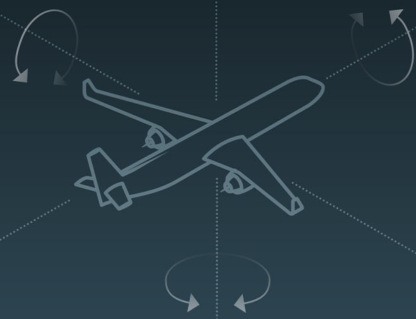
JOSEPH R. BADICK BRIAN A. JOHNSON



FLIGHT THEORY AND AERODYNAMICS

A PRACTICAL GUIDE FOR OPERATIONAL SAFETY

FOURTH EDITION

with website

WILEY

FLIGHT THEORY AND AERODYNAMICS

FLIGHT THEORY AND AERODYNAMICS

A Practical Guide for Operational Safety

FOURTH EDITION

Joseph R. Badick

Brian A. Johnson

WILEY

This edition first published 2022

Edition History
3e, 2017, John Wiley and Sons, Inc.

Registered Office
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

Editorial Office
111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data applied for:

ISBN: 9781119772392

Cover Design: Wiley
Cover Images: © ZernLiew / Getty Images, © Jag_cz/Getty Images

Set in 9/11pt and Times by Straive, Pondicherry, India

10 9 8 7 6 5 4 3 2 1

Contents

Preface

The fourth edition of *Flight Theory and Aerodynamics* was revised to further enhance the book's use as an introductory text for colleges and universities offering an aeronautical program. After surveying students enrolled in collegiate aviation programs, college professors, and aviation industry professionals, the result is this fourth edition that combines introductory concepts of aerodynamics with simple, yet important introductory practical application of math formulas.

All 15 chapters have some level of updating and additional content. The revision contains additional explanation of math equations with step-by-step examples on the application of the equation to flight. Most chapters have been updated with special areas of interest titled "Application," that offer opportunities for further exploration and application of the chapter material. The fourth revision was written for those in the aviation industry, regardless of their position and level of experience. Whether this textbook will serve as one's first venture into a career in aerodynamics, or simply serve as a reference handbook for those already established within the aviation industry, the core goals of this textbook are to improve the application of flight theory to introductory aerodynamics and expand operational flight safety.

Changes in the fourth edition:

- Added chapter objectives at the beginning of each chapter
- Consolidation of Chapters 6 and 7, and Chapters 8 and 9
- Added *Application* areas to expand the practical application of chapter material
- Added step-by-step examples of how to apply math equations to real-world situations
- Added additional end of chapter questions and solutions
- Added updated graphics, including correlation with current government agency publications
- Added detail in subject matter emphasizing practical application

The authors would like to thank their contacts at Wiley for their continuous support throughout this revision, as well as the support of colleagues and families. In particular, the authors would like to thank William O. Young for his technical and editorial contribution to this revision, in addition to his careful review of this manuscript Mr. Young's guidance based on his experience as a flight instructor in land and seaplane operations was instrumental.

Finally, the authors would like to acknowledge the previous work of Charles E. Dole and James E. Lewis, the original authors for the first two editions of this textbook, and to acknowledge their contribution to improving aviation safety through education and practical application.

Joseph R. Badick
Adjunct Faculty, Embry-Riddle Aeronautical University,
Daytona Beach, FL, USA

Brian A. Johnson
Adjunct Faculty, Embry-Riddle Aeronautical University,
Daytona Beach, FL, USA

About the Authors

Joseph R. Badick has over 40 years of flight experience in both single- and multi-engine, land/seaplane aircraft, with an airline transport certificate. He also holds a commercial certificate for rotorcraft with a helicopter rating. A licensed airframe and powerplant mechanic, with inspection authorization, he has installed numerous aircraft aerodynamic performance supplemental type certificates, with test flight checks. He holds a PhD (ABD) in business from Northcentral University of Arizona and a master's degree in aeronautical science. He was Naval Officer for 30 years as an Aeronautical Engineer Duty Officer (AEDO), involved in all aspects of aircraft maintenance, logistics, acquisition, and test/evaluation. Currently, he is an adjunct faculty member with Embry-Riddle Aeronautical University.

