# 1 Introduction

## 1.1 The Helicopter

The helicopter is an aircraft that uses rotating wings to provide lift, propulsion, and control. Figure 1.1 shows the principal helicopter configurations. The rotor blades rotate about a vertical axis, describing a disk in a horizontal or nearly horizontal plane. Aerodynamic forces are generated by the relative motion of a wing surface with respect to the air. The helicopter with its rotary wings can generate these forces even when the velocity of the vehicle is zero, in contrast to fixed-wing aircraft, which require a translational velocity to sustain flight. The helicopter therefore has the capability of vertical flight, including vertical take-off and landing. The efficient accomplishment of heavier-than-air hover and vertical flight is the fundamental characteristic of the helicopter rotor.

The rotor must supply a thrust force to support the helicopter weight. Efficient vertical flight means a high power loading (ratio of rotor thrust to rotor power required, $T/P$), because the installed power and fuel consumption of the aircraft are proportional to the power required. For a rotary wing, low disk loading (the ratio of rotor thrust to rotor disk area, $T/A$) is the key to a high power loading. Conservation of momentum requires that the rotor lift be obtained by accelerating air downward, because corresponding to the lift is an equal and opposite reaction of the rotating wings against the air. Thus the air left in the wake of the rotor possesses kinetic energy that must be supplied by a power source in the aircraft if level flight is to be sustained. This is the induced power, a property of both fixed and rotating wings that constitutes the absolute minimum power required for equilibrium flight. For the rotary wing in hover, the induced power loading is inversely proportional to the square root of the rotor disk loading ($P/T \propto \sqrt{T/A}$). Hence the efficiency of rotor thrust generation increases as the disk loading decreases.

For a given gross weight the induced power is inversely proportional to the rotor radius, and therefore the helicopter is characterized by large diameter rotors. The disk loading characteristic of helicopters is in the range of 5 to 15 lb/ft$^2$. The small diameter rotating wings found in aeronautics, including propellers and turbofan engines, are used mainly for aircraft propulsion. For such applications a high disk loading is appropriate, since the rotor is operating at high axial velocity (which reduces the induced power) and at a thrust equal to only a fraction of the gross weight. However, the use of high disk loading rotors for direct lift severely compromises the


Figure 1.1. Rotorcraft configurations; drawings by Eduardo Solis.

