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- A thorough introduction to basic concepts in physics and mechanics, aerodynamic terms and definitions, and the primary and secondary flight control systems of flown aircraft
- An exploration of atmosphere, altitude, and airspeed measurement, with an increased focus on practical applications
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A PRACTICAL GUIDE FOR OPERATIONAL SAFETY

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FLIGHT THEORY AND AERODYNAMICS

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FOURTH EDITION

Joseph R. Badick
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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

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.

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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

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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.

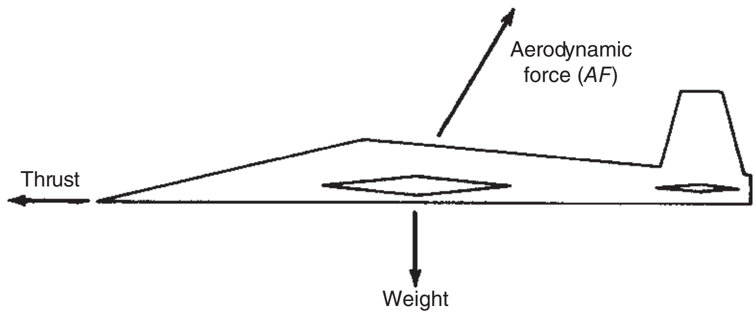


Figure 1.1. Forces on an airplane in steady flight.

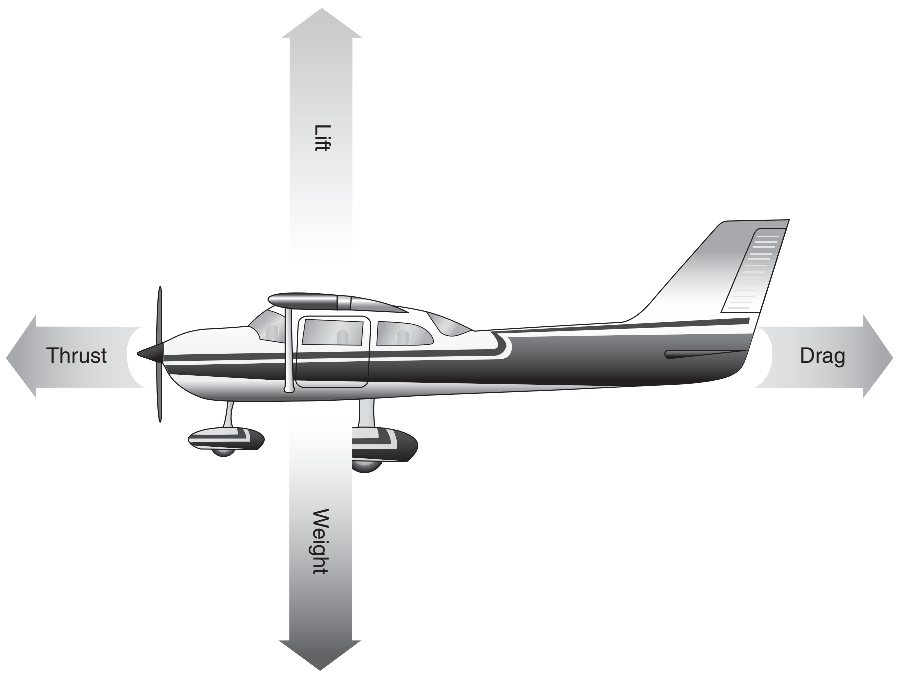


Figure 1.2. Resolved forces on an airplane in steady flight.
Source: U.S. Department of Transportation Federal Aviation Administration (2008a).

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.

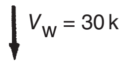


Figure 1.4. Vector of a north wind.

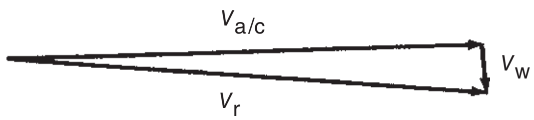


Figure 1.5. Vector addition.

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.

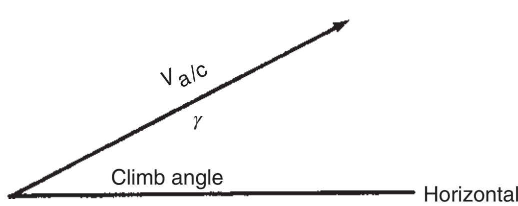


Figure 1.6. Vector of an aircraft in a climb.

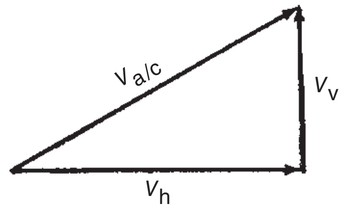


Figure 1.7. Vectors of groundspeed and rate of climb.

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.

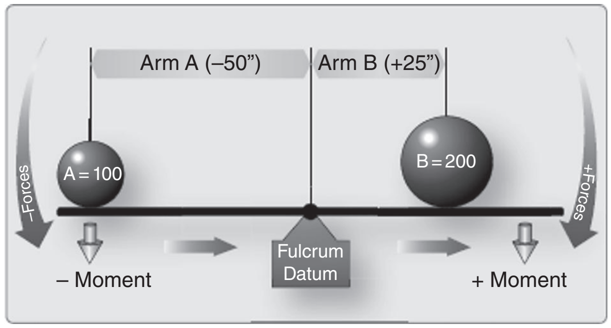


Figure 1.8. Balance Lever.

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 $100\text{ lb} \times -50'' = -5000$ lb-in. The weight of B is 200 lb and is located 25 inches to the right of datum, thus $200\text{ lb} \times 25'' = 5000$ 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?

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

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

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: $m = \dfrac{W}{g} \rightarrow m = \dfrac{15\,000\ \text{lb}}{32.2\ \text{ft/s}^2} \rightarrow m = 465.8$ 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: $s = \frac{V_f^2 - V_i^2}{2a} \rightarrow s = \frac{(185.9)^2 - (0)}{2(10.7 \text{ ft/s}^2)} \rightarrow s = 1614.9 \text{ ft}$

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:

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

and

$$\text{Speed} = \text{distance}/\text{time}$$
$$\text{Power} = \frac{\text{work}}{\text{time}} = \frac{\text{force} \times \text{distance}}{\text{time}} = \text{force} \times \text{speed} \quad (\text{ft-lb}/\text{s})$$

James Watt defined the term *horsepower* (HP) as 550 ft-lb/s:

$$\text{Horsepower} = \frac{\text{force} \times \text{speed}}{550}$$

If the speed is measured in knots, V_k, and the force is the *thrust*, T, of a jet engine, then

$$\text{HP} = \frac{\text{Thrust} \times V_k}{325} = \frac{TV_k}{325} \tag{1.13}$$

EXAMPLE

An aircraft's turbojet engine produces 8000 lb of thrust at 180 kts., what is the equivalent horsepower that engine is producing?

$$\text{HP} = \frac{TV_k}{325} \rightarrow \text{HP} = \frac{(8000\ \text{lb})(180\ \text{kts.})}{325} \rightarrow \text{HP} = 4431\ \text{HP}$$

Equation 1.13 is very useful in comparing thrust-producing aircraft (turbojets) with power-producing aircraft (propeller aircraft and helicopters); a more detailed discussion will follow in future chapters.

Application 1.3

Consider the example calculation provided to solve for horsepower (HP).

Would the horsepower remain the same if the thrust remained 8000 lb but the aircraft slowed to a speed of 160 kts.? Why or why not? How can the equation be altered to solve for thrust (T) if an aircraft was maintaining a constant speed with a known HP?

FRICTION

If two surfaces are in contact with each other, then a force develops between them when an attempt is made to move them relative to each other. This force is called *friction*. Generally, we think of friction as something to be avoided because it wastes energy and causes parts to wear. In our discussion on drag, we will discuss the parasite drag on an airplane in flight and the thrust or power to overcome that force. Friction is not always our enemy; however, without it there would be no traction between an aircraft's tires and the runway. Once an aircraft lands, lift is reduced and a portion of the weight contributes to frictional force. Depending on the aircraft type, aerodynamic braking, thrust reversers, and spoilers will be used to assist the brakes and shorten the landing, or rejected takeoff distance.

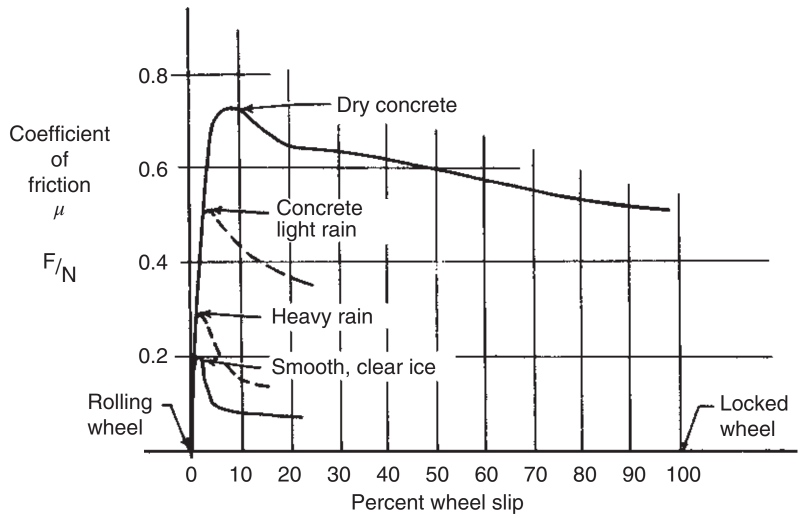


Figure 1.9. Coefficients of friction for airplane tires on a runway.