Brian A. Johnson is a former regional airline pilot and corporate pilot who holds an airline transport pilot certificate with a multi-engine rating, in addition to commercial pilot single-engine land/sea privileges and a remote pilot certificate with a small unmanned aircraft system rating. He is an active instrument and multi-engine Gold Seal flight instructor with an advanced ground instructor rating and serves as a FAASTeam representative. He holds a master's degree in aeronautical science from Embry-Riddle Aeronautical University and currently serves as an associate professor for a two-year Career Pilot/Aviation Management degree program, in addition to serving as an adjunct faculty member for the Aeronautics department in Embry-Riddle Aeronautical University's Worldwide campus.

About the Companion Website

This book is accompanied by a companion website.

www.wiley.com/go/badick/flight_theory_aerodynamics

This website includes:

- Lecture slides available to download in PowerPoint
- Test Bank of questions
- Abstracts

1 Introduction to the Flight Environment

CHAPTER OBJECTIVES

After completing this chapter, you should be able to:

- Define basic units of measurement used in the introduction to aerodynamics in flight and convert from one unit of measurement to another.
- Identify the four forces on an airplane in constant altitude, unaccelerated flight.
- Calculate the mass of an aircraft.
- Define vector addition and apply to an aircraft in a climb.
- Describe Newton's laws of motion and recognize how they apply to an introduction to aerodynamics.
- Define the purpose of linear motion in relation to constant acceleration, and then calculate aircraft acceleration, takeoff distance, and takeoff time.
- Describe the difference between energy and work and calculate the potential and kinetic energy of an aircraft in flight.
- Calculate the equivalent horsepower of an aircraft from a known thrust and speed.
- Define friction as it applies to an aircraft.

A basic understanding of the physical laws of nature that affect aircraft in flight and on the ground is a prerequisite for the study of aerodynamics. Modern aircraft have become more sophisticated, and more automated, using advanced materials in their construction requiring pilots to renew their understanding of the natural forces encountered during flight. Understanding how pilots control and counteract these forces better prepares pilots and engineers for the art of flying for harnessing the fundamental physical laws that guide them. Though at times this textbook will provide a quantitative approach to various principles and operating practices with formulas and examples using equations, it is more important that the reader understand WHY a principle of flight theory is discussed and how that subject matter intertwines with other materials presented; thus a qualitative approach is used throughout this textbook.

Perhaps your goal is to be a pilot, who will "slip the surly bonds of earth," as John Gillespie Magee wrote in his classic poem "High Flight." Or you may wish to build or maintain aircraft as a skilled

Flight Theory and Aerodynamics: A Practical Guide for Operational Safety, Fourth Edition.
Joseph R. Badick and Brian A. Johnson.

Companion website: www.wiley.com/go/badick/flight_theory_aerodynamics

technician. Or possibly you wish to serve in another vital role in the aviation industry, such as manager, dispatcher, meteorologist, engineer, teacher, or another capacity. Whichever area you might be considering, this textbook will build on what you already know and will help prepare you for a successful aviation career.

INTRODUCTION

This chapter begins with a review of the basic principles of physics and concludes with a summary of linear motion, mechanical energy, and power. A working knowledge of these areas, and how they relate to basic aerodynamics, is vital as we move past the rudimentary "four forces of flight" and introduce thrust and power-producing aircraft, lift and drag curves, stability and control, maneuvering performance, slow-speed flight, and other topics.

You may already have been introduced to the four basic forces acting on an aircraft in flight: lift, weight, thrust, and drag. Now, we must understand how these forces change as an aircraft accelerates down the runway, or descends on final approach to a runway and gently touches down even when traveling twice the speed of a car on the highway. Once an aircraft has safely made it into the air, what effect does weight have on its ability to climb, and should the aircraft climb up to the flight levels or stay lower and take "advantage" of the denser air closer to the ground?

By developing an understanding of the aerodynamics of flight, and of the ways in which design, weight, load factors, and gravity affect an aircraft during flight maneuvers from stalls to high-speed flight, the pilot learns how to control the balance between these forces. This textbook will help clarify these concepts among others, leaving you with a better understanding of the flight environment.

