Chapter 270 (from Volume 6)
Aircraft Flight Regimes and Applications

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1 FUNDAMENTAL CONSIDERATIONS

1.1 Definition of an aircraft: the atmosphere

By definition, an aircraft is a platform that relies upon the density of the atmosphere to maintain flight (see Volume 6, Chapter 273). In practice, this implies operation up to approximately 27.5 km altitude where the local air density is 2.7% of the sea level value of 1.225 kg m$^{-3}$ and the speed of sound $a$, is 300 m s$^{-1}$, the sea level value being 340 m s$^{-1}$. One notable exception to this generalization was the North American X-15 rocket-propelled research aircraft that achieved a maximum altitude of 108 km (354 000 ft) and a speed of 2030 m s$^{-1}$, but this included a ballistic flight phase. The majority of aircraft fly at altitudes below about 15 km (50 000 ft) where the local air density is 15.8% of that at sea level and $a$ is 295 m s$^{-1}$, although some military types exceed this.

As the flight velocity of an aircraft increases towards the speed of sound, the effects of air compressibility become significant and often place a limit on the forward speed (see Section 2.1). Once the transonic phase is passed further speed increase is less problematic. An important property of the real atmosphere is turbulence. This also may introduce a speed limitation either due to perceived discomfort of the occupants of the aircraft or, in the limit, the possibility of the loss of airframe structural integrity. For these reasons, among others, civil aircraft operate at subsonic speed. Supersonic flight is restricted to research and military applications where the operational advantages outweigh the difficulties to be overcome. The re-introduction of supersonic airliners, as exemplified by the Anglo-French Concorde, is fraught with problems (see Section 3.5.1).

The typical speed–altitude-operating regimes of various classes of civil aircraft are shown in Figure 1a and b while Figure 2 is for military types.

1.2 The generation of lift

To fly, the total weight $W$ of the vehicle has to be overcome by a vertical force. This upward force is the lift $L$ (see Volume 5, Chapter 212), or in the case of lighter-than-air platforms, it may be referred to as the buoyancy. Forward flight implies the development of an air resistance, or drag $D$, and this implies the need to provide a thrust $T$. The four primary forces acting in flight are shown in Figures 3–5 for different classes of platforms. There are other secondary forces, and as the forces do not all act through the same point, there are associated moments. The lifting force may be developed in several ways as described in the following sections.
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**Figure 1.** (a) Flight regimes for civil aircraft; (b) flight regimes for general aviation aircraft.

**Figure 2.** Flight regimes for military aircraft.

**Figure 3.** Primary forces on lighter-than-air craft.

**Figure 4.** Primary forces on fixed-wing aircraft.
1.2.1 Aerostatic

Aerostatic lift is independent of the forward speed of the platform and relies only upon the overall density of the craft being less than that of the surrounding air. This implies some form of envelope holding a gas having a density sufficiently less than that of air to overcome the weight of the envelope and any items attached to it. The very first man-carrying flight used a balloon built by the Montgolfier brothers in 1783. It was inflated by hot air. Today, hot air balloons are widely used for sport and ground observations. A hot air system has the advantage that the height may be controlled readily by adding heat to the lifting gas. However, a more useful lifting medium is a light gas such as hydrogen, or, more often, inert helium. The first manned hydrogen balloon, built by Charles, lifted off just 10 days after the Montgolfier success. An airship has controlled forward flight, and it is usual to select an elongated cigar shape for the envelope thereby achieving a reduction in air resistance (see also Section 1.2.3).

1.2.2 Aerodynamic

As the name implies, aerodynamic lift requires the passage of a lift-developing shape, usually an aerofoil, through the atmosphere. The force may be derived by using a fixed, nominally horizontal, lifting surface or wing, but a suitably shaped body may also be used. This requires the platform to achieve a certain forward speed before sufficient force can be developed to fly.

Alternatively, it is possible to generate the lift by using a driven aerofoil system consisting of a bladed horizontal rotor. Rotors have the potential to provide all the lift, thrust, and control forces in one basic element. Here, the vehicle may leave the ground vertically and forward flight achieved by tilting the rotor to provide a horizontal thrust component. It is possible to generate lift from a rotor system without actually driving it, but this requires a forward translation of the rotor disc such that it “autorotates”. Thus, it performs somewhat like a circular wing, and the zero forward speed vertical lift capability is lost. A difficulty associated with rotating wings is the high velocity experienced by the tips of the blades at the point in the rotation coinciding with the maximum component of forward speed. This limits the achievable forward speed of the craft and is dependent upon the local lift requirement as well as the rotational speed (see Volume 1, Chapter 27). For this reason, there are concepts where the vehicle is fitted with a fixed wing as well as a rotor. The idea is that at higher speeds, some of the rotor lift may be transferred to the wing, thereby reducing the local lift requirement and possibly enabling the rotor to be slowed down. Some designs take this idea to the limit and propose the stopping and stowing of the rotor for high-speed flight. In practice, most applications employ a relatively small wing to enable some degree of off-loading of the rotor. One example of the more complete approach was the Fairey Rotodyne demonstrated successfully in the mid-twentieth century. This aircraft was unusual in that it combined an essentially autorotating rotor with a comparatively large wing. It was intended to be an airliner operating between city centers, and at one time it held the world speed record for rotorcraft. Solely for vertical take-off and landing, the rotor was driven by tip jets using compressed air derived from the two propeller turbines employed for forward propulsion. Unfortunately, the very high noise level of these devices proved to be the Achilles heel of a vehicle intended for city center operation.