At the microscopic level, as in the surface of a wing, friction causes resistance and slows down the velocity of the air as it passes over it. The layer of air that is impacted by the friction of the wing, or any other surface of the aircraft, is referred to as the boundary layer.

Several factors are involved in determining friction effects on aircraft during takeoff and landing operations. Among these are runway surfacing material, condition of the runway, tire material and tread, and the amount of brake slippage. All of these variables determine a *coefficient of friction* μ (mu). The actual braking force, F_b, is the product of this coefficient μ (Greek symbol mu) and the normal force, N, between the tires and the runway (Eq. 1.14):

$$F_b = \mu N \quad (\text{lb}) \tag{1.14}$$

Figure 1.9 shows typical values of the coefficient of friction for various conditions. Note the value of μ for dry concrete is ~0.7 with ~10% wheel slip, while the μ on smooth, clear ice is ~0.2. This means that an airplane wheel rolling on smooth, clear ice will experience much lower friction (increased stopping distance) than a wheel rolling on dry concrete.

EXAMPLE

Calculate the braking force on dry concrete when the normal force (N) is 2000 lb.

$$F_b = \mu N \rightarrow F_b = (0.7)(2000\ \text{lb}) \rightarrow F_b = 1400\ \text{lb}$$

SYMBOLS

a	acceleration (ft/s^2)
E	Energy (ft-lb)

KE	Kinetic energy (ft-lb)
PE	Potential energy (ft-lb)
TE	Total energy (ft-lb)
F	Force (lb)
F_b	Braking force (lb)
g	Acceleration of gravity (ft/s^2)
h	Height (ft)
HP	Horsepower
L	Moment arm (ft or in.)
m	Mass (slugs, lb-s^2/ft)
M	Moment (ft-lb or in.-lb)
N	Normal force (lb)
r	Radius (ft)
rpm	Revolutions per minute
s	Distance (ft)
T	Thrust (lb)
t	Time (second)
V	Velocity (ft/s) or (kts.)
V_f	Final velocity (ft/s)
V_k	Velocity (kts.)
V_i	Initial velocity (ft/s)
V_t	Tangential (tip) speed (ft/s)
W	Weight (lb)
μ (mu)	Coefficient of friction (dimensionless)

KEY TERMS

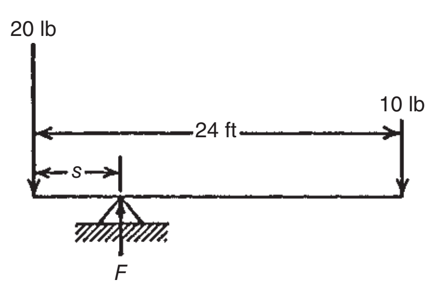
Acceleration
Area
Arm
Coefficient of friction
Centripetal force
Component vector
Energy
Equilibrium
Force
Friction
Kinetic energy
Laws of motion
Linear
Mass
Mechanical energy
Motion
Potential energy
Power
Pressure
Resultant vector
Rotational motion
Scalar quantity

Torque
Velocity
Vector quantity
Vector resolution
Work

PROBLEMS

Note: Answers to problems are given at the end of the book.

1. Convert 65 kts. to fps.
2. Convert 200 fps to kts.
3. Convert 35 kts. to fpm.
4. Convert 52 nm to sm.
5. An airplane weighs 16 000 lb. The local gravitational acceleration g is 32.2 fps^2. What is the mass of the airplane?
6. The airplane in Problem 5 accelerates down the runway with a net forward force (thrust less drag) of 6000 lb. Find the acceleration of the airplane.
7. The airplane in Problem 6 starts from a brakes-locked position on the runway. The airplane takes off at an airspeed of 200 fps. Find the time for the aircraft to reach takeoff speed.
8. Under no-wind conditions, what takeoff roll is required for the aircraft in Problem 7?
9. Upon reaching a velocity of 100 fps, the pilot of the airplane in Problem 7 decides to abort the takeoff and applies brakes and stops the airplane in 1000 ft. Find the airplane's deceleration.
10. An airplane is towing a glider to altitude. The tow rope is 20° below the horizontal and has a tension force of 300 lb exerted on it by the airplane. Find the horizontal drag of the glider and the amount of lift that the rope is providing to the glider. Sin 20° = 0.342; cos 20° = 0.940.
11. A jet airplane is climbing at a constant airspeed in no-wind conditions. The plane is directly over a point on the ground that is 4 statute miles from the takeoff point and the altimeter reads 15 840 ft. Find the plane's climb angle and the distance that it has flown through the air.
12. Find the distance s and the force F on the seesaw fulcrum shown in the figure. Assume that the system is in equilibrium.



13. A helicopter has a rotor diameter of 30 ft and it is being operated in a hover at 286.5 rpm. Find the tip speed V_t of the rotor.

14. An airplane weighs 16 000 lb and is flying at 5 000 ft altitude and at an airspeed of 200 fps. Find (a) the potential energy, (b) the kinetic energy, and (c) the total energy. Assuming no extra drag on the airplane, if the pilot drove until the airspeed was 400 fps, what would the altitude be?

15. An aircraft's turbojet engine produces 10 000 lb of thrust at 162.5 kts. true airspeed. What is the equivalent power that it is producing?

16. An aircraft weighs 24 000 lb and has 75% of its weight on the main (braking) wheels. If the coefficient of friction is 0.7, find the braking force F_b on the airplane.

17. Newton's third law of motion states:
   a. 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.
   b. For every action force there is an equal and opposite reaction force.
   c. 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.

18. An aircraft parked on an airport ramp would be an example of Newton's _______ law of motion.
   a. first.
   b. second.
   c. fourth.
   d. third.

19. An airplane in level flight increases thrust, resulting in an acceleration until once again thrust equals:
   a. aerodynamic force.
   b. lift.
   c. weight.
   d. drag.

20. An airplane in straight-and-level, unaccelerated flight weighs 2300 lb, what total lift must the aircraft produce to maintain a constant altitude assuming no additional forces are involved:
   a. 2000 lb
   b. 2300 lb
   c. 1150 lb
   d. >2300 lb

2 Atmosphere, Altitude, and Airspeed Measurement

CHAPTER OBJECTIVES

After completing this chapter, you should be able to:

- Identify the important properties of the atmosphere that influence the aerodynamics of flight.
- Define standard pressure and temperature, and calculate pressure and temperature ratios when a standard atmosphere is not encountered.
- Summarize the relationship between pressure altitude and density altitude.
- Analyze the standard atmosphere table and recognize the change in atmospheric properties with a change in altitude.
- Define and compare the definitions for various types of altitude used in aerodynamics and illustrate why each type is important.
- Explain the relationship between the continuity equation and Bernoulli's equation, and show how they apply to an aircraft in flight.
- Define and compare the definitions for various types of airspeed used in aerodynamics and illustrate why each type is important.
- Determine the true airspeed of an aircraft in flight.

PROPERTIES OF THE ATMOSPHERE

The aerodynamic forces and moments acting on an aircraft in flight are due, in great part, to the properties of the air mass in which the aircraft is flying. By volume, the atmosphere is composed of approximately 78% nitrogen, 21% oxygen, and 1% other gases. The most important properties of air that affect aerodynamic behavior are its static pressure, temperature, density, and viscosity.

It is important to remember at this point that air is a fluid, and like other gases takes on the shape of its container. Just as a liquid can fill a container, air has the capacity to expand and fill the container as well, though the density will differ significantly. Throughout this textbook, we will expand on this

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Joseph R. Badick and Brian A. Johnson.

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introduction to the fluid properties of air, especially as it relates to an airfoil and ultimately the impact on aircraft performance calculations.

Static Pressure

The *static pressure* of the air, *P*, is simply the weight per unit area of the air above the level under consideration. Air has mass and as we have discussed thus has weight, which means it exerts a force. For instance, the weight of a column of air with a cross-sectional area of 1 ft^2 and extending upward from sea level through the atmosphere is 2116 lb. The sea level static pressure is, therefore, 2116 pounds per square foot (psf), or 14.7 pounds per square inch (psi). Another commonly used measure of static pressure is *inches of mercury*. On a standard sea level day, the air's static pressure will support a column of mercury (Hg) that is 29.92″ high (Figure 2.1). Weather reports express pressure in *millibars*; standard atmospheric pressure is 1013.2 mb. In addition to these rather confusing systems, there are the metric measurements in use throughout most of the world. For the discussion of performance problems in this textbook, we will primarily use the measurement of static pressure in inches of mercury is the standard used unless stated otherwise.

