Airspeed in Aeronautics

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Introduction

An airspeed indicator is a flight instrument that displays airspeed. This airspeed indicator has standardized markings for a multiengine airplane

Aircraft have pitot probes for measuring airspeed

Airspeed is the speed of an aircraft relative to the air. Among the common conventions for qualifying airspeed are: indicated airspeed ("IAS"), calibrated airspeed ("CAS"), true airspeed ("TAS"), equivalent airspeed ("EAS") and density airspeed.

The measurement and indication of airspeed is ordinarily accomplished on board an aircraft by an airspeed indicator ("ASI") connected to a pitot-static system. The pitot-static system comprises one or more pitot probes (or tubes) facing the on-coming air flow to measure pitot pressure (also called stagnation, total or ram pressure) and one or more static ports to measure the static pressure in the air flow. These two pressures are compared by the ASI to give an IAS reading.

Indicated airspeed

Indicated airspeed (IAS) is the airspeed indicator reading (ASIR) uncorrected for instrument, position, and other errors. From current EASA definitions: Indicated airspeed means the speed of an aircraft as shown on its pitot static airspeed indicator calibrated to reflect standard atmosphere adiabatic compressible flow at sea level uncorrected for airspeed system errors.

Outside of the former Soviet bloc, most airspeed indicators show the speed in knots i.e. nautical miles per hour. Some light aircraft have airspeed indicators showing speed in miles per hour.

An airspeed indicator is a differential pressure gauge with the pressure reading expressed in units of speed, rather than pressure. The airspeed is derived from the difference between the ram air pressure from the pitot tube, or stagnation pressure, and the static pressure. The pitot tube is mounted facing forward; the static pressure is frequently detected at static ports on one or both sides of the aircraft. Sometimes both pressure sources are combined in a single probe, a pitot-static tube. The static pressure measurement is subject to error due to inability to place the static ports at positions where the pressure is true static pressure at all airspeeds and attitudes. The correction for this error is the position error correction (PEC) and varies for different aircraft and airspeeds. Further errors of 10% or more are common if the airplane is flown in “uncoordinated” flight.

Calibrated airspeed

Calibrated airspeed (CAS) is indicated airspeed corrected for instrument errors, position error (due to incorrect pressure at the static port) and installation errors.

Calibrated airspeed values less than the speed of sound at standard sea level (661.4788 knots) are calculated as follows:

$$V_c = a_0\sqrt{5\left[\left(\frac{q_c}{P_0}+1\right)^{\frac{2}{7}}-1\right]}$$ minus position and installation error correction.

Where

V_c is the calibrated airspeed,
q_c is the impact pressure (inches Hg) sensed by the pitot tube,
P_0 is 29.92126 inches Hg; static air pressure at standard sea level,
a_0 is 661.4788 knots;, speed of sound at standard sea level.

Units other than knots and inches of mercury can be used, if used consistently.

This expression is based on the form of Bernoulli's equation applicable to a perfect, compressible gas. The values for P_0 and A_0 are consistent with the ISA i.e. the conditions under which airspeed indicators are calibrated.

Equivalent airspeed

Equivalent airspeed (EAS) is defined as the speed at sea level that would produce the same incompressible dynamic pressure as the true airspeed at the altitude at which the vehicle is flying. An aircraft in forward flight is subject to the effects of compressibility. Likewise, the calibrated airspeed is a function of the compressible impact pressure. EAS, on the other hand, is a measure of airspeed that is a function of incompressible dynamic pressure. Structural analysis is often in terms of incompressible dynamic pressure, so that equivalent airspeed is a useful speed for structural testing. At standard sea level pressure, calibrated airspeed and equivalent airspeed are equal. Up to about 200 kts CAS and 10,000 ft the difference is negligable, but at higher speeds and altitudes CAS must be corrected for compressibility error to determinine EAS. The significance of equivalent airspeed is that at Mach numbers below the onset of wave drag, all of the aerodynamic forces and moments on an aircraft scale with the square of the equivalent airspeed. The equivalent airspeed is closely related to the Indicated airspeed speed shown by the airspeed indicator. Thus, the handling and 'feel' of an aircraft, and the aerodynamic loads upon it, at a given equivalent airspeed, are very nearly constant and equal to those at standard sea level irrespective of the actual flight conditions.