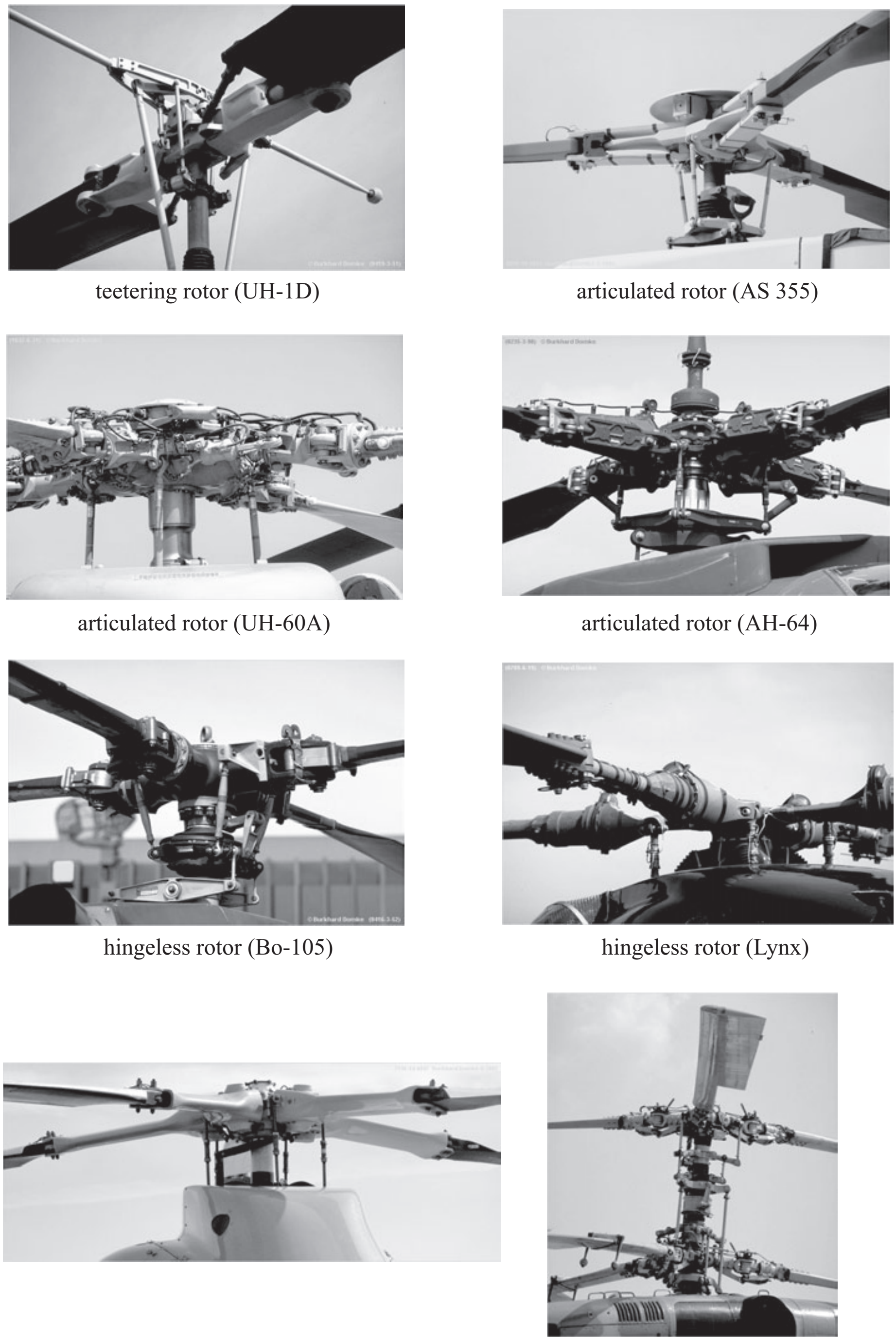
vertical flight capability in terms of greater installed power and much reduced hover endurance. The helicopter uses the lowest disk loading of all VTOL (vertical takeoff and landing) aircraft designs and hence has the most efficient vertical flight capability. The helicopter can be defined as an aircraft using large diameter, low disk loading rotary wings to provide the lift for flight.

Because the helicopter must also be capable of translational flight, a means is required to produce a propulsive force to oppose the aircraft drag and rotor drag in forward flight. For low speeds at least, this propulsive force is obtained from the rotor, by tilting the thrust vector forward. The rotor is also the source of the forces and moments on the aircraft that control its position, attitude, and velocity. In a fixed-wing aircraft, the lift, propulsion, and control forces are provided by largely separate aerodynamic surfaces. In the helicopter, all three are provided by the rotor.

Vertical flight capability is not achieved without a cost, which must be weighed against the value of VTOL capability in the desired applications of the aircraft. The task of the engineer is to design an aircraft that accomplishes the required operations in the most effective manner. The price of vertical flight includes a higher power requirement than for fixed-wing aircraft, a factor that influences the purchase price and operating cost. For most configurations, a large transmission is required to deliver the power to the rotor at low speed and high torque. The fact that the rotor is a mechanically complex system increases purchase price and maintenance costs. The rotor is a source of vibration, requiring a vibration alleviation system to avoid increased maintenance costs, passenger discomfort, and pilot fatigue. There are high alternating loads on the rotor, reducing the structural component life and in general resulting in increased maintenance cost. Aircraft noise is an important factor in air transportation, as the primary form of interaction of the aircraft with a large part of society. The helicopter is among the quietest of aircraft (or at least can be), but utilization of VTOL capability often involves operation close to urban areas, leading to stricter noise requirements. All these factors can be overcome to design a highly successful aircraft. The engineering analysis required for that task is the subject of this book.