Static pressure is reduced as altitude is increased because there is less air weight above. At 18 000 ft altitude, the static pressure is about half that at sea level, the higher you go the less air there is above. The accepted standard pressure lapse rate is approximately 1″ Hg decrease in pressure for every 1000 ft gain in altitude from sea level (Figure 2.2). This change in atmospheric pressure with altitude is an important concept during evaluation of aircraft performance as well as the operation of aircraft flight instruments.

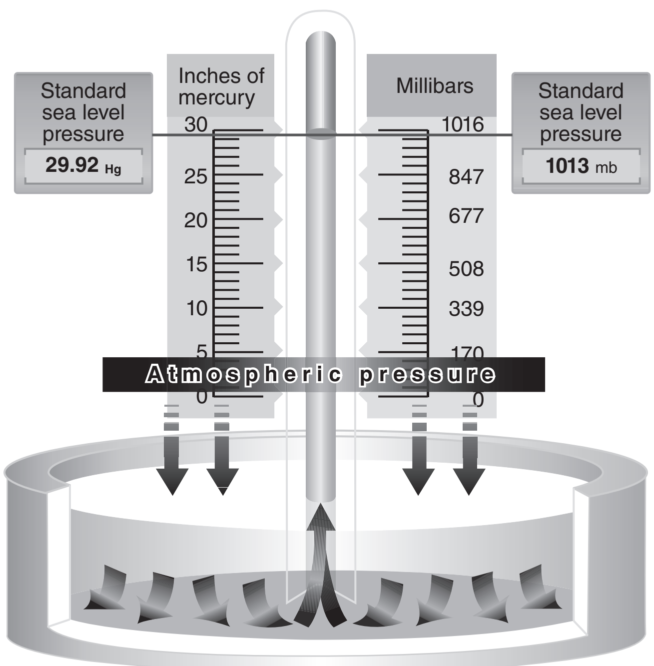


Figure 2.1. Standard pressure.
Source: U.S. Department of Transportation Federal Aviation Administration (2008a).

Standard atmosphere			
Altitude (ft)	Pressure (Hg)	Temperature	
		(°C)	(°F)
0	29.92	15.0	59.0
1 000	28.86	13.0	55.4
2 000	27.82	11.0	51.9
3 000	26.82	9.1	48.3
4 000	25.84	7.1	44.7
5 000	24.89	5.1	41.2
6 000	23.98	3.1	37.6
7 000	23.09	1.1	34.0
8 000	22.22	−0.9	30.5
9 000	21.38	−2.8	26.9
10 000	20.57	−4.8	23.3
11 000	19.79	−6.8	19.8
12 000	19.02	−8.8	16.2
13 000	18.29	−10.8	12.6
14 000	17.57	−12.7	9.1
15 000	16.88	−14.7	5.5
16 000	16.21	−16.7	1.9
17 000	15.56	−18.7	−1.6
18 000	14.94	−20.7	−5.2
19 000	14.33	−22.6	−8.8
20 000	13.74	−24.6	−12.3

Figure 2.2. Properties of a standard atmosphere.
Source: U.S. Department of Transportation Federal Aviation Administration (2016b).

In aerodynamics, it is convenient to use pressure ratios, rather than actual pressures; thus the units of measurement are canceled out. When at sea level on a standard day, the pressure ratio can be determined using equation:

$$\text{Pressure ratio } \delta \text{ (delta)} = \frac{P}{P_0} \tag{2.1}$$

where P_0 is the sea level standard static pressure (2116 psf or 29.92″ Hg). Thus, a pressure ratio of 0.5 means that the ambient pressure is one-half of the standard sea level value. At 18 000 ft, on a standard day, the pressure ratio is 0.4992.

Temperature

The commonly used measures of temperature are the Fahrenheit, °F, and Celsius, °C scales. Aviation weather reports for pilots, as well as performance calculation tables, will usually report the temperature in °C. In a standard atmosphere, the sea level surface temperature is 15 °C or 59 °F.

Since neither of these scales has absolute zero as a base, neither can be used in calculations; absolute temperature must be used instead. Absolute zero is −460 °F, or −273 °C. To convert from the Fahrenheit system to the absolute system, called Rankine, R, add 460 to the °F. To convert from the Celsius system to the absolute system, called Kelvin, K, add 273 to the °C. The symbol for absolute temperature is T and the symbol for sea level standard temperature is T_0:

$$T_0 = 519°\text{R} \ \ (59°\text{F} + 460)$$
$$T_0 = 288°\text{K} \ \ (15°\text{C} + 273)$$

By using temperature ratios, instead of actual temperatures, the units cancel. The temperature ratio is the Greek letter theta, θ:

$$\theta = \frac{T}{T_0} \tag{2.2}$$

At sea level, on a standard day, $\theta_{0°} = 1.0$. Temperature in a standard atmosphere decreases with altitude until the tropopause is reached (36 089 ft on a standard day). The rate of change of temperature with altitude is known as the lapse rate. The standard lapse rate is approximately a 2 °C decrease in temperature for every 1000 ft increase in altitude from sea level (Figure 2.2) up to the tropopause. Temperature then remains constant until an altitude of about 82 023 ft.

As an example, if the temperature at the tropopause is −69.7 °F, calculate θ:

$$\theta = \frac{(-69.7°\text{F} + 460)}{519°\text{R}} = 0.752$$

Density

Density is the most important property of air in the study of aerodynamics, and is directly impacted by pressure, temperature, and humidity changes. Since air can be compressed and expanded, the lower the pressure the less dense the air: density is directly proportional to pressure. Increasing the temperature of the air (giving the particles greater kinetic energy) also decreases the density of the air, so in this case density and temperature have an inverse relationship.

Less dense, thinner air has a lower air density and is said to be a *higher density altitude* (decreasing aircraft performance); more dense, thicker air is said to be a *lower density altitude* (improved aircraft performance). Decreasing the density of the air results in a higher density altitude, while increasing the density of the air results in a lower density altitude.

Atmospheric pressure decreases as altitude increases. Temperature also decreases with increasing altitude, with two exceptions: first, when a temperature inversion layer exists, and second, in the troposphere, where the temperature remains constant and may even rise with increasing altitude. The discussion above would indicate that greater the altitude (less dense air) and colder temperature (more dense air) would result in a conflict in regard to density. But usually, the effect of a decrease in pressure with altitude overcomes any improvement in performance the colder, dense air may have, and a lower density altitude is the rule of thumb the higher in altitude an aircraft climbs.

The effect of moisture content on performance will be largely ignored in this textbook because most textbooks treat the effect of humidity as being negligible for practical purposes, but it is important to understand that water vapor is lighter than air, so moist air is lighter than dry air. As the amount of water vapor increases, the density of the air decreases, resulting in a higher density altitude (decrease in aircraft performance).

Application 2.1

Consider an aircraft departing from an airport located at sea level in Florida on a hot, humid day. Now consider the same aircraft under the same weight, temperature, and pressure conditions on a much drier day from the same airport, the only change is the amount of water vapor in the atmosphere.

Using an online density altitude calculator such as the one provided by the National Oceanic and Atmospheric Administration (NOAA), calculate the impact on density altitude by adjusting the dewpoint values. Could a change in water vapor affect an aircraft's climb rate?

Density is the mass of the air per unit of volume. The symbol for density is ρ (rho):

$$\rho = \frac{\text{Mass}}{\text{Unit volume}} \quad \left(\text{slugs/ft}^3\right)$$

Standard sea level density is $\rho_0 = 0.002\,377$ slugs/ft^3. Density decreases with an increase in altitude. At 22000 ft, the density is 0.001183 slugs/ft^3 (about one-half of sea level density).

It is desirable in aerodynamics to use density ratios instead of the actual values of density. The symbol for density ratio is σ (sigma):

$$\sigma = \frac{\rho}{\rho_0} \tag{2.3}$$

The universal gas law shows that density is directly proportional to pressure and inversely proportional to absolute temperature:

$$\rho = \frac{P}{RT} \tag{2.4}$$

Forming a ratio gives

$$\frac{\rho}{\rho_0} = \frac{P/RT}{P_0/RT_0} = \frac{P/P_0}{T/T_0}$$

R is the gas constant and cancels, so the density ratio, or sigma, is a function of pressure and temperature:

$$\sigma = \frac{\delta}{\theta} \tag{2.5}$$

Viscosity

Viscosity can be simply defined as the internal friction of a fluid caused by molecular attraction that makes it resist its tendency to flow. The viscosity of the air is important when discussing airflow in the region very close to the surface of an aircraft. This region is called the *boundary layer*. We discuss viscosity in more detail when we take up the subject of boundary layer theory.