True airspeed

True airspeed (TAS) is the physical speed of the aircraft relative to the air surrounding the aircraft. The true airspeed is a vector quantity. The relationship between the true airspeed and the speed with respect to the ground (V_g)is:

$$V_t = V_g - V_w$$

Where:

V_w = Windspeed vector

Aircraft flight instruments, however, don't compute true airspeed as a function of groundspeed and windspeed. They use impact and static pressures as well as a temperature input. True airspeed is equivalent airspeed that is corrected for pressure altitude and temperature (which define density). The result is the true physical speed of the aircraft plus or minus the wind component. True Airspeed is equal to calibrated airspeed and equivalent airspeed at standard sea level conditions.

The simplest way to compute true airspeed is using a function of Mach number:

$$V_t = a_0 \cdot M\sqrt{\frac{T}{T_0}}$$

Where:

a_0 = Speed of sound at standard sea level (661.4788 knots)
M = Mach number
T = Temperature (kelvins)
T_0 = Standard sea level temperature (288.15 kelvins)

Or if Mach number is not known:

$$V_t = a_0 \cdot \sqrt{5\left[\left(\frac{q_c}{P}+1\right)^{\frac{2}{7}}-1\right] \cdot \frac{T}{T_0}}$$

Where:

a_0 = Speed of sound at standard sea level (661.4788 knots)
q_c = Impact pressure (inHg)
P = Static pressure (inHg)
T = Temperature (kelvins)
T_0 = Standard sea level temperature (288.15 kelvin)

The above equation is only for Mach numbers less than 1.0.

True airspeed differs from the equivalent airspeed because the airspeed indicator is calibrated at SL, ISA conditions, where the air density is 1.225 kg/m³, whereas the air density in flight normally differs from this value.

$$\frac{1}{2}\rho V^2 = q = \frac{1}{2}\rho_0 V_e^2$$

Thus

$$\frac{V}{V_e} = \sqrt{\frac{\rho_0}{\rho}}$$

Where

ρ is the air density at the flight condition.

The air density may be calculated from:

$$\frac{\rho}{\rho_0} = \frac{p\,T_0}{p_0\,T}$$

Where

p is the air pressure at the flight condition,

p_0 is the air pressure at sea level = 1013.2 hPa,

T is the air temperature at the flight condition,

T_0 is the air temperature at sea level, ISA = 288.15 K.

Source: *Aerodynamics of a Compressible Fluid.* Liepmann and Puckett 1947. Publishers John Wiley & Sons Inc.

Groundspeed

Groundspeed is the speed of the aircraft relative to the ground rather than through the air, which can itself be moving.

Chapter 1

Airspeed Indicator

Diagram showing the face of a true airspeed indicator typical for a faster single engine aircraft

The **airspeed indicator** or **airspeed gauge** is an instrument used in an aircraft to display the craft's airspeed, typically in knots, to the pilot.

Use

The airspeed indicator is used by the pilot during all phases of flight, from take-off, climb, cruise, descent and landing in order to maintain airspeeds specific to the aircraft type and operating conditions as specified in the Operating Manual.

During instrument flight, the airspeed indicator is used in addition to the Artificial horizon as an instrument of reference for pitch control during climbs, descents and turns.

The airspeed indicator is also used in dead reckoning, where time, speed, and bearing are used for navigation in the absence of aids such as NDBs, VORs or GPS.

A high sensitivity "540 degree" airspeed indicator used in a glider. The pointer swings past zero (top), but the colored arcs do not overlap. The needle shows an indicated airspeed of 60 knots.

On light aircraft

Airspeed indicator markings use a set of standardized colored bands and lines on the face of the instrument. The white range is the normal range of operating speeds for the aircraft with the flaps extended as for landing or takeoff. The green range is the normal range of operating speeds for the aircraft without flaps extended. The yellow range is the range in which the aircraft may be operated in smooth air, and then only with caution to avoid abrupt control movement.

A redline mark indicates V_{NE}, or *velocity (never exceed)*. This is the maximum demonstrated safe airspeed that the aircraft must not exceed under any circumstances. The red line is preceded by a yellow band which is the caution area, which runs from V_{NO} (*maximum structural cruise speed*) to V_{NE}. A green band runs from V_{S1} to V_{NO}. V_{S1} is the stall speed with flaps and landing gear retracted. A white band runs from V_{SO} to V_{FE}. V_{SO} is the stall speed with flaps extended, and V_{FE} is the highest speed at which flaps can be extended. Airspeed indicators in multi-engine aircraft show a short radial red line near to the bottom of green arc for V_{mc}, the minimum indicated airspeed at which the aircraft can be controlled with the critical engine inoperative and a blue line for V_{YSE}, the speed for best rate of climb with the critical engine inoperative.

Airspeed indicator markings for a light multiengine airplane.

