1 Introduction

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, and for harnessing the fundamental physical laws that guide them.

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 maybe you aspire to build or maintain aircraft as a skilled 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 attempt to build on previous material you have learned, and hopefully will prepare you for a successful aviation career.

THE FLIGHT ENVIRONMENT

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.

Up to this point you have seen that there are 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, how 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 issues, among others, hopefully 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 (sec)

From the fundamental units, other quantities can be derived:

Velocity (distance/time)	ft/sec (fps)
Area (distance squared)	square ft (ft^2)
Pressure (force/unit area)	lb/ft^2 (psf)
Acceleration (change in velocity)	ft/sec/sec (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	1.69	feet per second (fps)
fps	0.5925	knots
miles per hour (mph)	1.47	fps
fps	0.6818	mph
mph	0.8690	knots
knots	1.15	mph
nautical miles (nm)	6076	feet (ft)
nm	1.15	statute miles (sm)
sm	0.869	nm
knots	101.3	feet per minute (fpm)

FORCES

A force is a push or a pull tending to change the state of motion of a body. Typical forces acting on an aircraft in steady flight are shown in Fig. 1.1. Figure 1.2 shows the resolution of the aerodynamic forces during

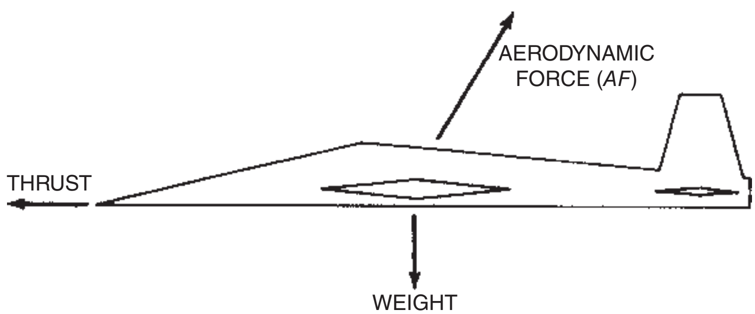


Fig. 1.1. Forces on an airplane in steady flight.

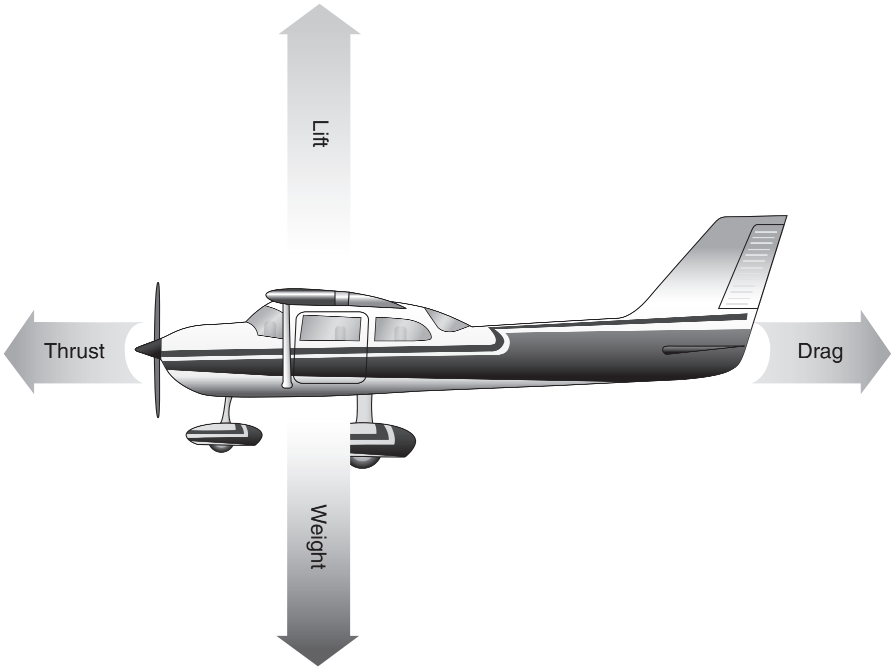


Fig. 1.2. Resolved forces on an airplane in steady flight.
U.S. Department of Transportation Federal Aviation Administration, *Pilot's Handbook of Aeronautical Knowledge,* 2008

straight-and-level, unaccelerated flight and is separated into four components. 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.

MASS

Mass is a measure of the amount of material contained in a body. *Weight*, on the other hand, is a force caused by the gravitational attraction of the earth ($g = 32.2\ \text{ft/s}^2$), moon, sun, or other heavenly bodies. Weight will vary, depending on where the body is located in space. Mass will not vary with position.

$$\text{Weight } (W) = \text{Mass } (m) \times \text{Acceleration of gravity } (g)$$

$$W = mg \tag{1.1}$$

Rearranging gives

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

This mass unit is called the *slug*.

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 knots, the velocity vector is as shown in Fig. 1.3. If there is a 30-knot wind from the north, the wind vector is as shown in Fig. 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 arrow of the aircraft vector and draw a straight line from the tail of the aircraft vector to the arrow of the wind vector. This *resultant* vector represents the path of 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 (Fig. 1.5).