BASIC QUANTITIES

An introduction to aerodynamics must begin with a review of physics, and, in particular, the branch of physics that will be presented here is called *mechanics*. We will examine the fundamental physical laws governing the forces acting on an aircraft in flight, and what effect these natural laws and forces have on the performance characteristics of aircraft. To control an aircraft, whether it is an airplane, helicopter, glider, or balloon, the pilot must understand the principles involved and learn to use or counteract these natural forces.

We will start with the concepts of work, energy, power, and friction, and then build upon them as we move forward in future chapters.

Because the metric system of measurement has not yet been widely accepted in the United States, the English system of measurement is used in this book. The fundamental units are

Force	Pounds (lb)
Distance	Feet (ft)
Time	Seconds (s)

From the fundamental units, other quantities can be derived:

Velocity (distance/time)	ft/s (fps)
Area (distance squared)	square ft (ft^2)
Pressure (force/unit area)	lb/ft^2 (psf)
Acceleration (rate of change in velocity)	ft/s/s (fps^2)

Aircraft measure airspeed in knots (nautical miles per hour) or in Mach number (the ratio of true airspeed to the speed of sound). Rates of climb and descent are measured in feet per minute, so quantities other than those above are used in some cases. Some useful conversion factors are listed below:

Multiply	by	to get
knots (kts.)	1.69	feet per second (fps)
fps	0.5925	kts.
miles per hour (mph)	1.47	fps
fps	0.6818	mph
mph	0.8690	kts.
kts.	1.15	mph
nautical miles (nm)	6076	feet (ft)
nm	1.15	statute miles (sm)
sm	0.869	nm
kts.	101.3	feet per minute (fpm)

EXAMPLES

Convert 110 kts. to fps: 110 kts. × 1.69 = 185.9 fps

Convert 50 kts. to fpm: 50 kts. × 101.3 = 5,065 fpm

Convert 450 fps to kts. = 450 fps × 0.5925 = 267 kts.

Convert 25 sm to nm: 25 sm × 0.869 = 21.7 nm

Application 1.1

An airplane flight manual (AFM) states a given aircraft should be rotated at 65 kts. indicated airspeed (IAS), yet the pilot misinterprets the airspeed indicator and rotates at 65 mph (IAS).

Does the aircraft rotate at a faster or slower airspeed than the manufacturer recommends? What are the implications?

FORCES

A force is a push or a pull tending to change the state of motion of a body. A resolution of the typical forces acting on an aircraft in steady flight is shown in Figure 1.1, while Figure 1.2 shows the four separate components of aerodynamic forces during straight-and-level, unaccelerated flight. The component that is 90° to the flight path and acts toward the top of the airplane is called *lift*. The component that is parallel to the flight path and acts toward the rear of the airplane is called *drag*; while the opposing forward force is *thrust* and is usually created by the engine. *Weight* opposes lift and as we will see is a function of the mass of the aircraft and gravity.

The sum of the opposing forces is always zero in steady flight, but this does not mean the four forces are equal. In future chapters of this textbook, we will further demonstrate the following statement regarding forces acting on an airplane in steady flight: The sum of all upward component of forces equals the sum of all downward components of forces, and the sum of all forward components of forces equals the sum of all backward components of forces.

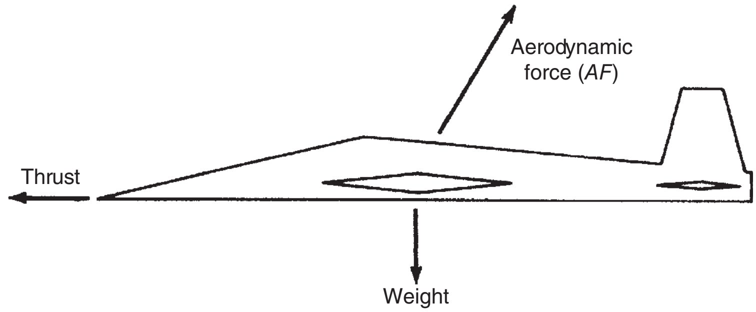


Figure 1.1. Forces on an airplane in steady flight.