ICAO STANDARD ATMOSPHERE

To provide a basis for comparing aircraft performance at different parts of the world and under varying atmospheric conditions, the performance data must be reduced to a set of standard conditions. These are defined by the International Civil Aviation Organization (ICAO) and are compiled in a standard atmosphere table. An abbreviated table is shown here as Table 2.1. Columns in the table show standard day density, density ratio, pressure, pressure ratio, temperature, temperature ratio, and speed of sound at various altitudes.

Table 2.1. Standard atmosphere table

Altitude (ft)	Density ratio, σ	$\sqrt{\sigma}$	Pressure ratio, δ	Temperature (°F)	Temperature ratio, θ	Speed of sound (kts.)	Kinematic viscosity, ν (ft^2/s)
0	1.0000	1.0000	1.0000	59.00	1.0000	661.7	0.000 158
1 000	0.9711	0.9854	0.9644	55.43	0.9931	659.5	0.000 161
2 000	0.9428	0.9710	0.9298	51.87	0.9862	657.2	0.000 165
3 000	0.9151	0.9566	0.8962	48.30	0.9794	654.9	0.000 169
4 000	0.8881	0.9424	0.8637	44.74	0.9725	652.6	0.000 174
5 000	0.8617	0.9283	0.8320	41.17	0.9656	650.3	0.000 178
6 000	0.8359	0.9143	0.8014	37.60	0.9587	647.9	0.000 182
7 000	0.8106	0.9004	0.7716	34.04	0.9519	645.6	0.000 187
8 000	0.7860	0.8866	0.7428	30.47	0.9450	643.3	0.000 192
9 000	0.7620	0.8729	0.7148	26.90	0.9381	640.9	0.000 197
10 000	0.7385	0.8593	0.6877	23.34	0.9312	638.6	0.000 202
15 000	0.6292	0.7932	0.5643	5.51	0.8969	626.7	0.000 229
20 000	0.5328	0.7299	0.4595	−12.32	0.8625	614.6	0.000 262
25 000	0.4481	0.6694	0.3711	−30.15	0.8281	602.2	0.000 302
30 000	0.3741	0.6117	0.2970	−47.98	0.7937	589.5	0.000 349
35 000	0.3099	0.5567	0.2353	−65.82	0.7594	576.6	0.000 405
36 089[a]	0.2971	0.5450	0.2234	−69.70	0.7519	573.8	0.000 419
40 000	0.2462	0.4962	0.1851	−69.70	0.7519	573.8	0.000 506
45 000	0.1936	0.4400	0.1455	−69.70	0.7519	573.8	0.000 643
50 000	0.1522	0.3002	0.1145	−69.70	0.7519	573.8	0.000 818

[a]The tropopause.

ALTITUDE MEASUREMENT

When a pilot uses the term altitude, the reference is usually to altitude above sea level as read on the altimeter, but it is important that the distinction is made to understand what *types* of altitude exist. When meteorologists refer to the height of the cloud layer above an airfield, they are usually referring to the altitude above the field elevation. When air traffic control refers to an altitude at FL180 and above, they are referring to pressure altitude. A flight crew in an aircraft approaching the runway during a low ceiling CAT III instrument approach will need to understand the value of a radar altimeter. Understanding what "altitudes" are important at different periods of flight, and the effect of temperature, pressure, and moisture on those altitudes, is imperative for safe flight.

Indicated Altitude

Indicated altitude is the *altitude* that is read directly from the altimeter and is uncorrected for any errors. In the United States, below FL180 the altimeter is set to the current altimeter setting of the field you are departing from or arriving to, or is given by air traffic control for the current area you are flying in. In the United States, when flying at or above 18 000 ft, altitude is measured in Flight Levels (e.g. FL180 for 18 000 ft). At FL180, the indicated altitude will be equal to pressure altitude as the altimeter setting is set to 29.92″, standard pressure, or QNE. The altitude at which the crew changes to 29.92 is called the transition altitude (TA). When the crew descends for landing, the altitude at which they return the altimeter setting to local barometric pressure corrected to sea level (QNH) is called the transition level (TL). (Remember it this way: 29.92 is selected at the TA, and the "A" stands for aloft, as in climbing or cruise. When returning to land, the TL is set on descent, and "L" stands for low, or landing.)

When QNE is lower than 29.92, the lowest usable flight level is no longer FL180. The lowest usable FL is obtained from the aeronautical publications. For instance, in the United States, if the pressure in the area of operations is between 29.91 and 29.42″, the lowest usable enroute altitude is FL185. It should also be noted that the TA and TL outside the United States will not always be 18 000. ICAO members set their own values.

Incidentally, QFE is the reference pressure set in the altimeter if the pilot wishes to know the elevation above the airfield. When the aircraft is on the airfield, the altimeter reads zero. QFE is seldom used as it would be of limited value when away from the immediate vicinity of the airfield.

Calibrated Altitude

Calibrated altitude is indicated altitude corrected for instrument and installation errors.

True Altitude

True altitude is the actual altitude above mean sea level and is referenced as mean sea level (MSL). On most aeronautical charts, MSL altitudes are published for man-made objects such as towers and buildings, as well as for terrain, since this is the altitude closest to the altitude read off the altimeter. An important note is that true altitude will only be the same as indicated altitude when flying in standard conditions, which is very rare. When flying in conditions colder than standard, the altimeter will indicate a higher altitude then you are flying, so true altitude will be lower than indicated altitude. The same dangerous situation can develop when you are flying from a high-pressure area to a low-pressure area and the altimeter is not corrected for the local altimeter setting. Your altimeter will interpret the lower pressure as a higher altitude and your true altitude will again be lower than your indicated altitude. From the variations in true altitude versus indicated altitude, the saying was developed "high to low, or hot to cold, look out below." Of course, this assumes that the altimeter is never reset to local pressure for an entire flight covering a long distance with varying temperatures and pressures.

Absolute Altitude

Absolute altitude is the vertical altitude above the ground (AGL), and can be measured with devices like a radar altimeter. Of course, your absolute altitude is more critical the closer to the ground you are flying; so even when not equipped with a radar altimeter, a pilot should be aware of their AGL altitude. When conducting an instrument approach in inclement weather, knowledge of your AGL altitude is vital to the safe completion of the approach or execution of a missed approach. Your height above airport (HAA), height above touchdown zone (HAT), and decision height (DH) are all AGL altitudes and should be briefed before the approach.

Pressure Altitude

Regarding aircraft performance, two types of altitude are of most interest to a pilot: pressure altitude and density altitude.

Pressure altitude is that corrected altitude in the standard atmosphere corresponding to a certain static pressure. Pressure altitude is the vertical distance above a standard datum plane where atmospheric pressure is 29.92″. In the United States, at FL180 and above, the altimeter is always set to 29.92″ unless abnormally low pressure exists in the area. Pressure altitude is used in performance calculations to compute true airspeed, density altitude, and takeoff and landing data.

Figure 2.3 provides a convenient method to determine pressure altitude. For example, if a given airport elevation is 3500 ft and the automated weather observation states a pressure value of 30.10″, use the altitude correction column to determine that 165 needs to be subtracted from 3500 ft. The pressure altitude in the given condition is 3335 ft, which makes sense as it is lower. The pressure given is higher than standard pressure, thus the air density is higher, resulting in a lower pressure altitude.