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

$$\text{Groundspeed} = V_r = \sqrt{(300)^2 + (30)^2} = 301.5 \text{ knots}$$

Fig. 1.3. Vector of an eastbound aircraft.

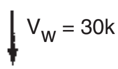


Fig. 1.4. Vector of a north wind.

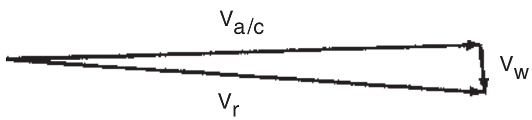


Fig. 1.5. Vector addition.

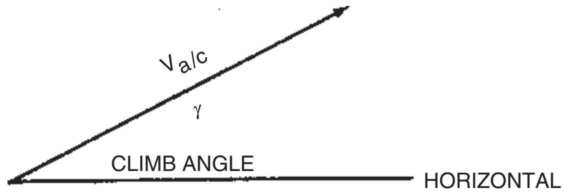


Fig. 1.6. Vector of an aircraft in a climb.

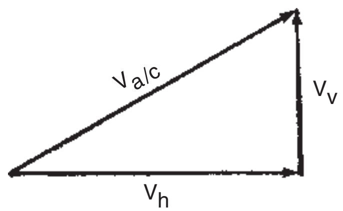


Fig. 1.7. Vectors of groundspeed and rate of climb.

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 knots, 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 Fig. 1.6.

In Fig. 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 knots and the climb angle is 30°, mathematically the values are

$$V_h = V_{a/c} \cos 30^\circ = 200(0.866) = 173.2 \text{ knots} \quad \text{(Groundspeed)}$$

$$V_v = V_{a/c} \sin 30^\circ = 200(0.500) = 100 \text{ knots or } 10{,}130 \text{ fpm} \quad \text{(Rate of climb)}$$

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*:

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

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 greater the moment.

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.

EQUILIBRIUM CONDITIONS

Webster defines equilibrium as "a state of balance or equality between opposing forces." 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." Figures 1.1 and 1.2 illustrate situations where this condition is satisfied (lift = weight, thrust = drag, etc.)
2. There must be no unbalanced moments acting on the body. Mathematically, $\Sigma M = 0$ (Fig. 1.8).

Moments at the fulcrum in Fig. 1.8 are 50 ft-lb clockwise and 50 ft-lb counterclockwise. So, $\Sigma M = 0$. To satisfy the first condition of equilibrium, the fulcrum must press against the seesaw with a force of 15 lb. So, $\Sigma F = 0$.

NEWTON'S LAWS OF MOTION

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

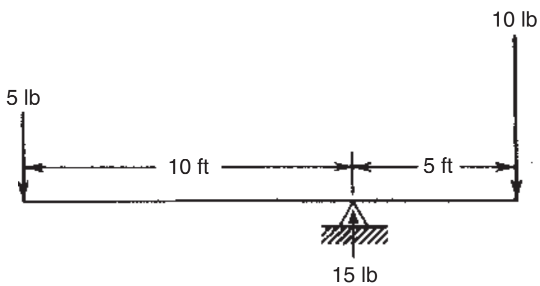


Fig. 1.8. Seesaw in equilibrium.

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, as with an aircraft at rest on a ramp without unbalanced forces acting upon 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 motion (speed) of a body in a unit of time, consider an aircraft accelerating down the runway, or decelerating after touchdown. 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. These two effects can be expressed by the simple equation

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

or, more commonly,

$$F = ma \tag{1.3}$$

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 backwards from the propeller, the aircraft moves 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,

$$\text{Acceleration } a = \frac{\text{Change in velocity}}{\text{Change in time}} = \frac{\Delta V}{\Delta t} = \frac{V - V_0}{t - t_0}$$

where

Δ (cap delta) means "change in"
V = velocity at time t
V_0 = velocity at time t_0

If we start the time at $t_0 = 0$ and rearrange the above, then

$$V = V_0 + at \tag{1.4}$$

If we start the time at $t_0 = 0$ *and* $V_0 = 0$ (brakes locked before takeoff roll) and rearrange the above where V can be any velocity given (for example, liftoff velocity), then

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

The distance s traveled in a certain time is

$$s = V_{av}t$$

The average velocity V_{av} is

$$V_{av} = \frac{V + V_0}{2}$$

Therefore,

$$s = \frac{V_0 + at + V_0}{2}t \quad \text{or} \quad s = V_0 t + \frac{1}{2}at^2 \tag{1.5}$$

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

$$s = \frac{V^2 - V_0^2}{2a} \tag{1.6}$$

Equations 1.3, 1.4, and 1.5 are useful in calculating takeoff and landing factors. They are studied in some detail in Chapters 10 and 11.

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. The centripetal force is that force that causes an airplane to turn. The apparent force that is equal and opposite to this is called the centrifugal force.

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

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

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

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 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:*

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

Work is measured in ft-lb.