Other hybrid rotor/wing configurations include tilt wings and tilt rotors. In these concepts, the rotors are arranged to rotate about a lateral horizontal axis, with or without the wing, so that at high speed they become propellers. Transition between the truly vertical and horizontal modes can be problematic.
1.2.3 Hybrid aerostatic–aerodynamic lift

Lighter-than-air vehicles, especially airships, are prone to problems of control and handling during take-off and landing, which are aggravated by their susceptibility to atmospheric turbulence. On a long airship flight, it is necessary to reduce the buoyancy as the fuel is used. This may partially be dealt with by adjusting the aerodynamic lift of the envelope, but the scope for this is limited. Early airships used a combination of lift gas venting and ballast release, but it is worth noting that the most successful of the earlier airships, the Graf Zeppelin, carried the fuel as a gas having the same density as air. Many recent airship proposals are hybrid craft, some employing a wing to give greater potential for lift control and others rotor systems. On craft with a small disposable load, these take the form of tilting/rotating propellers. Concepts for larger heavy-lift airships are often rotorcraft hybrids where nominally horizontal rotors produce the lift to compensate for the fuel and payload weights while the aerostatic lift supports only the empty weight.

2 FUNDAMENTAL CHARACTERISTICS

2.1 Flight forces

Aerodynamic lift is directly proportional to the local density of the air \( \rho \), the square of the forward velocity \( V_{0} \), and it is also dependent upon the shape of the wing aerofoil and its planform area \( S \).

The drag consists of two contributions: one results from the general shape of the aircraft, and the other is a consequence of the development of lift. The former depends on the same quantities as the lift except that the shape of the aircraft replaces the aerofoil characteristic. For a given lift, the latter is proportional to the reciprocal of the square of the speed so that, for any given configuration, it is possible to identify a so-called “minimum drag speed”, the total resistance increasing both at lower and higher speeds. This leads to an important sequence of the development of lift. The former depends on the general shape of the aircraft, and the other is a consequence of the lift control could be maintained. A dominant factor in determining this is the ratio of the square root of the maximum lift coefficient to the cube root of the zero lift drag coefficient, although the power available also matters. The original biplane Wright Flyer of 1903 achieved a speed range of only 1.28 with an L/D of about 8. Had a modern more powerful piston engine of the same weight been available, the speed range would have been about 2.8. A current, roughly comparable monoplane has a typical speed range nearer to 4. Means introduced to increase the speed range include retracting landing gear, variable pitch propellers, and variable wing geometry in the form of high-lift devices.

The speed range is of little concern for more recent designs, especially when propellers are not used. More important is the achievement of near-maximum lift-to-drag ratio in the critical flight phase such as long-range cruise. The primary factor here is the correct selection of wing loading, that is, the ratio \( W/S \), in the critical performance condition. This is usually found to be appreciably greater than that essential to give acceptable low-speed characteristics (see Volume 5, Chapter 213). As with earlier designs, the solution is the use of high-lift devices to satisfy the low-speed performance criteria without unduly compromising the higher speed potential.

The increase of drag coefficient as the speed of sound is approached may be mitigated by the use of wing sweep so that local velocity perpendicular to the leading edge is less than the freestream value. There can be other consequences of

\[
L = 0.5 \rho V_{0}^2 C_{L} \tag{1}
\]

where \( C_{L} \) is the lift coefficient of the aerofoil or, in the case of an airship the body, and \( S \) is the corresponding reference area.

\[
D = 0.5 \rho V_{0}^2 S \left( C_{D0} + \frac{4C_{L}^2}{\pi A} \right) \tag{2}
\]

where \( C_{D0} \) is the drag coefficient of the aircraft when \( C_{L} \) is zero, \( k \) is a factor depending the distribution of the lift, and \( A \) is the aspect ratio of the wing, that is, the ratio of the span \( b \) to its mean width (chord) \( c \).

From equation (1)

\[
D = 0.5 \rho V_{0}^2 C_{D0} + \frac{2Lk}{\pi \rho AV_{0}^2} \tag{3a}
\]

Drag is found to be a minimum when the two terms on the right-hand side of equation (3a) are equal, that is,

\[
D_{\text{min}} = \rho V_{0}^2 SC_{D0} \tag{3b}
\]

The maximum corresponding lift-to-drag ratio is

\[
\frac{L}{D_{\text{min}}} = \frac{C_{L}}{2C_{D0}} \tag{3c}
\]

which is achieved at the speed where the drag is a minimum for a given overall lift.

For older propeller-driven aircraft, an important criterion was the so-called “speed range”, this being the ratio of the maximum achievable speed to the minimum speed at which controlled flight could be maintained. A dominant factor in determining this is the ratio of the square root of the maximum lift coefficient to the cube root of the zero lift drag coefficient, although the power available also matters. The original biplane Wright Flyer of 1903 achieved a speed range of only 1.28 with an L/D of about 8. Had a modern more powerful piston engine of the same weight been available, the speed range would have been about 2.8. A current, roughly comparable monoplane has a typical speed range nearer to 4. Means introduced to increase the speed range include retracting landing gear, variable pitch propellers, and variable wing geometry in the form of high-lift devices.

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\[
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\]
compressibility, such as the formation of local shock waves, sometimes causing sudden changes in lift distribution with changes to the overall control characteristics (see Volume 1, Chapter 23).