### 1.1.1 The Helicopter Rotor

The conventional helicopter rotor consists of two or more identical, equally spaced blades attached to a central hub. The blades are maintained in uniform rotational motion, usually by a shaft torque from the engine. The lift and drag forces on these rotating wings produce the torque, thrust, and other forces and moments of the rotor. The large diameter rotor required for efficient vertical flight and the high aspect ratio blades required for good aerodynamic efficiency of the rotating wing result in blades that are considerably more flexible than high disk loading rotors such as propellers. Consequently, there is substantial elastic motion of the rotor blades in response to the aerodynamic forces in the rotary-wing environment. This motion can produce high stresses in the blades or large moments at the root, which are transmitted through the hub to the helicopter. Attention must therefore be given in the design of the helicopter rotor blades and hub to keeping these loads small. The centrifugal stiffening of the rotating blade results in the motion being predominantly about the blade root. Hence the design task focuses on the configuration of the rotor hub. Figure 1.2 shows some typical helicopter rotor hubs.



teetering rotor (UH-1D)
articulated rotor (AS 355)
articulated rotor (UH-60A)
articulated rotor (AH-64)
hingeless rotor (Bo-105)
hingeless rotor (Lynx)
bearingless rotor (MD 900)
coaxial rotor (Ka-29)

Figure 1.2. Rotor hub configurations; photos courtesy Burkhard Domke.

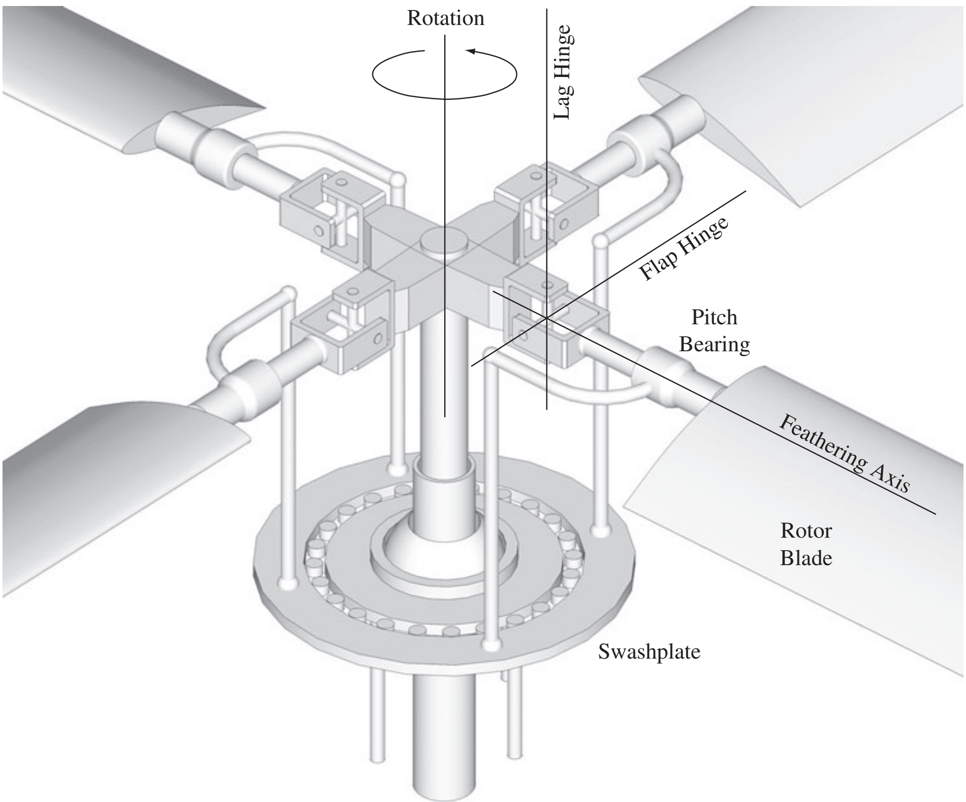



Figure 1.3. Schematic of an articulated rotor hub and root.