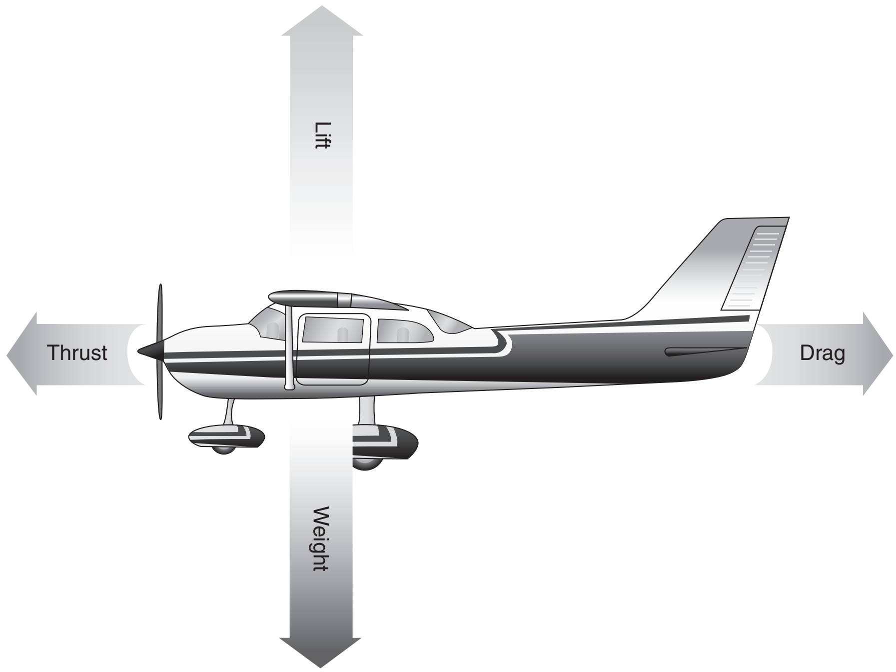


Figure 1.2. Resolved forces on an airplane in steady flight.
Source: U.S. Department of Transportation Federal Aviation Administration (2008a).

MASS

Mass is a measure of the amount of material contained in a body, usually measured in kilograms; we will use slugs as the unit in this textbook. *Weight*, on the other hand, is a force caused by the gravitational attraction of the earth ($g = 32.2$ ft/s^2), moon, sun, or other heavenly bodies. Weight will vary depending on where the body is located in space (specifically, how far from the source of gravitational attraction), but mass will not vary with position.

$$\begin{aligned} \text{Weight } (W) &= \text{Mass } (m) \times \text{Acceleration of gravity } (g) \\ W &= mg \end{aligned} \tag{1.1}$$

Rearranging gives

$$m = \frac{W}{g} \frac{\text{lb}}{\text{ft/s}^2} = \frac{\text{lb}\cdot\text{s}^2}{\text{ft}}$$

This mass unit is called the *slug*.

EXAMPLE

Calculate the mass of an aircraft that weighs 2576 lb.

$$m = \frac{W}{g} \rightarrow m = \frac{2576 \text{ lb}}{32.2 \text{ ft/s}^2}$$
$$m = 80.0 \text{ slugs}$$

SCALAR AND VECTOR QUANTITIES

A quantity that has size or magnitude only is called a *scalar* quantity. The quantities of mass, time, and temperature are examples of scalar quantities. A quantity that has both magnitude and direction is called a *vector* quantity. Forces, accelerations, and velocities are examples of vector quantities. Speed is a scalar, but if we consider the direction of the speed, then it is a vector quantity called *velocity*. If we say an aircraft traveled 100 nm, the distance is a scalar, but if we say an aircraft traveled 100 nm on a heading of 360°, the distance is a vector quantity.

Scalar Addition

Scalar quantities can be added (or subtracted) by simple arithmetic. For example, if you have 5 gallons of gas in your car's tank and you stop at a gas station and top off your tank with 9 gallons more, your tank now holds 14 gallons.

Vector Addition

Vector addition is more complicated than scalar addition. Vector quantities are conveniently shown by arrows. The length of the arrow represents the magnitude of the quantity, and the orientation of the arrow represents the directional property of the quantity. For example, if we consider the top of this page as representing north and we want to show the velocity of an aircraft flying east at an airspeed of 300 kts., the velocity vector is as shown in Figure 1.3. If there is a 30-kts. wind from the north, the wind vector is as shown in Figure 1.4.