2.2 Propulsion

There is a strong interaction between the type of propulsion employed and the flight regime of an aircraft. On the one hand, the power plant used is often directly determined by the required flight performance, and on the other, there are numerous instances where the performance is limited by a power plant selected for economic or other reasons (see Volume 2, Chapter 71).

2.2.1 Thrust (see Volume 2, Chapter 72)

The thrust $T$ of any power plant is defined by

$$T = \frac{d(m'v)}{dt}$$

(4a)

where $m'$ is the mass of the propelling medium and $v$ is its velocity.

For a rocket engine,

$$T = V_j \frac{dm'}{dt}$$

(4b)

where $V_j$ is the characteristic exhaust velocity and $dm'/dt$ is the rate of propellant burning.

For an air-breathing engine of exhaust area $A_j$,

$$T = m(V_j - V_0) + m_i V_j + (p_j - p_0)A_j$$

(4c)

where $m$ is the mass of air passing through the unit, $V_0$ is the forward speed of the aircraft, $m_i$ is the mass of fuel, and $p_j$ and $p_0$ are the exhaust and freestream pressures, respectively. Usually $m_i$ is small in comparison with $m$, and for complete expansion in the exhaust, $p_j$ is equal to $p_0$ so that approximately

$$T = m(V_j - V_0)$$

(4d)

2.2.2 Efficiency

The overall efficiency of an engine is the product of the so-called “ideal efficiency” and the mechanical and thermal efficiencies of the various components of the unit, inclusive of the air intake and the exhaust where relevant. The ideal propulsive efficiency is

$$n = \frac{2}{1 + (V_j/V_0)}$$

(5)

It can be seen that while $V_j$ must be greater than $V_0$ to produce thrust, the highest efficiency is realized when $V_j$ is only just greater than $V_0$. Thus, it is preferable to develop the thrust by imposing a relatively small velocity increment upon a relatively large mass of propulsive medium. Further, for a given propellant, the general trend is for efficiency to increase with forward speed. Equation (5) does not apply in static conditions when ideal efficiency is meaningless, and thrust is determined from a static coefficient.

An important component in the overall efficiency of a jet engine is the efficiency, or pressure recovery, of the air intake system. Up to around the speed of sound, an acceptably high value may be obtained with a simple pitot intake, but as Mach number rises further, it is desirable to incorporate increasingly more complex shock wave systems. Maintaining efficiency across the whole Mach number range of an aircraft that flies above a Mach number of 1.5 suggests the need for a variable geometry intake (see Volume 2, Chapter 79). Likewise, efficient flight at both sub and supersonic speeds requires the use of a variable exhaust nozzle.

2.2.3 Thrust and efficiency of propeller propulsion (see Volume 2, Chapter 77)

The relationship between thrust and power of a propeller engine is of particular importance:

$$T = \frac{\eta P}{V_0}$$

(6)

where $P$ is the power of the prime mover and $\eta$ is the efficiency derived from equation (5) for a particular design of propeller. Although $\eta$ may exceed 90%, a more usual value is around 85%.

2.2.4 Thrust of jet and related power plants (see Volume 2, Chapters 78 and 81)

For this class of engine, the thrust may be derived from equation (4c) or approximately from equation (4d). In a simple jet engine, all the intake air passes directly through the compressor, combustion chamber, and turbine into the exhaust nozzle. Greater efficiency may be obtained by passing some of the compressed air directly into the exhaust thereby effectively increasing the mass flow with some reduction in exhaust

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velocity and consequent reduction in exhaust noise. This bypass technique is extended to the ducted fan engine concept where much of the intake air passes directly to the exhaust after passing only through the first compressor, or fan, stage. Ducted fan or bypass engines find almost universal use on subsonic aircraft other than those that use propellers.

A development of the ducted fan engine is the concept where the turbine system drives a large un-ducted fan, that is, a propeller/ducted fan hybrid. Such an engine may be more efficient than a ducted fan and can be used at higher speeds than a propeller. It is not without mechanical and noise problems, which may be overcome by further development should economic considerations, such as fuel shortages, dictate its use.

### 2.3 Power plant flight regimes

Figure 6 illustrates the variation of the ideal efficiency with increase of Mach number for different types of power plants. Although the actual achieved efficiency depends on many detail considerations, this figure does give an overall picture of the potentials and limitations of the various types.

#### 2.3.1 Propeller propulsion

As an approximate indication, propeller systems may be designed to achieve high efficiency for Mach numbers up to about 0.65, that is, forward speeds up to about 200 m s$^{-1}$. The lower end of this range is usually covered by piston engine power, but as the required forward speed increases above 100 m s$^{-1}$, a turbine power plant becomes more practical. At Mach numbers in excess of about 0.7, the efficiency of a propeller starts to fall due to the formation of shock waves and the implied additional losses.

#### 2.3.2 Turbofan propulsion

The ducted turbofan engine has been the obvious choice of power plant when the normal operating speed is in the higher subsonic range, that is, for Mach numbers between about 0.7 and 0.9. As a general rule the bypass ratio, that is, the ratio of the air passing through the fan to that in the engine core, is usually in the range of 4–10. The higher values tend to be used for larger, longer-range aircraft where the implied large fan diameter can be accommodated. There is some application for smaller lower bypass ratio engines at Mach numbers in the 0.5–0.7 range, mainly for small executive aircraft (see Section 3.2.2). At very high subsonic Mach numbers, higher bypass ratio engines begin to lose efficiency for reasons similar to those associated with propellers.