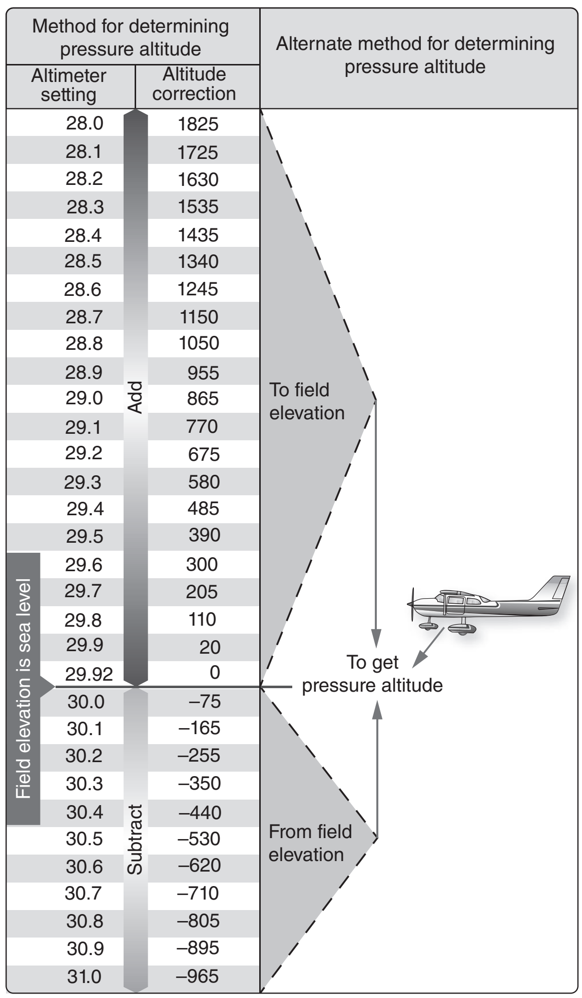
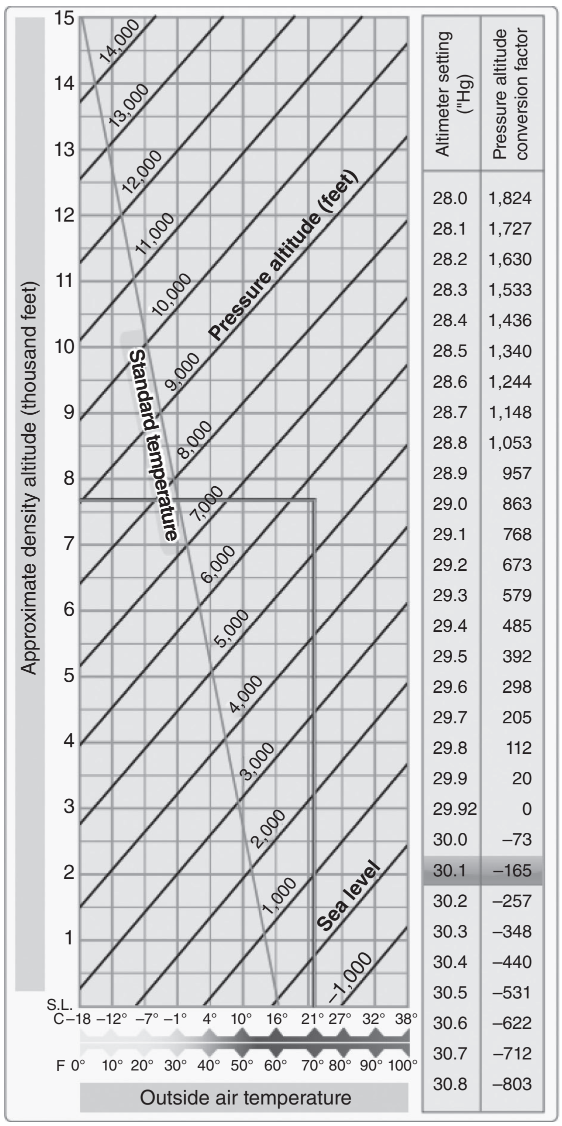


Figure 2.3. Field elevation versus pressure altitude.
Source: U.S. Department of Transportation Federal Aviation Administration (2008a).

Density Altitude

Density altitude is the altitude used to calculate aircraft performance in most situations. Density altitude is found by correcting pressure altitude for nonstandard temperature conditions. Pressure altitude and density altitude are the same when conditions are standard. Once pressure altitude has been determined, the density altitude is calculated using outside air temperature. If the temperature is below standard, then the density altitude is lower than pressure altitude and aircraft performance is improved. If the outside air temperature is warmer than standard, the density altitude is higher than pressure altitude and aircraft performance is degraded.

Figure 2.4 is a commonly used chart for performance calculations to determine density altitude. As provided by the *Pilot's Handbook of Aeronautical Knowledge*, using Figure 2.4, we will calculate the pressure



Altimeter setting ("Hg)	Pressure altitude conversion factor
28.0	1,824
28.1	1,727
28.2	1,630
28.3	1,533
28.4	1,436
28.5	1,340
28.6	1,244
28.7	1,148
28.8	1,053
28.9	957
29.0	863
29.1	768
29.2	673
29.3	579
29.4	485
29.5	392
29.6	298
29.7	205
29.8	112
29.9	20
29.92	0
30.0	–73
30.1	–165
30.2	–257
30.3	–348
30.4	–440
30.5	–531
30.6	–622
30.7	–712
30.8	–803

Figure 2.4. Pressure altitude conversion and density altitude chart.
Source: U.S. Department of Transportation Federal Aviation Administration (2016b).

altitude first, and then calculate the resulting density altitude based on temperature. With a given airport elevation of 5883 ft and an altimeter setting of 30.10″, as shown in Figure 2.3 the resulting pressure altitude is calculated to be 5718 ft. Since the density altitude is pressure altitude corrected for nonstandard temperature, we then use the provided 70 °C temperature and move from the *X*-axis vertically until we reach the diagonal line (interpolated) for 5718 ft. Moving horizontally to the *Y*-axis, the density altitude is determined to be 7700 ft, which makes sense as it is higher than the pressure altitude since the temperature is above standard for that altitude, resulting in lower air density (higher density altitude).

EXAMPLE

Using Table 2.1 and several of the equations from earlier in this chapter, the density altitude can also be determined using ratios. An aircraft at an indicated altitude of 1800 ft has an altimeter setting of 29.70″ Hg (sea level) and an outside air temperature of 75 °F. Calculate the density altitude:

Pressure altitude (P.A.) = 2005 ft is found using Figure 2.3.

Referencing Table 2.1 for P.A. 2000 ft, $\delta = 0.9298$

Using Eq. 2.2, $\theta = 1.031$

Using Eq. 2.5, solve for the density ratio

$$\sigma = \frac{\delta}{\theta} \rightarrow \sigma = \frac{0.9298}{1.031} \rightarrow \sigma = 0.902$$

Using Table 2.1, it can be interpolated that with a density ratio of 0.902, the resultant density altitude is 3500 ft. This makes sense as the sea level pressure is lower than standard and the temperature is above standard for that altitude, which results in lower air density (higher density altitude).

As discussed, density altitude influences aircraft performance; the higher the density altitude, the lower the aircraft performance. So, in the previous problem, even though the aircraft is at an indicated altitude of 1800 ft, the density altitude for performance calculations is 3500 ft. Low air density equals a higher density altitude; high air density equals a lower density altitude. Therefore, aircraft performance charts are provided for various density altitudes.

Application 2.2

A non-pressurized, single-engine aircraft departs for a cross-country flight at 6500 ft. A portion of the route crosses rising terrain with peaks at 5000 ft. The pilot is only concerned with maintaining an indicated altitude of 6500 ft as filed on the visual flight rules (VFR) flight plan.

What other altitudes must the pilot consider along the route of flight? What are the implications of failing to adjust the altimeter setting if the barometric pressure is decreasing along the route? Consider the FAA definition of Maximum Elevation Figure (MEF) on VFR Sectionals and if nonstandard pressure and temperature may impact obstacle clearance.

CONTINUITY EQUATION

Consider the flow of air through a pipe of varying cross section as shown in Figure 2.5. There is no flow through the sides of the pipe: air flows only through the ends. The mass of air entering the pipe, in a given unit of time, equals the mass of air leaving the pipe, in the same unit of time. The mass flow through the pipe, must remain constant. The mass flow at each station is equal. Constant mass flow is called *steady-state flow*. The mass airflow is equal to the volume of air multiplied by the density of the air. The volume of air, at any station, is equal to the velocity of the air multiplied by the cross-sectional area of that station.

The mass airflow symbol Q is the product of the density, the area, and the velocity:

$$Q = \rho A V \tag{2.6}$$

The continuity equation states that the mass airflow is a constant:

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 = \rho_3 A_3 V_3 = \text{constant} \tag{2.7}$$

The continuity equation is valid for steady-state flow, both in subsonic and supersonic flow. For subsonic flow, the air is considered to be incompressible, and its density remains constant. The density symbols can then be eliminated; thus, for subsonic flow,

$$A_1 V_1 = A_2 V_2 = A_3 V_3 = \text{constant} \tag{2.8}$$

Velocity is inversely proportional to cross-sectional area: as cross-sectional area decreases, velocity increases.

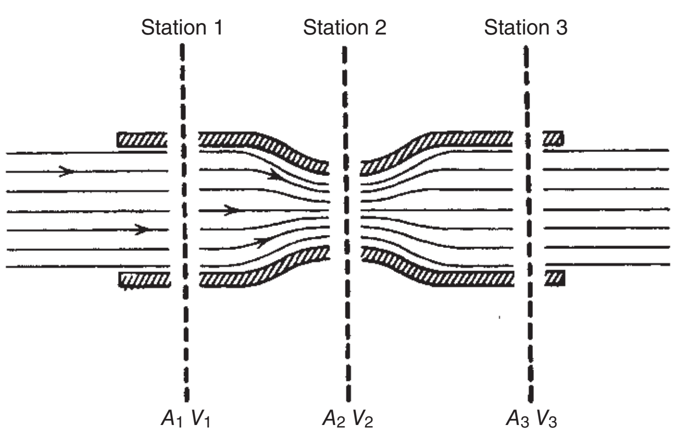


Figure 2.5. Flow of air through a pipe.

BERNOULLI'S EQUATION

The continuity equation explains the relationship between velocity and cross-sectional area. It does not explain differences in static pressure of the air passing through a pipe of varying cross sections. Bernoulli, using the principle of conservation of energy, developed a concept that explains the behavior of pressures in flowing gases.