To find the aircraft's flight path, groundspeed, and drift angle, we add these two vectors as follows. Place the tail of the wind vector at the head of the arrow of the aircraft vector and draw a straight line from the tail of the aircraft vector to the head of the arrow of the wind vector. This *resultant* vector represents the path of

Figure 1.3. Vector of an eastbound aircraft.

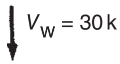


Figure 1.4. Vector of a north wind.

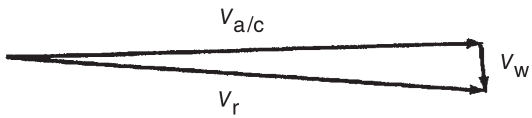


Figure 1.5. Vector addition.

the aircraft over the ground. The length of the resultant vector represents the groundspeed, and the angle between the aircraft vector and the resultant vector is the drift angle (Figure 1.5).

The groundspeed is the hypotenuse of the right triangle and is found by use of the Pythagorean theorem $V_r^2 = V_{a/c}^2 + V_w^2$:

$$\text{Groundspeed} = V_r = \sqrt{(300)^2 + (30)^2} = 302 \text{ kts.}$$

The drift angle is the angle whose tangent is $V_w/V_{a/c} = 30/300 = 0.1$, which is 5.7° to the right (south) of the aircraft heading.

Vector Resolution

It is often desirable to replace a given vector by two or more other vectors. This is called *vector resolution*. The resulting vectors are called component vectors of the original vector and, if added vectorially, they will produce the original vector. For example, if an aircraft is in a steady climb, at an airspeed of 200 kts., and the flight path makes a 30° angle with the horizontal, the groundspeed and rate of climb can be found by vector resolution. The flight path and velocity are shown by vector $V_{a/c}$ in Figure 1.6.

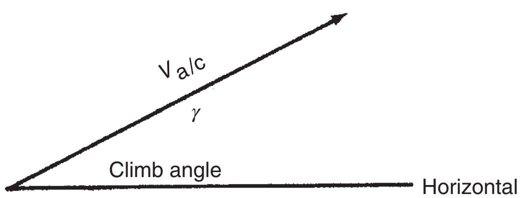


Figure 1.6. Vector of an aircraft in a climb.

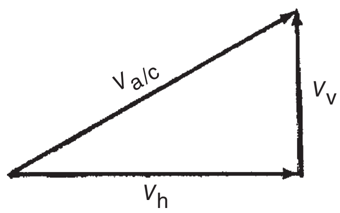


Figure 1.7. Vectors of groundspeed and rate of climb.

In Figure 1.7, to resolve the vector $V_{a/c}$ into a component V_h parallel to the horizontal, which will represent the groundspeed, and a vertical component, V_v, which will represent the rate of climb, we simply draw a straight line vertically upward from the horizontal to the tip of the arrow $V_{a/c}$. This vertical line represents the rate of climb and the horizontal line represents the groundspeed of the aircraft. If the airspeed $V_{a/c}$ is 200 kts. and the climb angle is 30°, mathematically the values are

$$V_h = V_{a/c} \cos 30^\circ = 200(0.866) = 173.2 \text{ kts.} \quad \text{(Groundspeed)}$$
$$V_v = V_{a/c} \sin 30^\circ = 200(0.500) = 100 \text{ kts. or } 10130 \text{ fpm} \quad \text{(Rate of climb)}$$

MOMENTS

If a mechanic tightens a nut by applying a force to a wrench, a twisting action, called a *moment*, is created about the center of the bolt. This particular type of moment is called *torque* (pronounced "tork"). Moments, M, are measured by multiplying the amount of the applied force, F, by the *moment arm*, L:

$$\text{Moment} = \text{force} \times \text{arm} \quad \text{or} \quad M = FL \tag{1.2}$$

The moment arm is the perpendicular distance from the line of action of the applied force to the center of rotation. Moments are measured as foot–pounds (ft-lb) or as inch–pounds (in.-lb). If a mechanic uses a 10 in.-long wrench and applies 25 lb of force, the torque on the nut is 250 in.-lb.