#### 2.3.3 Low bypass ratio and jet engines

It can be seen from equation (4d) that as the flight speed increases, it is necessary to increase the jet exhaust velocity to produce thrust. This implies the use of engines that operate on relatively smaller masses of air, and the great majority of aircraft that operate in the supersonic regime use power plants having bypass ratios in the range of 0.4–1.0. It is also usual to incorporate afterburning, that is, secondary burning of fuel in the exhaust, to augment thrust at transonic and higher supersonic speeds. Typical jet exhaust velocities are around 700 m s$^{-1}$, increased to 1100 m s$^{-1}$ with afterburning. Flight nearer to a Mach number of 3.0 at altitude is likely to require the use of a pure jet engine, but very few aircraft operate under this condition.

#### 2.3.4 Ramjets

In a ramjet engine, all the compression is obtained from air intake pressure recovery, the rotating components of a turbojet being dispensed with. Although ramjets are simple engines, they suffer because useful thrust is only produced at supersonic speeds (see Volume 2, Chapter 78). Conventional, internal burning ramjets do find application on guided missiles where the initial flight phase is by rocket booster. There have also been proposals for the use of ramjets in conjunction with turbojets, or even hybrid arrangements, but no practical platforms using these techniques have been developed. At hypersonic speed, Mach numbers above about 4, there is the possibility of incorporating an external burning ramjet in the underside of the aircraft, and there have been successful tests. The combustion process occurs at supersonic speed – so-called “scramjets” (see Volume 2, Chapter 90).
2.3.5 Rockets
Apart from particular research aircraft, such as the X-15 aircraft mentioned in Section 1.1, liquid rocket engines no longer have application to aircraft. On the other hand, solid rocket units are commonly employed for guided weapons where the operating time is short and their simplicity is overriding.

2.4 Airframe and overall efficiency
Although range is by no means the only performance requirement, it is a dominant one for many aircraft (see Volume 5, Chapter 217). In any given flight condition at a given Mach number $M_a$, the range $R$ is

$$ R = \alpha \left\{ \frac{M_a}{c} \right\} \left[ \frac{L}{D} \right] \log \left( \frac{m_1}{m_2} \right) $$

where $c$ is the specific fuel consumption of the power plant and $m_1$ and $m_2$ are the aircraft masses at the commencement and the end of the cruise, respectively.

This equation may be regarded as giving an indication of the overall flight efficiency. As can be seen, it is the product of three components:

1. $\left\{ \frac{M_a}{c} \right\}$
   - As the flight speed/Mach number is intimately connected with the power plant and its performance, this term may be taken as a measure of the propulsion efficiency.

2. $\left[ \frac{L}{D} \right]$
   - The lift-to-drag ratio is clearly a measure of the aerodynamic efficiency, and the design should be such that the flight condition is as near as is possible to the minimum drag speed. In practice, it may be somewhat higher for operational reasons, but the achieved $L/D$ is usually close to the maximum value. While a typical subsonic airliner may have an $L/D$ approaching 20, in supersonic cruise, the Concorde barely matched the value 8 achieved by the 1903 Wright Flyer.

3. $\log \left( \frac{m_1}{m_2} \right)$
   - Except when a weapon is released, the fuel used in the cruise is $(m_1 - m_2)$ and although the ratio $m_1/m_2$ is directly determined by the required range, it follows that the lower the value of $m_2$, the lower will be the actual quantity of fuel needed. The mass $m_2$ is made up of the empty equipped mass of the aircraft, the payload, and the fuel remaining at the end of the cruise. The equipped empty mass includes that of the power plant and the airframe systems, but the major contribution is the airframe itself. Thus, this term may be regarded as a measure of the airframe efficiency. The empty equipped mass must always be as low as is economically feasible.

3 FLIGHT REGIMES AND PLATFORM APPLICATIONS
The great majority of aircraft operate at speeds below a Mach number of 0.9. Apart from the Anglo-French Concorde, which was withdrawn from service in November 2003 at the very end of the first century of manned flight, operations at higher speeds have been limited to military and research applications. The following paragraphs outline the speed/altitude regimes for various platform applications. There are examples of platforms that fall outside the defined categories. These are commented upon where relevant.

Flying boats played an important role in opening up early long-distance air routes as well as making a major contribution to World War II, but they are now obsolete. Smaller floatplanes continue to be used extensively in regions where land access is difficult but where water is available for take-off and landing, as in western Canada (see Volume 7, Chapter 333).

Most fixed-wing platforms use a conventional layout; that is, a separate payload-carrying body with a wing of aspect ratio typically between 4 and 10 (see equation (2)) and rear stabilizer and control surfaces. Some military combat aircraft have lower aspect ratio wings, and there is interest in so-called “blended-wing-body” arrangements. Sailplanes and long-endurance, high-altitude reconnaissance types may have aspect ratios in excess of 20.

3.1 Subsonic, operating up to a Mach number of 0.4 and 4 km altitude

3.1.1 Lighter-than-air platforms
With the exception of high-altitude research and weather balloons, all lighter-than-air platforms normally operate at less than 1000 m height and fly at low speed, usually less than 25 m s$^{-1}$, that is, a Mach number of 0.07 (see Volume 7, Chapter 336). Hot air balloons used for ground observation and other recreational purposes are at the mercy of local winds for horizontal motion, and the flight altitude is often kept to the minimum demanded by the role. Helium and hydrogen-filled
balloons are less constrained in altitude, and it is this type that is used for high-altitude research, reaching up to more than 20 km.