On large aircraft

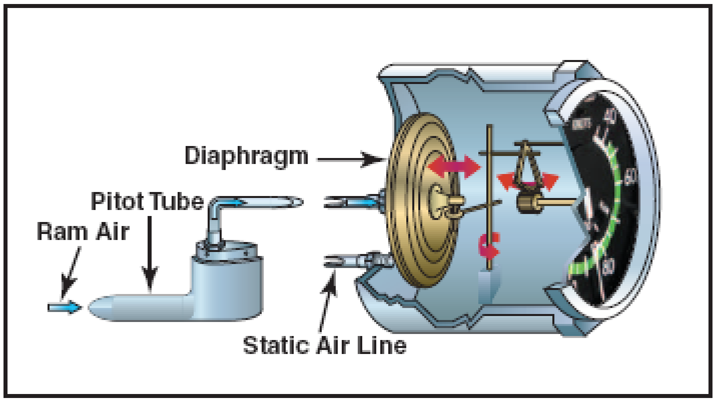
The airspeed indicator is especially important for monitoring V-Speeds while operating an aircraft. However, in large aircraft, V-speeds can vary considerably depending on airfield elevation, temperature and aircraft weight. For this reason the coloured ranges found on the ASIs of light aircraft are not used - instead the instrument has a number of moveable pointers known as *bugs* which may be preset by the pilot to indicate appropriate V-speeds for the current conditions.

Jet aircraft do not have V_{NO} and V_{NE} like piston-engined aircraft, but instead have a maximum operating IAS, V_{MO} and maximum Mach number, M_{MO}. To observe both limits, the pilot of a jet airplane needs both an airspeed indicator and a Machmeter, each with appropriate red lines. In some general aviation jet airplanes, the Machmeter is combined into a single instrument that contains a pair of concentric indicators, one for the indicated airspeed and the other for indicated Mach number.

An alternative single instrument is the "maximum allowable airspeed indicator." It has a movable pointer that indicates the never-exceed speed, which changes with altitude to avoid the onset of transonic shock waves on the wing. The pointer is usually red-and-white striped, and thus known as a "barber pole". As the aircraft climbs to high altitude, such that M_{MO} rather than V_{MO} becomes the limiting speed, the barber pole moves to lower IAS values.

Modern aircraft employing glass cockpit instrument systems employ two airspeed indicators: an electronic indicator on the primary flight data panel and a traditional mechanical instrument for use if the electronic panels fail. The airspeed is typically presented in the form of a "tape strip" that moves up and down, with the current airspeed in the middle. The same color scheme is used as on a mechanical airspeed indicator to represent the V speeds.