The aircraft moments that are of particular interest to pilots include pitching moments, yawing moments, and rolling moments. If you have ever completed a weight and balance computation for an aircraft, you have calculated a moment, where weight was the *force* and the *arm* was the inches from datum. Pitching moments, for example, occur when an aircraft's elevator is moved. Air loads on the elevator, multiplied by the distance to the aircraft's center of gravity (CG), create pitching moments, which cause the nose to pitch up or down. As you can see from Eq. 1.2, if a force remains the same but the arm is increased, the moment increases.

Several forces may act on an aircraft at the same time, and each will produce its own moment about the aircraft's CG. Some of these moments may oppose others in direction. It is therefore necessary to classify each moment, not only by its magnitude, but also by its direction of rotation. One such classification could be by *clockwise* or *counterclockwise* rotation. In the case of pitching moments, a *nose-up* or *nose-down* classification seems appropriate.

Mathematically, it is desirable that moments be classified as positive (+) or negative (–). For example, if a clockwise moment is considered to be a + moment, then a counterclockwise moment must be considered to be a – moment. By definition, aircraft nose-up pitching moments are considered to be + moments.

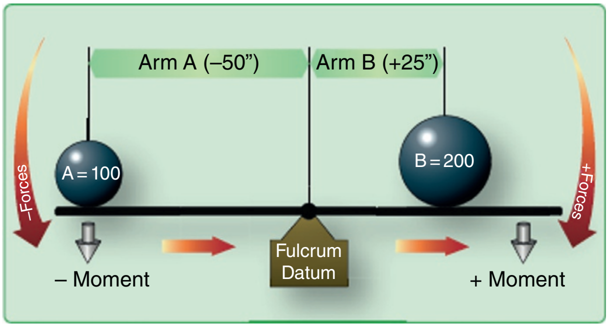


Figure 1.8. Balance Lever.

EQUILIBRIUM CONDITIONS

Webster defines equilibrium as “a state in which opposing forces or actions are balanced so that one is not stronger or greater than the other.” A body must meet two requirements to be in a state of equilibrium:

1. There must be no unbalanced forces acting on the body. This is written as the mathematical formula $\Sigma F = 0$, where Σ (cap sigma) is the Greek symbol for “sum of.” Figure 1.2 illustrates the situation where this condition is satisfied (lift = weight, thrust = drag, etc.)
2. There must be no unbalanced moments acting on the body. Mathematically, $\Sigma M = 0$.

   Moments at the fulcrum in Fig. 1.8 are 5000 ft-lb clockwise and 5000 ft-lb counterclockwise. The weight (force) of A is 100 lb and is located 50 inches (″) to the left of datum (fulcrum), thus 100 lb × −50″ = −5000 lb-in. The weight of B is 200 lb and is located 25 inches to the right of datum, thus 200 lb × 25″ = 5000 lb-in. So, $\Sigma M = 0$.

NEWTON’S LAWS OF MOTION

Sir Isaac Newton summarized three generalizations about force and motion. These are known as the *laws of motion*.

Newton’s First Law

In simple language, the first law states that *a body at rest will remain at rest and a body in motion will remain in motion, in a straight line, unless acted upon by an unbalanced force*. The first law implies that bodies have a property called *inertia*. Inertia may be defined as the property of a body that results in its maintaining its velocity unchanged unless it interacts with an unbalanced force. For example, an aircraft parked on the ramp would not even need chocks unless an unbalanced force (such as wind, or gravity if parked on a slope) acted on it. The measure of inertia is what is technically known as *mass*.

Newton’s Second Law

The second law states that *if a body is acted on by an unbalanced force, the body will accelerate in the direction of the force and the acceleration will be directly proportional to the force and inversely proportional to the mass of the body. Acceleration* is the change in the velocity of a body in a unit of time. Consider an aircraft accelerating down the runway, or decelerating after touchdown. For our discussion, the primary forces acting on an aircraft accelerating or decelerating down a runway are thrust, drag, and friction. Future chapters will discuss the *net* force on an aircraft during the takeoff and landing regimes.

The amount of the acceleration a is directly proportional to the unbalanced force, F, and is inversely proportional to the mass, m, of the body. For a constant mass, force equals mass times acceleration.