A common design solution that was adopted early in the development of the helicopter is to use hinges at the blade root that allow free motion of the blade normal to and in the plane of the disk. A schematic of the root hinge arrangement is given in Figure 1.3. The bending moment is zero at the blade hinge and small throughout the root area, and no hub moment is transmitted through the blade hinges to the helicopter. This configuration makes use of the blade motion to relieve the bending moments that would otherwise arise at the root of the blade. The motion of the blade allowed by these hinges has an important role in the behavior of the rotor and in the analysis of that behavior. Some current rotor designs eliminate the hinges at the root, so that the blade motion involves structural bending. The hub and blade loads are necessarily higher for a hingeless design. The design solution is basically the same, because the blade must be provided with enough flexibility to allow substantial motion or the loads would be unacceptably high even with advanced materials and design technology. Hence blade motion remains a dominant factor in rotor behavior, although the root load and hub moment capability of a hingeless blade has a significant influence on helicopter design and operating characteristics.

The motion of a hinged blade consists basically of rigid-body rotation about each hinge, with restoring moments due to the centrifugal forces acting on the rotating blade. Motion about the hinge lying in the rotor disk plane (and perpendicular to the blade radial direction) produces out-of-plane deflection of the blade and is called flap motion. Motion about the vertical hinge produces deflection of the blade in the plane of the disk and is called lag motion (or lead-lag). For a blade without hinges the fundamental modes of out-of-plane and in-plane bending define the flap and lag motion. Because of the high centrifugal stiffening of the blade these modes are similar to the rigid body rotations of hinged blades, except in the vicinity of the root, where most of the bending takes place. In addition to the flap and lag motion, the ability to change the pitch of the blade is required to control the rotor. Pitch motion allows control of the aerodynamic angle-of-attack of the blade, and hence control of the aerodynamic forces on the rotor. This blade pitch change, called feathering motion, is usually accomplished by movement about a hinge or bearing. The pitch bearing on a hinged or articulated blade is typically outboard of the flap and lag hinges; on a hingeless blade the pitch bearing can be either inboard or outboard of the major flap and lag bending at the root. There are also rotor designs that eliminate the pitch bearings as well as the flap and lag hinges; the pitch motion then occurs about a region of torsional flexibility at the blade root.

The mechanical arrangement of the rotor hub to accommodate the flap and lag motion of the blade provides a fundamental classification of rotor types:

Articulated rotor: The blades are attached to the hub with flap and lag hinges.

Teetering rotor: Two blades forming a continuous structure through the hub are attached to the rotor shaft with a single flap hinge in a teetering or seesaw arrangement. The rotor has no lag hinges.

Gimballed rotor: Three or more blades are attached to the hub without hinges, and the hub is attached to the rotor shaft by a gimbal or universal joint arrangement.

Hingeless rotor: The blades are attached to the hub without flap or lag hinges, although still with a feathering bearing or hinge. The blade is attached to the hub with cantilever root restraint, so that blade motion occurs through bending at the root. This rotor configuration is also called a rigid rotor. The limit of a truly rigid blade, which is so stiff that there is no significant bending motion, is applicable only to high disk loading rotors (such as a propeller).

Bearingless rotor: The blades are attached to the hub without flap or lag hinges and without load-carrying pitch bearings. Flap, lag, and torsion motion occur through deflection of a flexbeam at the root. Pitch control is accomplished using a torque rod or torque tube.

Chapter 8 discusses rotor configurations in more detail.