Consider the flow of air through a venturi tube as shown in Figure 2.6. In Image A, as the mass of air experiences a constriction in the tube and as the velocity of the mass increases, the pressure decreases. A comparative image of a wing experiencing Bernoulli's principle during flight is in Image B. Note the decreased density toward the rear of the airfoil, this will be a discussion area in Chapters 3 and 4.

The energy of an airstream is in two forms: It has a *potential energy*, which is its static pressure, and a *kinetic energy*, which is its dynamic pressure. The total pressure of the airstream is the sum of the static pressure and the dynamic pressure. The total pressure remains constant, according to the law of conservation of energy. Thus, an increase in one form of pressure must result in an equal decrease in the other.

Static pressure is an easily understood concept (see the discussion earlier in this chapter). Dynamic pressure, q, is similar to kinetic energy in mechanics and is expressed by

$$q = \frac{1}{2}\rho V^2 \quad \text{(psf)} \tag{2.9}$$

where V is measured in feet per second. Pilots are much more familiar with velocity measured in knots instead of in feet per second, so a new equation for dynamic pressure, q, is used in this book. Its derivation is shown here:

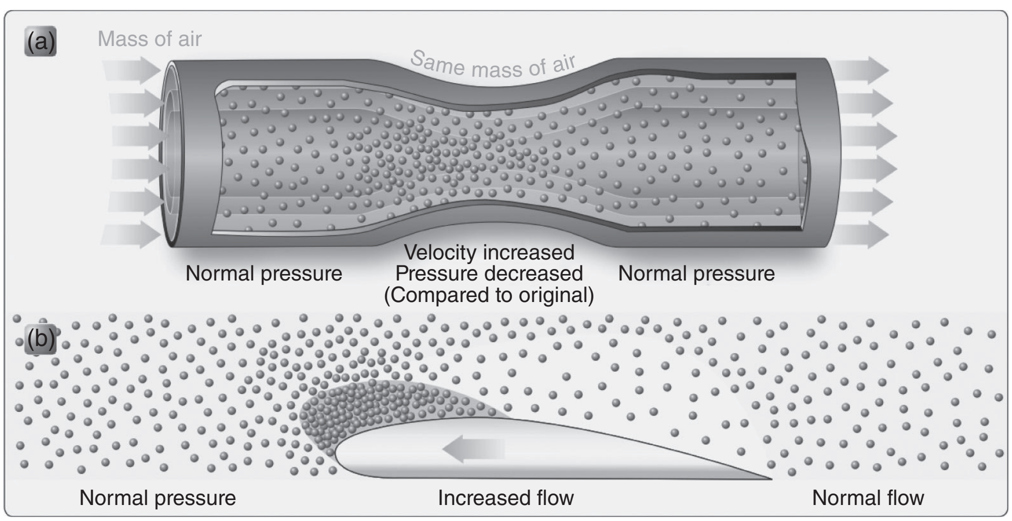


Figure 2.6. Pressure change in a venturi tube.
Source: U.S. Department of Transportation Federal Aviation Administration (2018).

$$\text{Density ratio}, \sigma = \frac{\rho}{\rho_0} = \frac{\rho}{0.002\,377}$$
$$\text{or } \rho = 0.002\,377\sigma$$
$$V_{\text{fps}} = 1.69 V_{\text{k}}$$
$$\left(V_{\text{fps}}\right)^2 = 2.856 (V_{\text{k}})^2$$

Substituting in Eq. 2.9 yields

$$q = \frac{\sigma V_{\text{k}}^2}{295} \ (\text{psf}) \tag{2.10}$$

Bernoulli's equation can now be expressed as

Total pressure (head pressure), H = Static pressure, P + Dynamic pressure, q:

$$\text{Total pressure (head pressure)}, H = \text{Static pressure}, P + \text{Dynamic pressure}, q: \quad H = P + \frac{\sigma V_{\text{k}}^2}{295} \ (\text{psf}) \tag{2.11}$$

To visualize how lift is developed on a cambered airfoil, draw a line down the middle of a venturi tube. Discard the upper half of the figure and superimpose an airfoil on the constricted section of the tube (Figure 2.7). Note that the static pressure over the airfoil is less than that ahead of it and behind it, so, as dynamic pressure increases, static pressure decreases.

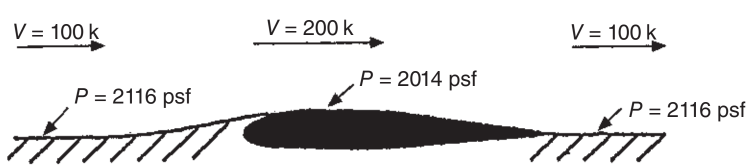


Figure 2.7. Velocities and pressures on an airfoil superimposed on a venturi tube.

AIRSPEED MEASUREMENT

If a symmetrically shaped object is placed in a moving airstream (Figure 2.8), the flow pattern will be as shown. Some airflow will pass over the object and some will flow beneath it, but at the point at the nose of the object, the flow will be stopped completely. This point is called the *stagnation point*. Since the air velocity at this point is zero, the dynamic pressure is also zero. The stagnation pressure is, therefore, all static pressure and must be equal to the total pressure, H, of the airstream.

In Figure 2.9, the free stream values of velocity and pressure are used to measure the indicated airspeed of an aircraft. The pitot tube is shown as the *total pressure port* and must be pointed into the relative wind for accurate readings. Static pressure, sometimes referred to as ambient pressure, is the pressure around the

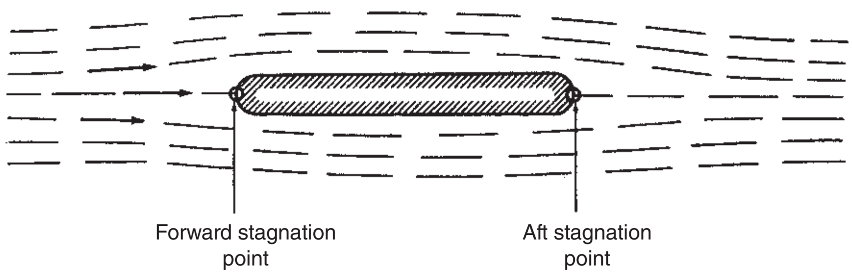


Figure 2.8. Flow around a symmetrical object.

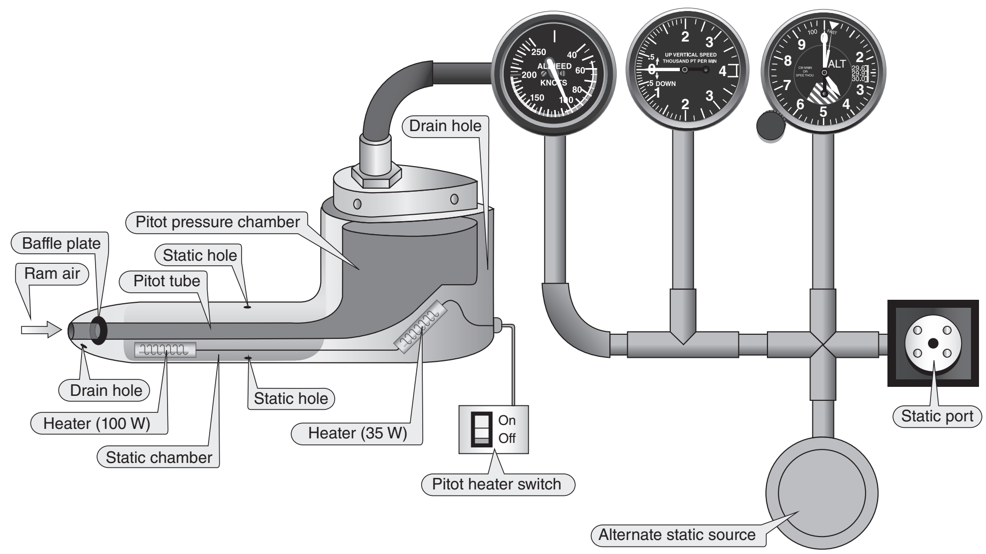


Figure 2.9. Schematic of a pitot–static airspeed indicator.
Source: U.S. Department of Transportation Federal Aviation Administration (2012c).

aircraft whether it is moving or at rest, and is the same "local" pressure your body experiences. When in motion, the air entering the pitot tube comes to a complete stop and thus the static pressure in the tube is equal to the total free stream pressure, *H*. This pressure is ducted into a diaphragm inside the airspeed indicator.

The static pressure port(s) can be made as a part of the point tube or it can be at a distance from the pitot tube on the side of the aircraft. It should be located at a point where the local air velocity is exactly equal to the airplane velocity. The static port is made so that none of the velocity enters the port. The port measures only static pressure, and none of the dynamic pressure. The static pressure is ducted into the chamber surrounding the diaphragm within the inside of the airspeed indicator.

