$, we get

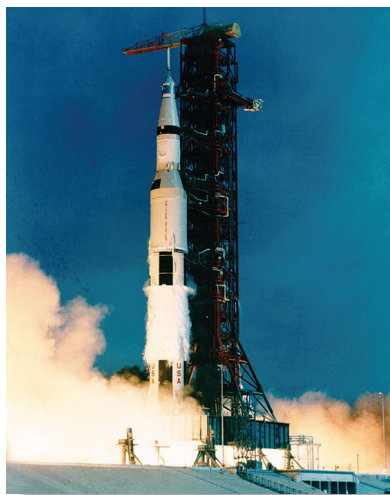
$$\int_{v_0}^v v dv = \int_{s_0}^s a_c ds$$

(\pm)

$$v^2 = v_0^2 + 2a_c(s - s_0)$$

Constant Acceleration

(12-6)



During the time this rocket undergoes rectilinear motion, its altitude as a function of time can be measured and expressed as $s = s(t)$. Its velocity can then be found using $v = ds/dt$, and its acceleration can be determined from $a = dv/dt$.

The algebraic signs of s_0 , v_0 , and a_c , used in these equations, are determined from the positive direction of the s axis as indicated by the arrow written at the left of each equation. It is important to remember that these equations are useful *only when the acceleration is constant and when $t = 0$, $s = s_0$, $v = v_0$* . A typical example of constant accelerated motion occurs when a body falls freely toward the earth. If air resistance is neglected and the distance of fall is short, then the constant *downward* acceleration of the body when it is close to the earth is approximately 9.81 m/s^2 .

IMPORTANT POINTS

- Dynamics is the study of bodies that have accelerated motion.
- Kinematics is a study of the geometry of the motion.
- Kinetics is a study of the forces that cause the motion.
- Rectilinear kinematics refers to straight-line motion.
- Speed refers to the magnitude of velocity.
- Average speed is the total distance traveled divided by the total time. This is different from the average velocity, which is the displacement divided by the time.
- A particle that is slowing down is decelerating.
- A particle can have an acceleration and yet have zero velocity.
- The relationship $a ds = v dv$ is derived from $a = dv/dt$ and $v = ds/dt$, by eliminating dt .

PROCEDURE FOR ANALYSIS

Coordinate System.

- Establish a position coordinate s along the path and specify its *fixed origin* and positive direction.
- Since motion is along a straight line, the vector quantities position, velocity, and acceleration can be represented as algebraic scalars. For analytical work the sense of s , v , and a is then defined by their *algebraic signs*.
- The positive sense for each of these scalars can be indicated by an arrow shown alongside each kinematic equation as it is applied.

Kinematic Equations.

- If a relation is known between any *two* of the four variables a , v , s , and t , then a third variable can be obtained by using one of the kinematic equations, $a = dv/dt$, $v = ds/dt$ or $a ds = v dv$, since each equation relates all three variables.*
- Whenever integration is performed, it is important that the position and velocity be known at a given instant in order to evaluate either the constant of integration if an indefinite integral is used, or the limits of integration if a definite integral is used.
- Remember that Eqs. 12–4 through 12–6 have limited use. These equations apply *only* when the *acceleration is constant* and the initial conditions are $s = s_0$ and $v = v_0$ when $t = 0$.

* Some standard differentiation and integration formulas are given in Appendix A.



EXAMPLE 12.1

12

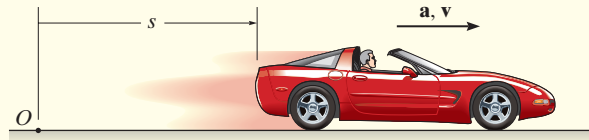


Fig. 12-2

The car in Fig. 12-2 moves in a straight line such that for a short time its velocity is defined by $v = (0.9t^2 + 0.6t)$ m/s, where t is in seconds. Determine its position and acceleration when $t = 3$ s. When $t = 0$, $s = 0$.

SOLUTION

Coordinate System. The position coordinate extends from the fixed origin O to the car, positive to the right.

Position. Since $v = f(t)$, the car's position can be determined from $v = ds/dt$, since this equation relates v , s , and t . Noting that $s = 0$ when $t = 0$, we have*

$$\begin{aligned}
 (\pm) \quad v &= \frac{ds}{dt} = (0.9t^2 + 0.6t) \\
 \int_0^s ds &= \int_0^t (0.9t^2 + 0.6t) dt \\
 s \Big|_0^s &= 0.3t^3 + 0.3t^2 \Big|_0^t \\
 s &= 0.3t^3 + 0.3t^2
 \end{aligned}$$

When $t = 3$ s,

$$s = 0.3(3)^3 + 0.3(3)^2 = 10.8 \text{ m} \quad \text{Ans.}$$

Acceleration. Since $v = f(t)$, the acceleration is determined from $a = dv/dt$, since this equation relates a , v , and t .

$$(\pm) \quad a = \frac{dv}{dt} = \frac{d}{dt}(0.9t^2 + 0.6t) = 1.8t + 0.6$$

When $t = 3$ s,

$$a = 1.8(3) + 0.6 = 6.00 \text{ m/s}^2 \rightarrow \quad \text{Ans.}$$

NOTE: The formulas for constant acceleration *cannot* be used to solve this problem, because the acceleration is a function of time.

* The *same result* can be obtained by evaluating a constant of integration C rather than using definite limits on the integral. For example, integrating $ds = (0.9t^2 + 0.6t)dt$ yields $s = 0.3t^3 + 0.3t^2 + C$. Using the condition that at $t = 0$, $s = 0$, then $C = 0$.