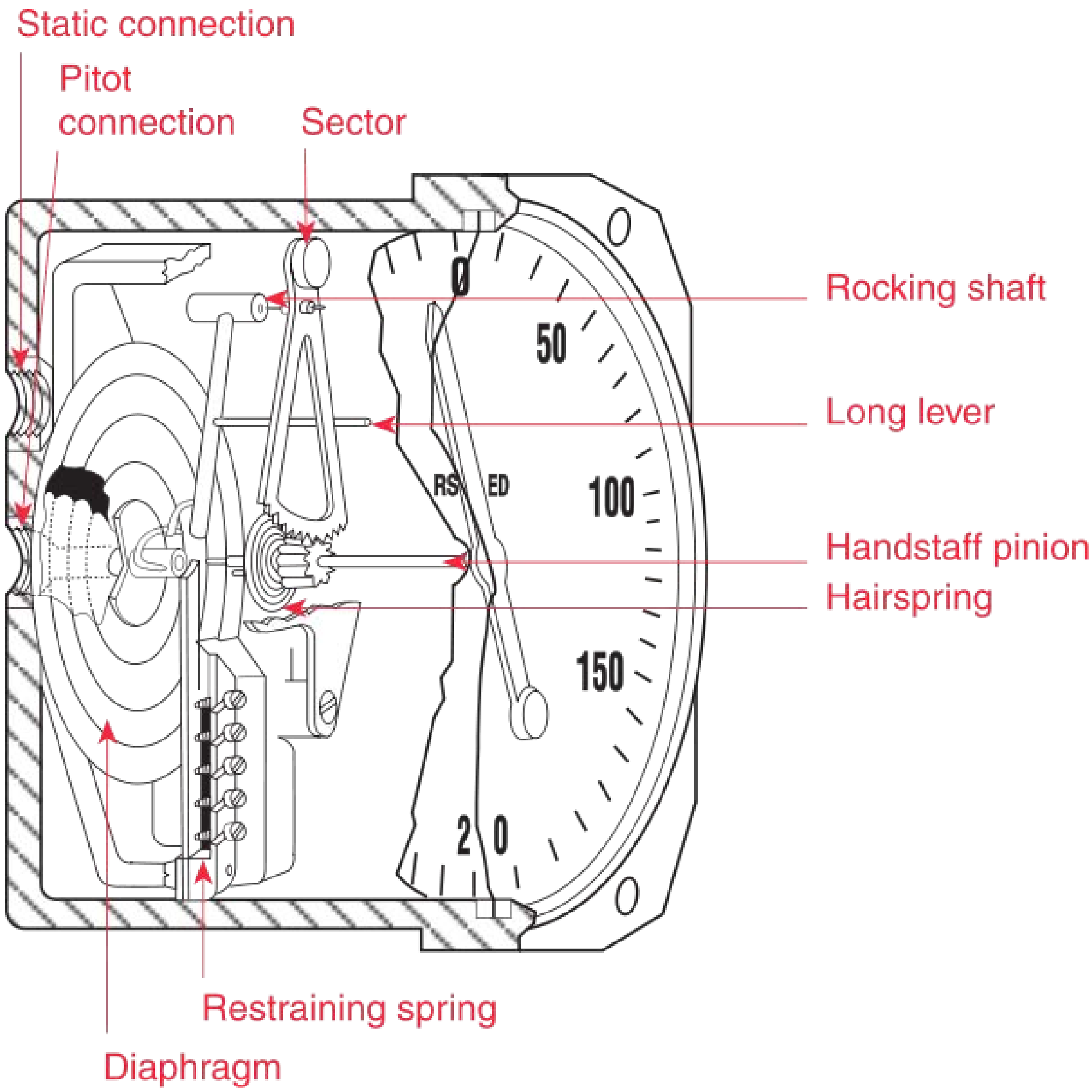
Operation



Airspeed indicator connections

Along with the altimeter and vertical speed indicator, the airspeed indicator is a member of the pitot-static system of aviation instruments, so named because they operate by measuring pressure in the pitot and static circuits.

Airspeed indicators work by measuring the difference between static pressure, captured through one or more static ports; and stagnation pressure due to "ram air", captured through a pitot tube. This difference in pressure due to ram air is called impact pressure.



Internal mechanism of an airspeed indicator

The static ports are located on the exterior of the aircraft, at a location chosen to detect the prevailing atmospheric pressure as accurately as possible, that is, with minimum disturbance from the presence of the aircraft. Some aircraft have static ports on both sides of the fuselage or empennage, in order to more accurately measure static pressure during slips and skids. Aerodynamic slips and skids cause either or both static ports and pitot tube(s) to present themselves to the relative wind in other than basic forward motion. Thus, alternative placement on some aircraft.

Icing is a problem for pitot tubes when the air temperature is below freezing and visible moisture is present in the atmosphere, as when flying through cloud or precipitation. Electrically heated pitot tubes are used to prevent ice forming over the tube.

The airspeed indicator and altimeter will be rendered inoperative by blockage in the static system. To avoid this problem, most aircraft intended for use in instrument meteorological conditions are equipped with an alternate source of static pressure. In unpressurised aircraft, the alternate static source is usually achieved by opening the static pressure system to the air in the cabin. This is less accurate, but is still workable. In pressurised aircraft, the alternate static source is a second set of static ports on the skin of the aircraft, but at a different location to the primary source.

Variations

Lift Reserve Indicator as installed

The **Lift Reserve Indicator** (LRI) has been proposed as an alternative or backup to the Airspeed Indicator (ASI) during critical stages of flight. This is an elegant device but is rarely found in light aircraft or even transport jets. The conventional Airspeed Indicator is less sensitive and less accurate as airspeed diminishes, thus providing less reliable information to the pilot as the aircraft slows towards the stall. The actual stall speed of an aircraft also varies with flight conditions, particularly changes in gross weight and wing loading during maneuvers. The ASI does not show the pilot directly how the stall is being approached during these maneuvers, whereas the LRI does.

The LRI shows the pilot directly the Potential of Wing Lift (POWL) above the stall at all times and at any airspeed, so it is more descriptive and easier for the pilot to use. The LRI uses dynamic differential pressure and **Angle of Attack** to operate. It is very fast acting and extremely accurate at slow airspeeds, thus providing more reliable information to the pilot as airspeed diminishes and becomes critical.