### 1.1.2 Helicopter Configuration

The arrangement of the rotors is the most distinctive external feature of a rotorcraft, and is an important factor in the aircraft behavior, particularly the stability and control characteristics. Usually the power is delivered to the rotor through the shaft, accompanied by a torque. The aircraft in steady flight has no net force or moment acting on it, so the rotor torque must be balanced in some manner. The method chosen to accomplish this torque balance is the primary determinant of the helicopter configuration. Two methods are in general use: a configuration with a single main rotor and a tail rotor, and configurations with twin contra-rotating rotors. Chapter 8 has a further discussion of rotorcraft configurations.

The single main rotor and tail rotor configuration uses a small auxiliary rotor to provide the torque balance and yaw control. This rotor is on the tail boom, typically slightly beyond the edge of the main rotor disk. The tail rotor is normally vertical, with the shaft horizontal and parallel to the helicopter lateral axis. The torque balance is produced by the tail rotor thrust acting on an arm about the main rotor shaft. The main rotor provides lift, propulsive force, and roll, pitch, and vertical control for this configuration. The tail rotor provides yaw control.

A twin main rotor configuration uses two contra-rotating rotors, of equal size and loading, so that the torques of the rotors are equal and opposing. There is then no net yaw moment on the helicopter due to the main rotors. This configuration automatically balances the main rotor torque without requiring a power-absorbing auxiliary rotor. The rotor-rotor and rotor-airframe aerodynamic interference typically absorbs about the same amount of power as a tail rotor. The most common twin rotor arrangement is the tandem helicopter configuration: fore and aft placement of the main rotors on the fuselage, usually with significant overlap of the rotor disks and the rear rotor raised vertically above the front rotor. Coaxial and side-by-side twin rotor arrangements have also found some application.

### 1.1.3 Helicopter Operation

Operation in vertical flight, with no translational velocity, is the particular role for which the helicopter is designed. Operation with no velocity at all relative to the air, either vertical or translational, is called hover. Lift and control in hovering flight are maintained by rotation of the wings to provide aerodynamic forces on the rotor blades. General vertical flight involves climb or descent with the rotor horizontal, and hence with purely axial flow through the rotor disk. A useful aircraft must be capable of translational flight as well. The helicopter accomplishes forward flight by keeping the rotor nearly horizontal, so that the rotor disk sees a relative velocity in its own plane in addition to the rotational velocity of the blades. The rotor continues to provide lift and control for the aircraft. It also provides the propulsive force to sustain forward flight, by means of a small forward tilt of the rotor thrust.

Safe operation after a loss of power is required of any successful aircraft. The fixed-wing aircraft can maintain lift and control in power-off flight, descending in a glide at a shallow angle. Rotary-wing aircraft also have the capability of sustaining lift and control after a loss of power. Power-off descent of the helicopter is called autorotation. The rotor continues to turn and provide lift and control. The power required by the rotor is taken from the air flow provided by the aircraft descent. The procedure on recognition of a loss of power is to set the controls as required for autorotative descent and to establish equilibrium flight at the minimum descent rate. Then near the ground the helicopter is flared, using the rotor stored kinetic energy of rotation to eliminate the vertical and translational velocity just before touchdown. The helicopter rotor in vertical power-off descent is nearly as effective as a parachute of the same diameter as the rotor disk; about half that descent rate is achievable in forward flight.

A rotary-wing aircraft called the autogyro uses autorotation as the normal working state of the rotor. In the helicopter, power is supplied directly to the rotor, and the rotor provides propulsive force as well as lift. In the autogyro, no power or shaft torque is supplied to the rotor. The power and propulsive force required to sustain