Gas-filled airships have a means of forward propulsion that, as mentioned in Section 1.2.3, is often also used for control purposes. For small airships, this is by piston engine-driven propellers, the whole power plant assembly being arranged to rotate about a horizontal axis. Unless local terrain dictates otherwise, the flight altitude is rarely above 300 m, since the lifting capacity decreases as local air density falls with an increase in height. The expansion of the lifting gas as height increases is normally offset by an initial underinflation of the gas cells such that the volume available is just filled at the operating altitude.

3.1.2 Fixed-wing platforms

The great majority of small propeller-driven aircraft fly in this regime (see Volume 7, Chapters 323, 327 and 332). Applications include private light and corporate types used for recreation and communication; competitive flying such as racing and aerobatics; primary training and special operations such as air ambulances. Recreational platforms include sailplanes, hang gliders, and ultralight machines. Some more advanced military trainers also come into the higher speed, higher-altitude part of this regime.

Since the operating conditions are relatively modest, it is easy to achieve the compromise between low and high-speed performance, and high-lift devices are usually limited to simple trailing edge flaps. Retractable landing gear is only usual for aircraft that operate at higher speeds in this category. Cabin pressurization is unusual as the operating altitude presents no inherent difficulties, but advanced military trainers may be equipped with oxygen systems for the occasional flight at higher altitudes.

Smaller cheaper aircraft use one or two piston engines driving propellers. While gasoline fuel is common, supply problems associated with this type of fuel have led to proposals for a greater use of diesel as well as smaller propeller turbines. The latter are the chosen power plant for the more advanced, faster aircraft operating in this category.

3.1.3 Rotorcraft

With a few exceptions, all rotorcraft fly in this regime (see Volume 7, Chapters 324, 328, and 334). The exceptions are the use for mountain rescue and the occasional higher speed, hybrid rotorcraft such as the Bell-Boeing V-22 military tilt rotor transport. Nearly all rotorcraft are helicopters, the few autogiros flying being limited to light recreational craft. The ability of helicopters to hover and to take-off and land from very restricted locations confers a special advantage over fixed-wing aircraft as well as land and sea transport. Civilian uses of helicopters include personal training, communications, air ambulances, police observation, survey for such purposes as power line inspection, and air/sea and mountain rescue.

As well as having roles similar to those of civil rotorcraft, military applications include the significant use of helicopters for shipboard operations where an air support role may be achieved when there is inadequate deck space to operate fixed-wing aircraft. Another important use is for the support of ground troops where the only similar fixed-wing types are short/vertical take-off and landing aircraft such as the BAe Systems Harrier and Lockheed-Martin F-35.

With the notable exception of the twin rotor Boeing CH-47 Chinook, helicopters in service use a single main rotor configuration. Smaller craft sometimes use piston engine power, but the smoother running properties of gas turbines are preferred wherever the greater cost can be justified.

3.1.4 Unmanned platforms (see Volume 7, Chapter 335)

Most unmanned platforms operate at Mach numbers below 0.4, and although fixed-wing designs predominate, rotorcraft have some application, especially for shipboard use and crop spraying. The exceptions are mostly aerial targets that can operate at speeds up to, and including, the supersonic regime and combat types (see Section 3.5.3). Earlier unmanned platforms were used for research and military roles, but there is a growing interest in their application to civilian uses such as observation and road traffic control. Proven military operations include general reconnaissance, gunnery target spotting, observation, and tactical strike using air-launched guided weapons. The operating altitude of some craft can be higher than 4 km.

Many unmanned aircraft have relatively modest performance, and this implies the use of piston engine-driven propeller power plants. Some observation platforms fly at much greater altitudes, possibly up to as high as 25 km to be above the capability of antiaircraft missiles. There is often a requirement for very long duration of the order of 24–30 h. They may fly faster than a Mach number of 0.4 and use turbofan propulsion, but an alternative is to use electrically driven propellers with solar cell power supplemented by onboard batteries.

3.1.5 Guided weapons

Apart from the possible use of short-range anti-armor types, most guided weapons fly at speeds greater than a Mach number of 0.4 (see Section 3.5.4).
3.2 Subsonic, operating between Mach numbers of 0.4 and 0.75 and up to 8 km altitude

This flight regime is occupied by platforms powered by turbo-propeller engines and some, smaller, turbojet/turbofan applications (see Volume 7, Chapters 330, and 331). Apart from the upper end of this Mach number range, it is unlikely that compressibility causes any major difficulty, and so wing sweep is not generally needed.

3.2.1 Turboprop transports and executive aircraft

Single-, twin-, and four-engine passenger and freight turboprop platforms as well as single- and twin-engine personal aircraft normally operate in the Mach number range of 0.5–0.65. This applies both to civil and military designs although a few of the latter do fly faster than Mach 0.7. Cruising altitude is usually in excess of 4 km, and cabin pressurization is necessary. Although flight altitude in excess of 8 km is feasible, it is not often expedient for reasons of air traffic control. Compared with somewhat faster turbofan-powered aircraft, the fuel consumption is less, and hence this class of transport has an advantage, especially for shorter range operations.

3.2.2 Small executive turbojet powered aircraft

As well as the turboprop executive types mentioned above, this flight regime is used by a class of small turbojet/turbofan-powered private aircraft. Although two engines are usually installed, single-engine examples do exist. Turboprops, rather than turboprop power plants, are especially suitable for this class of aircraft for two reasons. One is the potential for somewhat higher cruise speeds, but, more significantly, the absence of propellers confers a much greater flexibility on the layout of the platform.