Newton's second law can be expressed by the simple equation:

$$F = m\,a \tag{1.3}$$

Then, solving for a,

$$a = \frac{F}{m}$$

EXAMPLE

An airplane that weighs 14 400 lb accelerates down a runway with a net force of 4 000 lb, what is the acceleration (a) assuming constant acceleration?

$$m = \frac{W}{g} = \frac{14\,400 \text{ lb}}{32.2 \text{ ft/s}^2} = 447.2 \text{ slugs}$$

$$a = \frac{F}{m} \rightarrow a = \frac{4000 \text{ lb}}{447.2 \text{ slugs}} \rightarrow a = 8.9 \text{ ft/s}^2$$

Newton's Third Law

The third law states that *for every action force there is an equal and opposite reaction force*. Note that for this law to have any meaning, there must be an interaction between the force and a body. For example, the gases produced by burning fuel in a rocket engine are accelerated through the rocket nozzle. The equal and opposite force acts on the interior walls of the combustion chamber, and the rocket is accelerated in the opposite direction. As a propeller aircraft pushes air backward from the propeller, the aircraft is pushed forward.

LINEAR MOTION

Newton's laws of motion express relationships among force, mass, and acceleration, but they stop short of discussing velocity, time, and distance. These are covered here. In the interest of simplicity, we assume here that acceleration is constant. Then,

$$\text{Acceleration } a = \frac{\text{Change in velocity}}{\text{Change in time}} = \frac{\Delta V}{\Delta t} = \frac{V_f - V_i}{t_f - t_i} \quad \text{or} \quad \frac{V_f - V_i}{t}$$

where

Δ (cap delta) means "change in"

V_f = final velocity at time t_f

V_i = initial velocity at time t_i

If we start the time at $t_i = 0$ and rearrange the above, then

$$V_f = V_i + at \tag{1.4}$$

If we start the time at $t_i = 0$ and $V_i = 0$ (brakes locked before takeoff roll) and rearrange the above where V_f can be any velocity given, for example liftoff velocity, then

$$t = \frac{V_f}{a}$$

The distance s traveled in a certain time is

$$s = V_{av}t$$

where the average velocity V_{av} is

$$V_{av} = \frac{V_i + V_f}{2}$$

And incorporating Eq. 1.4, and substituting for V_f, we get

$$s = \left(\frac{((V_i + at) + V_i)}{2}\right)(t)$$

which yields

$$s = V_i t + \frac{1}{2}at^2 \tag{1.5}$$

Solving Eqs. 1.4 and 1.5 simultaneously and eliminating t, we can derive a third equation:

$$s = \frac{V_f^2 - V_i^2}{2a} \tag{1.6}$$

Equations 1.3–1.6 are useful in calculating takeoff and landing factors, and are studied in more detail in Chapters 8 and 9.

EXAMPLE

An aircraft that weighs 15 000 lb begins from a brakes-locked position on the runway, and then accelerates down the runway with a net force of 5000 lb until liftoff at a velocity of 110 kts. Calculate the average acceleration down the runway, the average time it takes to reach liftoff speed, and the total takeoff distance on the runway.

First, to calculate the acceleration, we need find the force (F) and the mass of the aircraft during the takeoff roll, Eq. 1.3: $F = m\,a$

Finding the mass: $m = \frac{W}{g} \rightarrow m = \frac{15\,000\text{ lb}}{32.2\text{ ft/s}^2} \rightarrow m = 465.8$ slugs

Finding the average acceleration: $a = \frac{F}{m} \rightarrow a = \frac{5000\ \text{lb}}{465.8\ \text{slugs}} \rightarrow a = 10.7\ \text{ft/s}^2$

Average time to liftoff:

$V_f = V_i + at \rightarrow$ where, $V_i = 0$

so,

$t = \frac{V_f}{a} \rightarrow t = \frac{185.9\ \text{ft/s}}{10.7\ \text{ft/s}^2} \rightarrow t = 17.4$ seconds

Total takeoff distance: $s = \frac{V_f^2 - V_i^2}{2a} \rightarrow s = \frac{(185.9)^2 - (0)}{2(10.7\ \text{ft/s}^2)} \rightarrow s = 1614.9$ ft