Now we have static pressure inside the diaphragm that is equal to total pressure (*H*), and then static pressure measured from the static port outside the diaphragm. The difference between the pressure inside the diaphragm and outside the diaphragm is the differential pressure that deflects the flexible diaphragm that is geared to the airspeed pointer. The static pressures cancel each other, thus the dynamic pressure is left and

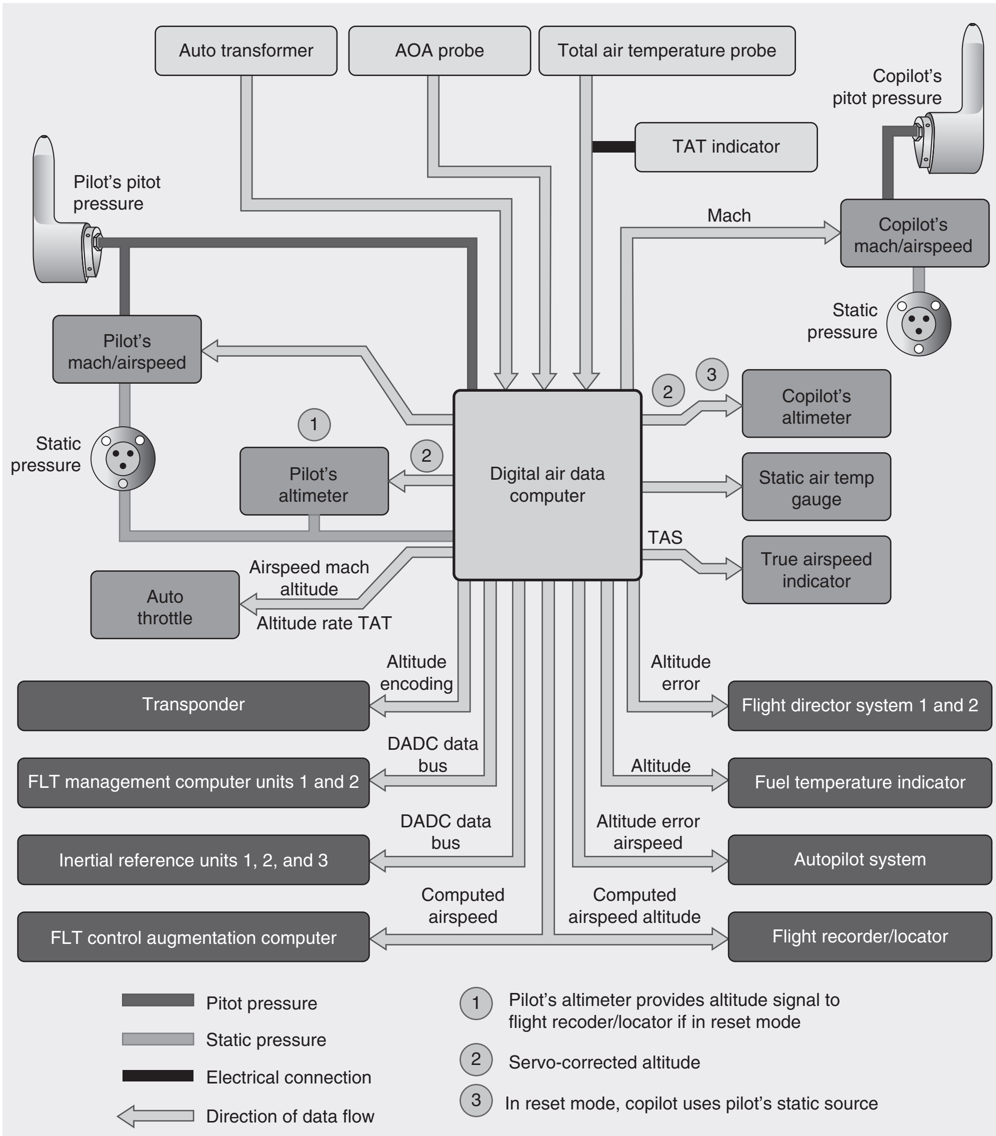


Figure 2.10. Air data computer and pitot–static sensing.
Source: U.S. Department of Transportation Federal Aviation Administration (2012a).

indicated on the airspeed indicator. The airspeed indicator measures differential pressure. The airspeed indicator is calibrated to read airspeed.

Figure 2.10 shows a modern pitot–static system associated with an air data computer (ADC). Though the concept with this solid state device is the same as in traditional pitot–static systems, the signal sent to modern "glass" instruments is digital and often has the ability to generate trend vectors.

Application 2.3

Figure 2.11 indicates the impact of a blockage of the pitot tube while an aircraft is flying at altitude. The resultant effect is that the airspeed indicator acts like an altimeter: as the aircraft climbs in altitude, the airspeed increases, and when the aircraft descends, the airspeed decreases.

In a traditional airspeed indicator with a diaphragm, what is happening in reference to our discussion on q, P, and H in the situation above? What is the impact of the blockage on the other pitot–static instruments? Why?

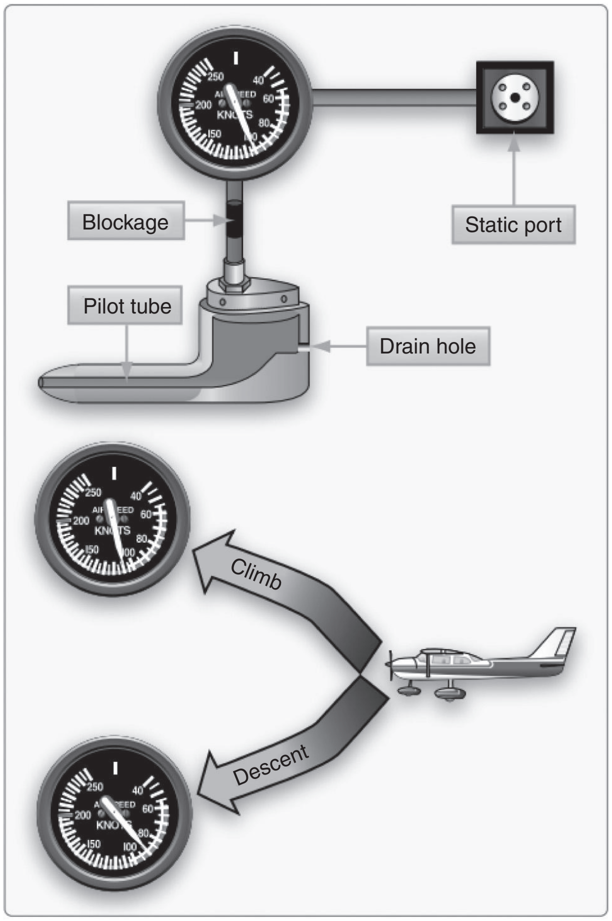


Figure 2.11. Blocked pitot tube and drain hole.
Source: U.S. Department of Transportation Federal Aviation Administration (2016b).

Indicated Airspeed

Indicated airspeed (IAS) is the direct reading of the airspeed indicator, and is uncorrected for errors related to installation or nonstandard atmospheric density. If there are any errors in the instrument, they may be shown on an instrument error card located near the instrument and/or in the AFM.

Calibrated Airspeed

Calibrated airspeed (CAS) is obtained when the necessary corrections have been made to the IAS for installation error and instrument error. These position errors are especially prevalent at lower airspeeds, and the IAS may be "indicating" slower than the CAS. Most of the time in non-pressurized aircraft operating at lower altitudes, the CAS can be assumed to be within several knots of the IAS.

Equivalent Airspeed

Equivalent airspeed (EAS) results when the CAS has been corrected for compressibility effects. Figure 2.12 shows a compressibility correction chart. In general, if flying above 10 000 ft and 200 kts., the compressibility correction should be made. Unlike the instrument and position error charts, which vary with different aircraft, this chart is good for any aircraft.

EAS is not a significant factor in airspeed computations when aircraft fly at relatively low speeds and altitudes, but at higher speeds and altitudes, the compressibility correction must be taken into account. For example, if an aircraft is flying at a pressure altitude of 20 000 ft at a CAS of 400 kts., Figure 2.12 indicates a compressibility correction of −17.5 kts. The EAS for this example is 382.5 kts.