3.2.3 Other platforms

Other types of vehicles that operate in this flight regime include some military advanced trainers and ground support aircraft. These are usually turboprop powered.

As mentioned in Section 3.1.4, there are also instances of high-altitude turbofan-powered unmanned platforms that fly typically at Mach numbers of around 0.65. Some ground-to-ground infantry-operated guided weapons also have operating speeds in this regime (see Section 3.5.4).

3.3 Subsonic, operating at Mach numbers between 0.65 and 0.9

3.3.1 Civil and military turbofan-powered transports, altitudes between 7 and 14 km

Most civil “jet” airliners and comparable military types use turbofan power plants (see Volume 7, Chapters 330). A typical cruise condition is somewhat in excess of Mach 0.8 at altitudes in the range of 9 to 12 km. Whenever possible, the actual cruise speed is optimized for minimum fuel consumption, but flight altitude is frequently dictated by air traffic control. On long haul flights, it increases in steps to compensate for the reduction of aircraft weight as fuel is consumed, possibly up to as high as 13 km. Executive turbofan platforms fly at similar speeds but may achieve somewhat greater altitudes where there are less air traffic control restrictions.

Cabin pressurization is essential for all these aircraft as is some sweep of the wing. As it is necessary to optimize the overall layout for the cruise conditions, it is inevitable that the low-speed performance requirements are achieved by employing extensive high-lift devices in the form of leading- and trailing-edge flaps. Landing conditions are particularly critical as the approach and touchdown speeds have to be within air traffic control limits (see Section 4.5). There is a tendency for the number of engines to be restricted to two as power plant and system reliability has improved. Large transports do need four engines to give the required thrust.

3.3.2 Military, operating up to 20 km altitude (see Volume 7, Chapter 331)

A wide range of military operations are undertaken within this speed regime using platforms powered by turbojet and turbofan engines. The roles performed include

1. Offensive strike, both tactical short range and strategie longer range. Most sorties employ some form of air-launched guided weapons or “smart” bombs. Subsonic cruise missiles used for strategic operations have the advantage that they can be launched by the parent aircraft from outside highly defended target locations;
2. Interception and combat with enemy aircraft, again most often using air-launched supersonic guided weapons;
3. High-altitude reconnaissance employing both manned and unmanned platforms (see Sections 3.1.4 and 3.2.3);
4. Advanced trainers.

There is frequently a requirement for military types in these categories to be able to perform several roles, including...
supersonic ones (see Section 3.5.2). For this reason, at one period of aeronautical development, there was an emphasis on the use of variable sweep wings. More recent developments have concentrated on a fixed low aspect ratio, almost unswept, wing geometry in conjunction with closely coupled tail surfaces or fore-planes and possibly thrust vector control to achieve the required compromises that usually include stealth.

3.3.3 Guided missiles
Guided weapons in the cruise missile and similar categories fly in this regime (see Section 3.3.2).

3.4 Transonic, operation at Mach numbers between 0.9 and 1.4
Flight at transonic speeds introduces many problems and is usually avoided except for the essential passage from subsonic to supersonic flight. The problems include very high relative drag and control difficulties due to the formation and movement of shock waves across the airframe (see Volume 1, Chapter 23). There is little advantage of increase in speed beyond a Mach number of 0.9 for a low-level military strike platform. Transonic acceleration may occur at any altitude, but it is often undertaken around 11 km where the speed of sound has its lowest value.

3.5 Supersonic, operating at Mach numbers between 1.4 and 4.0

3.5.1 Civil aircraft
Although the Soviet Union produced the Tupelov Tu 144 supersonic airliner and it operated briefly in a freight role, the only true supersonic airliner has been the Anglo-French Concorde. Arguably this aircraft was not commercially viable, primarily due to its limited passenger capacity of around 100 and operational restrictions imposed to avoid ground-perceived shock waves over populated areas. Among other things its technical success depended on advanced variable geometry air intakes for the four turbojet engines (see Section 2.2.2). Major technological issues have to be overcome if an economically competitive and environmentally acceptable successor is to be put into service. For this reason, most of the emphasis on supersonic transport is placed on relatively small platforms intended for executive operations. Even these are confronted by severe economic and technical problems.

3.5.2 Manned military operations
At one time there was considerable interest in manned supersonic aircraft for strategic strike operations, but it seems that it is now generally accepted that a preferable approach is to employ subsonic, possibly stealthy, platforms equipped with cruise missiles (see Section 3.3.2). Most supersonic military aircraft fall into the general category of interceptor aircraft where high forward speed and high rate of climb are necessary to enable rapid engagement of a potential enemy. Achieved Mach numbers at altitude usually exceed 2. With the general emphasis on a multi-role capability, discussed in Section 3.3.2, these aircraft must also possess good high subsonic speed performance so that they are capable of operating in ground strike and support roles. The Lockheed SR-71 reconnaissance aircraft was unique in that it flew at Mach 3.2 at an altitude of 25.6 km (84 000 ft).

3.5.3 Unmanned platforms
Provision for human crew in a military aircraft is both restrictive and costly. Hence, there is a considerable emphasis on the replacement of high-performance combat aircraft by unmanned equivalents (see Section 3.1.4).