ROTATIONAL MOTION

Without derivation, some of the relationships among tangential (tip) velocity, V_t; radius of rotation, r; revolutions per minute, rpm; centripetal forces, CF; weight of rotating parts, W; and acceleration of gravity, g, are shown below. A more detailed discussion regarding rotorcraft can be found in Chapter 15 of this textbook.

$$V_t = \frac{r(\text{rpm})}{9.55}(\text{fps}) \tag{1.7}$$

$$\text{CF} = \frac{WV_t^2}{gr}(\text{lb}) \tag{1.8}$$

$$\text{CF} = \frac{W\,r(\text{rpm})^2}{2930} \tag{1.9}$$

For our discussion, the units of work will be measured in ft-lb.

ENERGY AND WORK

Energy is the ability to do work. In physics, work has a meaning different from the popular definition. You can push against a solid wall until you are exhausted but, unless the wall moves, you are not doing any work. Work requires that a force must move an object (displacement) in the direction of the force. Another way of saying this is that *only the component of the force in the direction of movement does any work:*

$$\text{Work} = \text{Force} \times \text{Distance}$$

There are many kinds of energy: solar, chemical, heat, nuclear, and others. The type of energy that is of interest to us in aviation is *mechanical energy*.

There are two kinds of mechanical energy: The first is called *potential energy of position*, or more simply *potential energy*, PE. No movement is involved in calculating PE. A good example of this kind of energy is water stored behind a dam. If released, the water would be able to do work, such as running a generator. As a fighter aircraft zooms to a zenith point, it builds PE; once it starts to accelerate downward, it converts PE to KE. PE equals the weight, W, of an object multiplied by the height, h, of the object above some base plane:

$$\text{PE} = Wh \quad (\text{ft-lb}) \tag{1.10}$$

The second kind of mechanical energy is called *kinetic energy*, KE. As the name implies, kinetic energy requires movement of an object. It is a function of the mass, m, of the object and its velocity, V:

$$\text{KE} = \frac{1}{2}mV^2 \quad (\text{ft-lb}) \tag{1.11}$$

The total mechanical energy, TE, of an object is the sum of its PE and KE:

$$\text{TE} = \text{PE} + \text{KE} \quad (\text{ft-lb}) \tag{1.12}$$

The law of conservation of energy states that the total energy (of a closed system) remains constant. Both potential and kinetic energy can change in value, but the total energy must remain the same. For example, when a ball is thrown upward, if the height of the thrower is the reference plane, its energy is all kinetic when it leaves the thrower's hand. As it rises, PE is continually increasing, but KE is always decreasing by the same amount, so the sum remains constant. At the top of its travel, PE is at its maximum (the same amount as the KE it had when it left the thrower's hand) and KE is zero. *Energy cannot be created or destroyed, but can change in form.*

EXAMPLE

An aircraft that weighs 15 000 lb is flying at 10 000 ft altitude at an airspeed of 210 kts. Calculate the potential energy, kinetic energy, and the total energy.

PE: $\text{PE} = Wh \rightarrow \text{PE} = 15000\text{ lb} \times 10000\text{ ft} \rightarrow \text{PE} = 1.5 \times 10^8$

KE: $\text{KE} = \frac{1}{2}mV^2 \rightarrow \text{KE} = \frac{1}{2}(465.8\text{ slugs})(354.9\text{ ft/s})^2 \rightarrow \text{KE} = 2.9 \times 10^7$

Total Energy: $\text{TE} = \text{PE} + \text{KE} \rightarrow \text{TE} = 1.79 \times 10^8$

Application 1.2

Consider a general aviation airplane that weighs 3000 lb with a designated approach speed over the runway threshold of 65 kts., calculate the KE. Now, consider if that same airplane approaches the runway with an extra 10 kts. of speed due to poor planning, calculate the new KE.

Why does only a 10 kts. change in approach speed result in such a wide margin of KE? What are the consequences of this "extra" energy?

POWER

In our discussion of work and energy, we have not mentioned time. *Power* is defined as "the rate of doing work" or work/time. We know:

$$\text{Work} = \text{force} \times \text{distance}$$