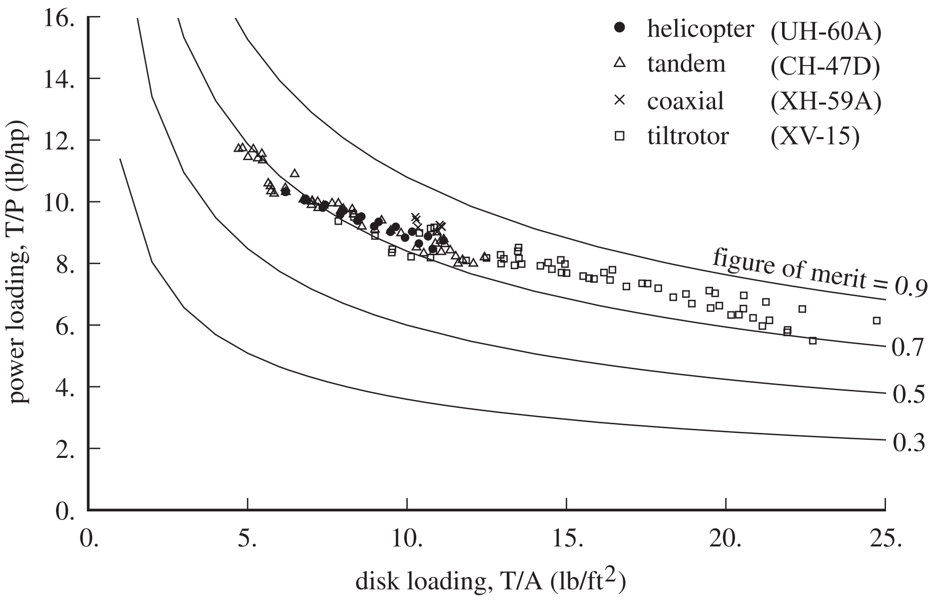



Figure 1.4. Rotor hover performance: rotor power loading as a function of rotor disk loading (based on projected disk area) for four rotors.

level forward flight are supplied by a propeller or other propulsion device. Hence the autogyro is like a fixed-wing aircraft, because the rotor takes the role of the wing in providing only lift for the vehicle, not propulsion. Sometimes the aircraft control forces and moments are supplied by fixed aerodynamic surfaces as in the airplane, but obtaining the control from the rotor is better. The rotor performs much like a wing and has a fairly good lift-to-drag ratio. Although rotor performance is not as good as that of a fixed wing, the rotor is capable of providing lift and control at much lower speeds. Hence the autogyro is capable of flight speeds much slower than fixed-wing aircraft. Without power to the rotor, it is not capable of actual hover or vertical climb. Because autogyro performance is not that much better than the performance of an airplane with a low wing loading, usually the requirement of actual VTOL capability is necessary to justify a rotor on an aircraft.

## 1.2 Design Trends

The power of a hovering rotor is dominated by the power resulting from the wing drag due to lift, which is called induced power. The induced power is the product of the thrust $T$ and induced velocity $v_i$: $P_i = T v_i$ (see Chapter 2 for a complete description of notation). Dimensional analysis shows that the induced velocity scales with the disk loading: $v_i = \kappa v_h$, where $v_h^2 = T/2\rho A$. With the factor of 2, $v_h$ is the ideal (momentum theory) induced velocity for hover. In hover the induced power is typically 10–15% larger than ideal, so $\kappa = 1.10$–$1.15$. Hence $P_i/T = \kappa\sqrt{T/2\rho A}$, and low power requires low disk loading, thus large disk area and a large rotor diameter. The rotor also has a power loss due to the wing viscous drag, called profile power $P_o$. A figure of merit for a hovering rotor is defined as the ratio of the ideal induced power to the total rotor power: $M = T\sqrt{T/2\rho A}/P$. Because of profile and non-ideal induced losses, this figure of merit must be less than 1. Figure 1.4 plots for