3.5.4 Guided weapons (see Volume 7, Chapters 325, 326, and 344)
Many guided missiles, both ground and air launched, operate in the supersonic regime. Ground-launched platforms utilize solid rocket boosters to propel them rapidly to their operating state in which they may be sustained by a second rocket unit or, possibly, a ramjet. Air-launched weapons often only require one stage of propulsion. Cruise missiles use turbofan engines.

3.6 Hypersonic regime, flight in excess of a Mach number of about 4.0
As yet, few platforms operate in this regime and effectively all the examples are research craft. The North American X-15 rocket-powered aircraft is mentioned in Section 1.1, and more recent experiments with external burning ramjets are mentioned in Section 2.3.4. Considerable technological development is required, especially in the realm of high-temperature materials, before there will be any possibility of regular flight at hypersonic speed within the atmosphere as defined in Section 1.1. Quite possibly, like the X-15, any such platform will be a hybrid of aerodynamic and ballistic flight.
Chapter 7: Aircraft Flight Regimes and Applications

1. Impact of aircraft on ground environment

The environment in which an aircraft operates when it is in the vicinity of the ground and its impact on the environment are both of major importance.

1.1 Noise (see Volume 6, Chapters 286, 288 and 287)

Noise is significant during both the take-off and landing phases of aircraft flight:

1. At take-off, the engines are initially at maximum power, but the time and distance of the ground exposure to the noise are relatively short. Sometimes a performance penalty can be accepted to alleviate the noise by reducing power once a safe altitude has been reached (see Section 4.3) or by changing the flight path direction to avoid sensitive ground locations.

2. During landing, the engines operate at reduced power so noise from this source is much less than during take-off, but the airframe of a large aircraft may make a significant contribution to the noise level (see Volume 6, Chapters 290 and 291). However, the approach angle is usually shallow (see Section 4.4), and this phase of the flight is long and covers a large area of ground. Noise impact may be reduced if a steep approach is employed (see Section 4.5.2(2)).

1.2 Emissions (see Volume 6, Chapter 300)

Emissions from the power plants, especially during take-off, make a major contribution to atmospheric contamination. They consist of various gases, especially oxides of carbon and nitrogen, and although power plant development is leading to a reduction of the more noxious compounds, the carbon dioxide remains a problem.

1.3 Atmospheric turbulence

An aircraft passing through the atmosphere produces vortices that are a form of atmospheric turbulence. The impact on other aircraft can be important (see Section 4.5.2).

2. Flight of an aircraft in ground environment

Flying characteristics are influenced by aircraft proximity to the ground. During the initial phase of the take-off and the final phase of the landing, handling characteristics are different from those in free air. The reflective effect of the ground plane is to increase the lift of the main and stabilizing surfaces, the amount being dependent on the height of the surface above ground. It is significant when a lifting surface is nearer to the ground than about 20% of its span but negligible when the height is above a span. Lift-induced drag is reduced by ground effect, and the different effective heights of the main and horizontal stabilizing surfaces may cause changes in the control and stability characteristics.

4.3 The take-off environment (see Volume 5, Chapter 213)

Figure 7 illustrates the characteristics of a typical take-off path, where $V_{mn}$ is the lowest left off speed. It consists of acceleration from standstill to a “rotation” speed at which point the nose is lifted and the aircraft leaves the ground, passing over the runway threshold at a minimum specified height, typically 10.7 m. The climb out is divided into three phases, introducing some operational flexibility when an engine failure occurs or a noise abatement procedure is used.

An important point in the acceleration phase is when the “decision” speed is reached. This is the speed above which the take-off must be completed even if an engine fails. Below the decision speed, the aircraft can be stopped before the end of the runway by application of emergency braking. The major considerations of take-off performance are the acceleration throughout the maneuver and the emergency braking capability. Take-off start point is well defined, and the required runway length determined by reference to design conditions is usually factored by only 1.15 to cover the various environmental contingencies.

4.3.1 Impact of high temperature and altitude

Increase of both runway altitude and ambient temperature results in reduction of power plant and airframe performance, in part due to lower air density. When determining the required runway length, the calculated and measured performances are based on specific altitude/temperature conditions. Typical examples of this are standard temperature +30°C at sea level or +15°C at 1527 m (5000 ft) altitude.

4.3.2 Visibility

Impaired visibility due to the presence of ground mist, fog, or a sandstorm has a safety implication on take-off. Providing taxiway and runway lighting is adequate for the aircraft to reach the take-off point, and radar, or other means, is available to ensure that the runway is clear, take-off can proceed. In
severe conditions, runway lighting may be inadequate and take-offs have to be discontinued.

4.3.3 Ice

The formation of ice on the airframe and power plant intakes has a serious impact on take-off performance. It causes greater drag and lower lift capability due to change in the wing aerofoil contour. Icing of propellers reduces efficiency, and there is the possibility that ice may break off and damage the airframe. It is essential that all relevant parts of the aircraft are thoroughly de-iced before take-off is attempted. De-icing may need to be repeated if there is a delay before clearance is given for the take-off (see also Section 4.3.4(2)).