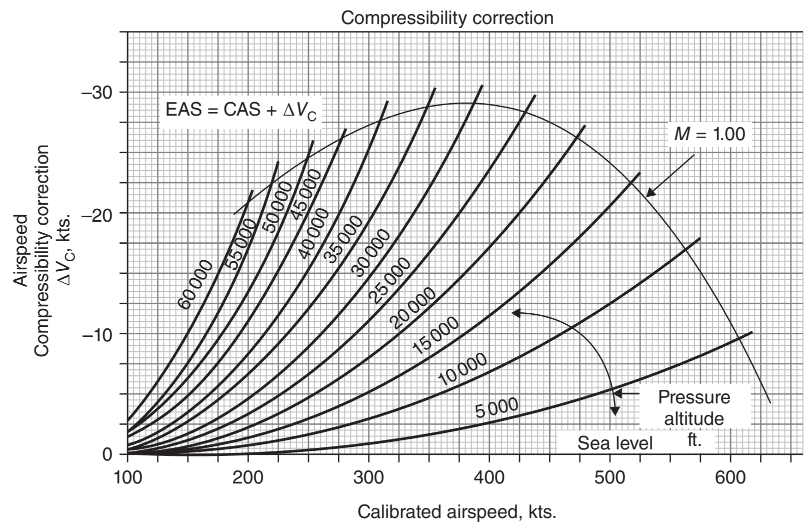


Figure 2.12. Compressibility correction chart.

True Airspeed

True airspeed (TAS) is obtained when EAS has been corrected for density ratio, the airspeed indicator measures dynamic pressure and is calibrated for sea level standard day density. As altitude increases, the density ratio decreases and a correction must be made. The correction factor is $\sqrt{\sigma}$:

$$\text{TAS} = \frac{\text{EAS}}{\sqrt{\sigma}} \tag{2.12}$$

Values of $\sqrt{\sigma}$ can be found in the ICAO Standard Altitude Chart (Table 2.1); values of $1/\sqrt{\sigma}$ can be found in Figure 2.13.

Due to the decrease in air density with an increase in altitude, for any given TAS, CAS will decrease as altitude increases. As higher altitudes are attained, the aircraft must fly faster to obtain the same pressure differential. For a given CAS, as an aircraft increases in altitude, the TAS will increase. The higher the aircraft travels in altitude, the greater the difference between CAS and TAS.

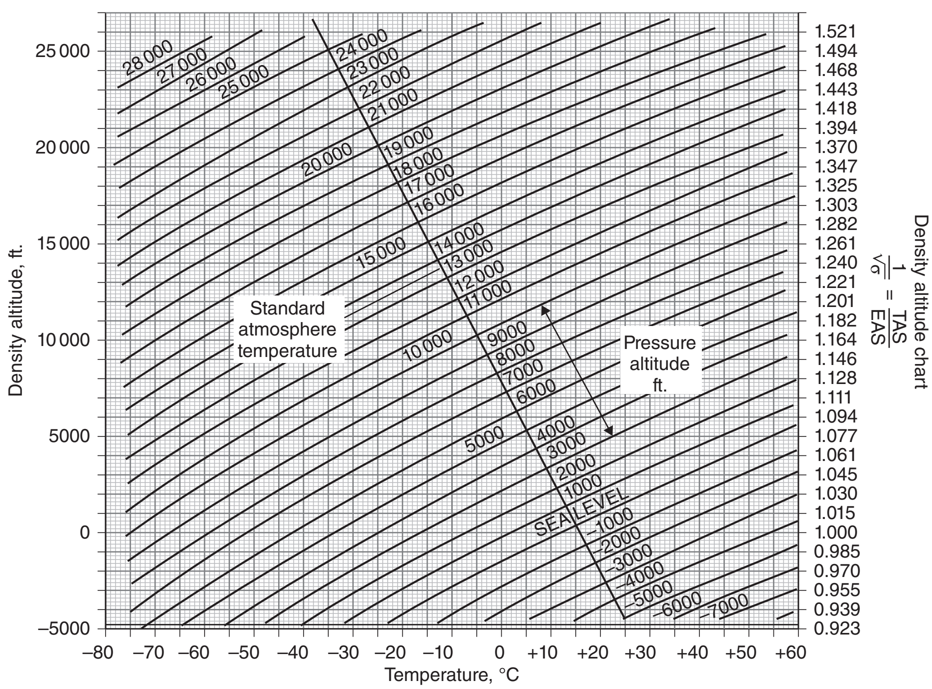


Figure 2.13. Altitude and EAS to TAS correction chart.

EXAMPLE

Using our example from the CAS discussion, EAS was determined to be 382.5 kts. If the outside air temperature at a pressure altitude of 20 000 ft is −30 °C, we can utilize Eq. 2.12 to find the TAS. From Table 2.1, the pressure ratio (δ) is 0.4595.

$$\theta = \frac{T}{T_0} \rightarrow \theta = \frac{(-30^\circ\text{C} + 273^\circ\text{K})}{288^\circ\text{K}} \rightarrow \theta = 0.844$$

$$\sigma = \frac{\delta}{\theta} = \frac{0.4595}{0.844} = 0.544$$

$$\text{TAS} = \frac{382.5\ \text{kts.}}{\sqrt{0.544}} = 518.6\ \text{kts.}$$

Figure 2.14 depicts the change in TAS between sea level and 15 000 ft when the IAS remains constant. For the respective IAS, the CAS calibration has been applied. As the aircraft climbs, the TAS increases as the air density decreases. The aircraft must travel at 130 kts. TAS to register 100 kts. on the airspeed indicator.

Understanding the relationship between the speeds above, and the calculation of each one, can be facilitated by remembering "ICE-T." *I*AS is read off the airspeed indicator, *C*AS is IAS corrected for installation/position errors, *E*AS is CAS corrected for compressibility, and finally *T*AS is EAS corrected for temperature and pressure.

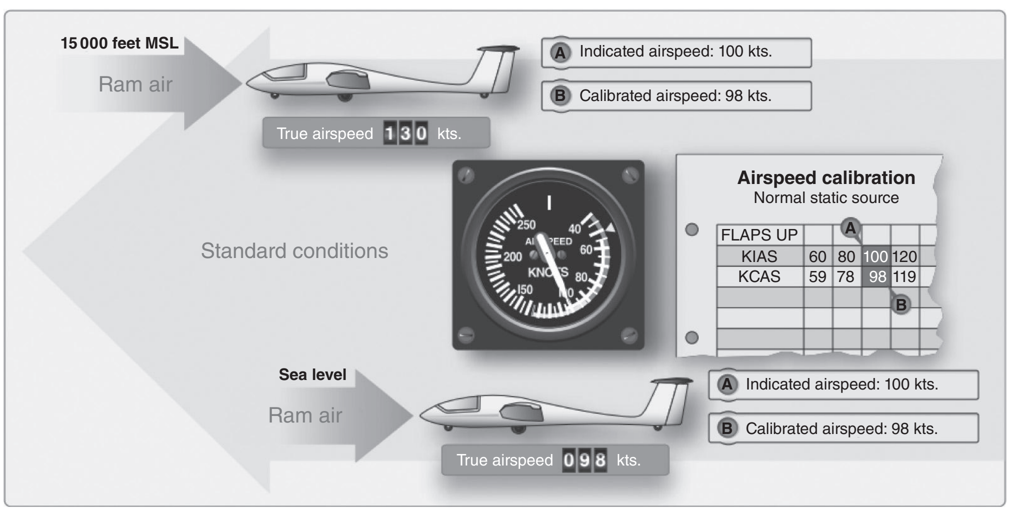


Figure 2.14. IAS, CAS, and TAS comparison.
Source: U.S. Department of Transportation Federal Aviation Administration (2013).

Mach

The Mach number is found by comparing TAS to the speed of sound for a given set of conditions at a specific altitude. The speed of sound is an important factor in the study of high-speed flight and is discussed in depth in Chapter 14. Because the aircraft's speed in relation to the speed of sound is so important in high-speed flight, airspeeds are usually measured as Mach number (named after the Austrian physicist Ernst Mach). Mach number is the aircraft's true airspeed divided by the speed of sound (in the same atmospheric conditions):

$$M = \frac{V}{a} \tag{2.13}$$

where

M = Mach number

V = true airspeed (kts.)

a = local speed of sound (kts.)

EXAMPLE

Using the TAS from the previous example (518.6 kts.), when $a = 607.3$ kts., calculate the Mach number for the aircraft.

$$M = \frac{V}{a} \rightarrow M = \frac{518.6\text{ kts.}}{607.3\text{ kts.}} \rightarrow M = 0.85$$

Groundspeed

Groundspeed (GS) is the actual speed of the aircraft over the ground, either calculated manually or more commonly nowadays read off the GPS (Global Positioning Satellite) navigational unit. The GS increases with a tailwind and decreases with a headwind, and is TAS adjusted for the wind. Groundspeed equals true airspeed in a no wind situation. Consider an airplane that has departed an airport located at sea level, then lands on a runway located at 5000 ft. Even though the IAS on approach will remain the same as if the airplane was landing at sea level, the TAS (and GS) will be higher at the airport with the higher elevation, thus more runway will be utilized during the landing.

SYMBOLS

a	Speed of sound (local for a given condition)
A	Area (ft^2)
AGL	Above ground level
CAS	Calibrated airspeed (kts.)
°C	Celsius temperature (°)
DA	Density altitude
EAS	Equivalent airspeed
°F	Fahrenheit temperature
GS	Groundspeed
H	Total pressure(head) (psf)
IAS	Indicated airspeed