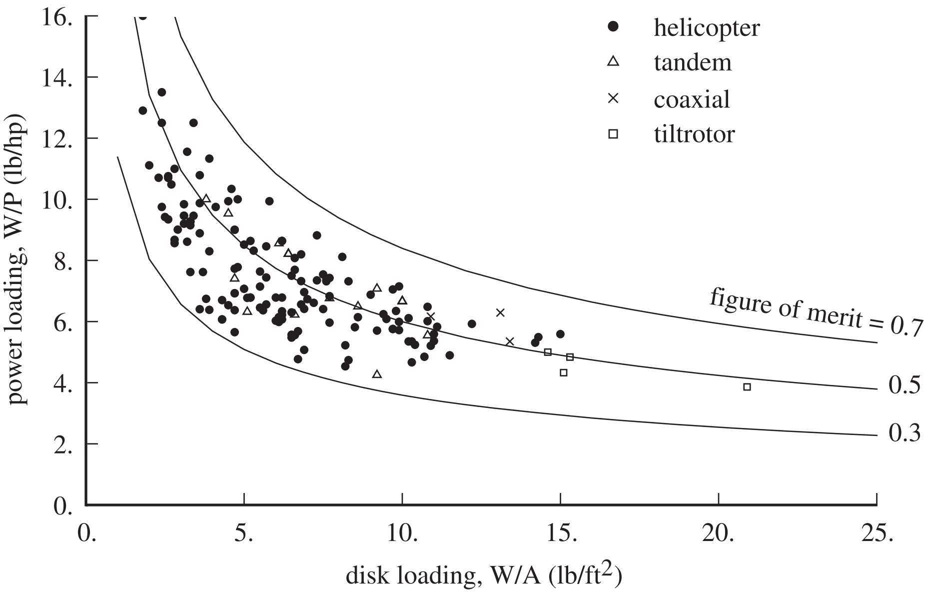



Figure 1.5. Rotorcraft design: power loading of various aircraft as a function of disk loading; from takeoff power, maximum takeoff weight, and projected disk area.

several rotors the measured power loading as a function of disk loading (based on projected disk area), as the rotor thrust is varied. The peak figure of merit is typically $M = 0.74$–$0.77$ for helicopters. Tiltrotors achieve a somewhat larger figure of merit, $M = 0.78$–$0.81$, partly due to higher twist but primarily the result of operating at larger disk loading (and thus lower power loading). Mutual interference between coaxial rotors increases the figure of merit (for $M$ based on the projected disk area).

The hover power required dominates the determination of installed power for a rotorcraft, as illustrated in Figure 1.5. Each point in Figure 1.5 is for a single aircraft, calculated from the takeoff power and the maximum takeoff weight (and sea-level-standard air density). The aircraft figure of merit in these terms ranges from 0.40 to 0.55, smaller than the figure of merit of the rotor alone because of other power losses (such as accessory, tail rotor, and interference losses) and the need to operate over a range of flight conditions. As an aircraft metric, the large range of figure of merit values reflects design choices more than rotor performance. In addition to low disk loading, efficient hover operation depends on low propulsion system weight, including rotor, transmission, engine, and fuel weight. At constant disk loading, the propulsion system weight would increase faster than the gross weight. Thus for good empty weight fraction, the design choice for disk loading tends to increase with rotorcraft size, as shown in Figure 1.6. The power loading tends to decrease with size (Figure 1.7). The trend lines shown are $W/A = 0.15W^{0.4}$ and $W/P = 18W^{-0.1}$, so with an increase in rotorcraft size the rotor diameter increases less and the installed power increases more than would be implied by constant disk loading.

The induced power of the rotor decreases with forward speed. Viewed as a circular wing, the induced power of the edgewise-moving rotor at speed $V$ is $P_i/T = \kappa T/2\rho AV$. For a circular wing with uniform disk loading, hence elliptical span loading, $\kappa = 1$. For a helicopter rotor the loading is far from uniform, because of the asymmetry of the rotor blade aerodynamic environment, and at high speed $\kappa$