4.3.4 Lightning and precipitation

Lightning strikes rarely cause serious damage as provision is made for this eventuality, but there is a remote possibility of interference with avionic systems. Precipitation in the form of rain, hail, and snow is of more concern:

1. Rain on the airframe does not usually present a serious problem although there is evidence that heavy rain may reduce the lift of some laminar flow aerofoil sections. Of more concern is the accumulation of large quantities of water on the runway surface. This can result in

   (a) reduced take-off acceleration due to the additional rolling resistance;
   (b) possible ingestion of water into the power plant and lower thrust or even flameout;
   (c) reduction of braking performance in an emergency stop. In the limit, the aircraft may “aquaplane” and lose directional control as well as brake performance. Part of the certification process is actual testing on a flooded runways. Large hailstones cause airframe damage, and if this includes high-lift devices, it may result in reduction of take-off performance.

2. Apart from the implied possibility of ice formation on the aircraft (see Section 4.3.3), the presence of soft snow on a runway results in a large increase of rolling resistance and consequent reduction in take-off acceleration. The effect is less severe when the snow has a hard, compacted surface, but for most operations, it is essential to clear snow and ensure that the runway surface has been de-iced before operations can continue.

4.4 The landing environment (see Volume 5, Chapter 213)

Many of the environmental effects discussed in the previous paragraph apply to landing as well as take-off, but there are some differences.
A diagram of a typical landing is given in Figure 8. The maneuver commences as the aircraft is established on a final approach path having a typical descent angle of 3°. At a busy airport, the approach speed has to be maintained within limits (see Section 4.5.2). The aircraft passes over the airport boundary at a typical height of 10.7 m having commenced a flare intended to reduce its vertical descent velocity to zero at the instant the main wheels contact the ground. Ground effect (see Section 4.2) may cause the aircraft to “float”, delaying touchdown, and often lift spoilers are used to minimize this. Brakes, possibly augmented by reverse thrust, are applied as soon as the main wheels touchdown to bring the forward speed to a safe taxiing value. Typical mean deceleration may be 0.25\(g\) although values approaching 0.4\(g\) are possible.

The major factors during landing are adequate visibility to ensure the correct touchdown point, touchdown to occur soon after passing the runway threshold, and adequate braking and steering capability during the deceleration phase. Automatic landing systems can greatly facilitate the landing, but there is always a minimum visibility requirement.

There is more variability in landing than in take-off, and a large proportion of aircraft accidents occur during the approach and landing phases. Thus, when the required landing runway lengths are based on “ideal” conditions, it is usual to factor the calculated value by as much as 1.67. Factors as low as 1.10 are used when full allowance is made for environmental variations.

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### 4.4.1 Effect of high temperature and altitude

Apart from the situation where the landing has to be aborted and the thrust increased to initiate a “go-around”, these conditions have less impact on landing than they do on take-off.

### 4.4.2 Visibility

Except when aircraft is equipped with an automatic landing system, good landing visibility is essential to ensure an acceptable touchdown point. Reasonable visibility is also necessary once the aircraft is on the ground to ensure safe braking and taxiing. Mist, fog, and sandstorms frequently result in cessation of operations.

### 4.4.3 Icing

The passage of an aircraft through icing conditions during approach and landing presents a severe hazard. Ice accretion increases when high-lift devices are deployed with consequent reduction of lift capability, considerable drag penalty and, probably, change in handling characteristics. Aircraft intended for all-weather operations must be equipped with de-icing or anti-icing systems on at least the main planes and, for smaller aircraft, also the stabilizing surfaces. Engine air intakes, including those of piston engines, sensitive sensors such as pitot heads, and propellers must be included in the de-icing systems.
4.4.4 Precipitation
Heavy rain causing flooding of the runway and soft snow on the surface can result in reduced braking and loss of directional control (see Section 4.3.4).

4.5 Aspects of the operational environment

4.5.1 Air traffic control
Take-off and landing maneuvers are undertaken in a strict Air Traffic Control (ATC) environment (see Volume 6, Chapter 283), and this imposes restrictions on the operation. It is often necessary to maximize runway usage, see below, as well as ensuring safe flight of all the aircraft in the local ATC zone. Although many aspects of ATC are fully automated, and aircraft are equipped with many navigational aids, there is inevitably a large human factor element in the operation. The ATC controllers have to observe numerous aircraft flying on different tracks at any given time. They issue instructions that have to be acknowledged and implemented by the crew of the aircraft. Flight path conflicts can occur, but actual collisions are very rare due to use of anti-collision warning devices and well-established flight procedures. Aircraft approach to runways used for mixed take-off and landings, and ground operations where aircraft are required to cross, or use, active runways can be particularly hazardous.

4.5.2 Runway usage
It is preferable, where available, to use two runways at any given time, one for take-offs and the other for landings. Safe take-offs can follow one another at about 1.5 min intervals although the gap may be longer if a small aircraft follows a large one to avoid vortex wake turbulence. To reduce uncertainties during landing, the final approach speed is often kept within limits, typically 55–70 m s\(^{-1}\). Approach and landings require around 2–2.5 min spacing, the latter when a smaller aircraft follows a larger one. Typically 40 instrument-controlled take-offs may be achieved in each hour but as few as 24 landings. On a mixed-usage runway, 30–32 operations per hour are feasible.

Apart from the use of multiple runways, there are a number of ways of maximizing runway usage:

1. In good visibility, it may be possible to integrate general aviation aircraft, especially taking off, into the normal, heavier traffic, as they can depart and approach over shorter ground distances.
2. Short take-off and landing (STOL) aircraft may also be introduced for similar reasons to those of (1) above. Steep climb outs in association with descent angles as high as 6° or more are possible with lower implied approach speeds than usual. However, it is preferable to enhance the total capacity of an airport by providing a shorter, dedicated runway for such operations.

FURTHER READING