ENERGY

Energy is the ability to do work. 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:

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

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

$$\text{TE} = \text{PE} + \text{KE} \tag{1.12}$$

The law of conservation of energy states that the total energy remains constant. Both potential and kinetic energy can change in value, but the total energy must remain the same: *Energy cannot be created or destroyed, but can change in form*.

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

$$\text{Speed} = \text{distance/time}$$

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

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

$$\text{Horsepower} = \frac{\text{Force} \times \text{Speed}}{550}$$

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

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

Equation 1.13 is very useful in comparing thrust-producing aircraft (turbojets) with power-producing aircraft (propeller aircraft and helicopters).

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

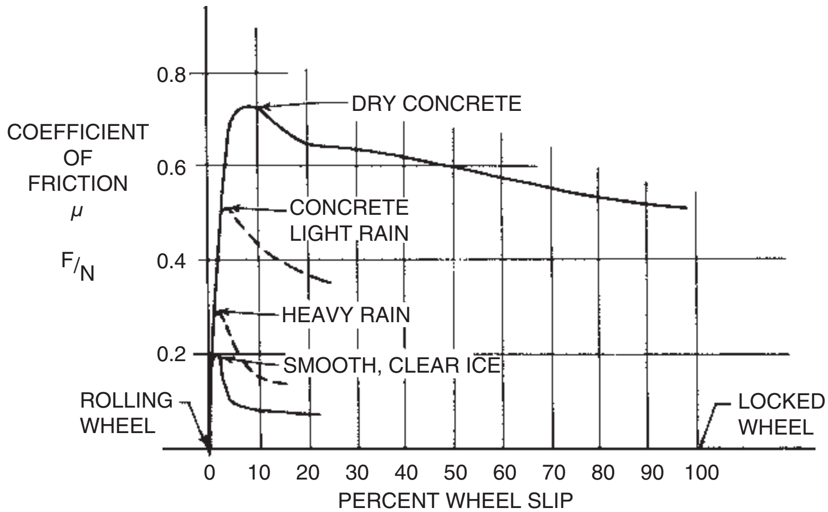


Fig. 1.9. Coefficients of friction for airplane tires on a runway.

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, for 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 is converted 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.

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:

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

Figure 1.9 shows typical values of the coefficient of friction for various conditions.

SYMBOLS

a	Acceleration (ft/sec^2)
CF	Centrifugal force (lb)
E	Energy (ft-lb)
KE	Kinetic energy
PE	Potential energy
TE	Total energy
F	Force (lb)
F_b	Braking force
g	Acceleration of gravity (ft/sec^2)

h	Height (ft)
HP	Horsepower
L	Moment arm (ft or in.)
m	Mass (slugs, lb-sec^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 (sec)
V	Speed (ft/sec)
V_k	Speed (knots)
V_0	Initial speed
V_t	Tangential (tip) speed
W	Weight (lb)
μ (mu)	Coefficient of friction (dimensionless)

EQUATIONS

1.1 $W = mg$

1.2 $M = FL$

1.3 $F = ma$

1.4 $V = V_0 + at$

1.5 $s = V_0 t + \frac{1}{2}at^2$

1.6 $s = \dfrac{V^2 - V_0^2}{2a}$

1.7 $V_t = \dfrac{r(\text{rpm})}{9.55}$

1.8 $\text{CF} = \dfrac{WV_t^2}{gr}$

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

1.10 $\text{PE} = Wh$

1.11 $\text{KE} = \frac{1}{2}mV^2$

1.12 $\text{TE} = \text{PE} + \text{KE}$

1.13 $\text{HP} = \dfrac{TV_k}{325}$

1.14 $F_b = \mu N$

PROBLEMS

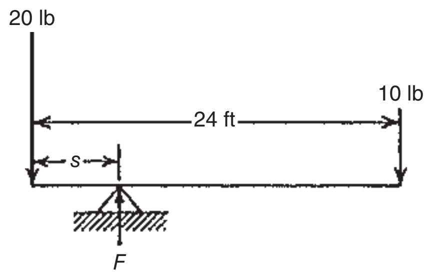
Note: Answers to problems are given at the end of the book.

1. An airplane weighs 16,000 lb. The local gravitational acceleration g is 32 fps^2. What is the mass of the airplane?

2. The airplane in Problem 1 accelerates down the takeoff runway with a net force of 6000 lb. Find the acceleration of the airplane.

3. 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.

4. 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 tangent of the plane's climb angle and the distance that it has flown through the air.



5. Find the distance s and the force F on the seesaw fulcrum shown in the figure. Assume that the system is in equilibrium.

6. The airplane in Problem 2 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.

7. Under no-wind conditions, what takeoff roll is required for the aircraft in Problem 6?

8. Upon reaching a velocity of 100 fps, the pilot of the airplane in Problem 6 decides to abort the takeoff and applies brakes and stops the airplane in 1000 ft. Find the airplane's deceleration.

9. 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.

10. An airplane weighs 16,000 lb and is flying at 5000 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 dove until the airspeed was 400 fps, what would the altitude be?

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

12. 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.