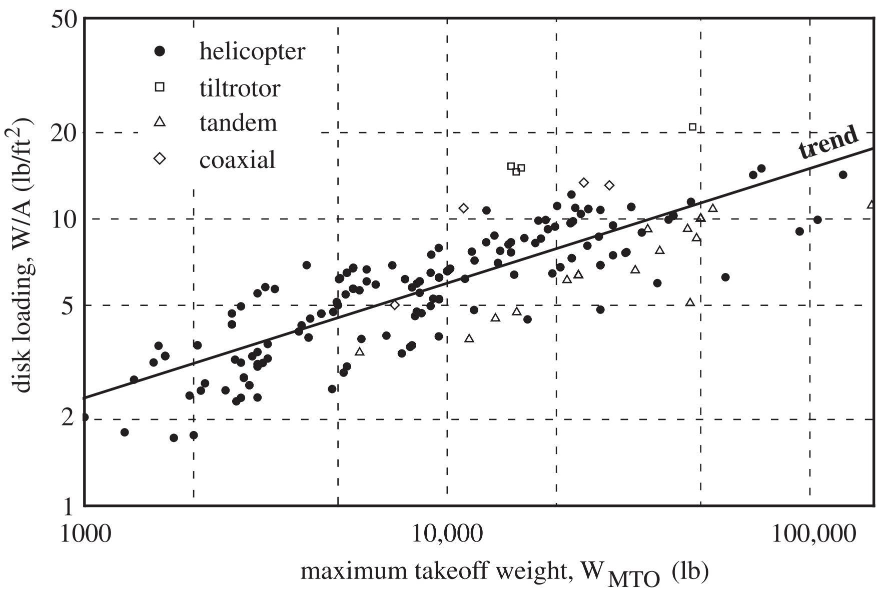



Figure 1.6. Disk loading as a function of maximum takeoff weight.

is much greater than 1, and the induced power can even increase with speed. Profile power $P_o$ increases with speed, especially when that asymmetry leads to significant areas of high Mach number or stall on the rotor disk. The helicopter in forward flight has a parasite drag $D = {}^1\!/\!_2\rho V^2 f$ that must be balanced by a propulsive force from the rotor. The rotor power required to provide the propulsive force, $P_p = DV$, is called parasite power. Eventually the parasite power dominates the power required. If the installed power is determined by hover, then the maximum flight speed is fallout and is largely determined by the aircraft drag. Figure 1.8 shows the drag area

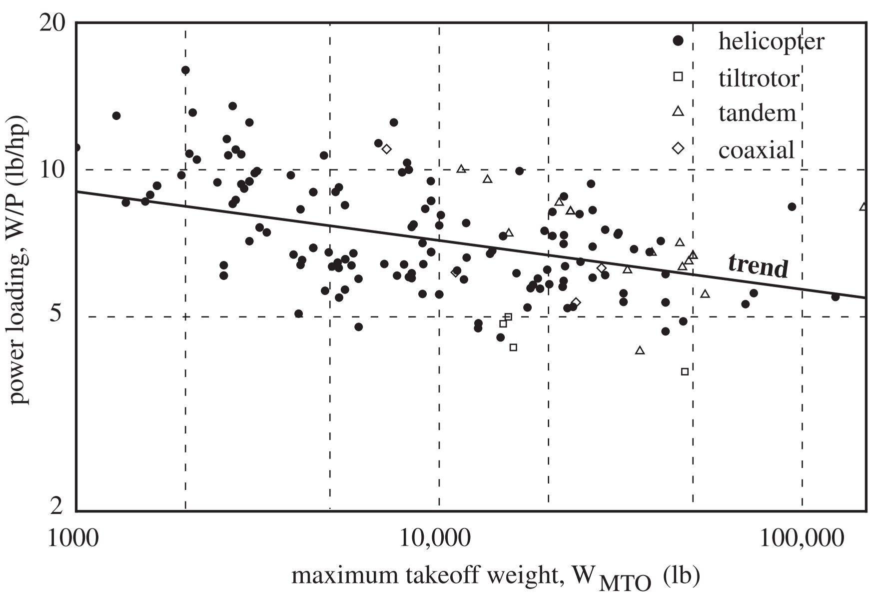



Figure 1.7. Power loading as a function of maximum takeoff weight.