The LRI uses a three zone, red-white-green display. During flight, the green zone is well above the stall where flight controls are firm, angle of attack is low, and the unused POWL is high. The white zone is near the stall where flight controls soften, angle of attack is high, and the unused POWL is diminished. The top of the red zone defines the beginning of the stall. The severity of stall increases as the needle travels deeper into the red. During the takeoff, the LRI uses dynamic pressure to operate and will not lift the needle above the red zone until enough airspeed energy is available to fly.

The pilot adjusts the instrument to indicate the edge of the red-white zone during minimum airspeed practice at altitude, indicating the aircraft has zero POWL beyond that point. Since the wing will stall at the same angle of attack at any airspeed, once properly adjusted the LRI will indicate the red-white edge anytime the stall is approached. This includes landing stalls, climbing stalls, and accelerated stalls. After adjustment, the black line in the center of the white indicates maximum angle of climb and maximum angle of descent with enough reserve lift for the landing flare. With practice, the pilot can use the LRI to determine the exact moment for liftoff with minimum ground roll and maximum angle of climb combined.

The LRI has been well received by STOL pilots and pilots of experimental or home-built aircraft. The LRI is very useful for short field landings, short field takeoffs, and slow speed maneuvers such as steep turns, steep climbs, and steep descents, and also allows pilots of fast or "slippery" aircraft to land with little or no float very reliably. Since the LRI is so useful at the critical lower end of the flight envelope, most pilots will use the LRI as a complement to the ASI, using the LRI for slow speed work and the ASI for cruising and navigational work.

Types of airspeed measurements

Memory aid: "**ICE-T**" (*iced tea*), or **I**ndicated->**C**alibrated->**E**quivalent->**T**rue. This is a **P**retty **C**ool **D**rink, giving you the errors compensated for between the speeds **P**osition, **C**ompression and **D**ensity

At increased Density Altitude, for the same given indicated airspeed the aircraft's true airspeed (TAS) will be higher, but the same indicated airspeed limits (IAS) apply. Likewise, most efficient cruise speed, total drag, available lift, stall speed, and other aerodynamic information depend on calibrated, not true airspeed. Most aircraft exhibit a small difference between the airspeed actually shown on the instrument (indicated airspeed, or IAS) and the speed the instrument should theoretically show (calibrated airspeed or CAS). This difference, called position error, is mainly due to inaccurate sensing of static pressure. It is usually not possible to find a position for the static ports which, at all angles of attack, accurately senses the atmospheric pressure at the altitude at which the aircraft is flying.

Bernoulli's principle states that total pressure is constant along a streamline. Pitot pressure is equal to total pressure so pitot pressure is constant all around the aircraft and does not suffer position error. (However, pitot pressure can suffer alignment error if the pitot tube is not aligned directly into the oncoming airflow.)

The position of static ports must be selected carefully by an aircraft designer because position error must be small at all speeds within the operating range of the aircraft. A calibration chart specific to the type of aircraft is usually provided.

At high speeds and altitudes, calibrated airspeed must be further corrected for compressibility error to give equivalent airspeed (EAS). Compressibility error arises because the impact pressure will cause the air to compress in the pitot tube. The calibration equation accounts for compressibility, but only at standard sea level pressure. At other altitudes compressibility error correction may be obtained from a chart. In practice compressibility error is negligible below about 3,000 m / 10,000 feet and 100 m/s / 200 knots CAS.

The true airspeed can be calculated as a function of equivalent airspeed and local air density, (or temperature and pressure altitude which determine density). Some airspeed indicators incorporate a slide rule mechanism to perform this calculation. Otherwise, it can be performed with a calculator such as the E6B handheld circular slide rule. For a quick approximation of TAS add 2% per 300m / 1000 feet of altitude to IAS (or CAS). e.g. IAS = 52 m/s /100 Knots. At 3000 m / 10,000' Above Sea Level, TAS is 62 m/s / 120 Knots.

Chapter 2

Equivalent Airspeed & Calibrated Airspeed

Equivalent Airspeed

Equivalent airspeed (EAS) is the airspeed at sea level in the International Standard Atmosphere that would produce the same dynamic pressure as the true airspeed (TAS) at the altitude at which the aircraft is flying. In low-speed flight, it is the speed which would be shown by an airspeed indicator with zero error. It is useful for predicting aircraft handling, aerodynamic loads, stalling etc.

$$EAS = TAS \times \sqrt{\frac{\rho}{\rho_0}}$$

Where:

$\rho$is actual air density.

$\rho_0$is standard sea level density (1.225 kg/m³ -or- 0.00237 slugs/ft&sup3).

EAS is a function of dynamic pressure.

$$EAS = \sqrt{\frac{2q}{\rho_0}}$$

Where:

$q$is dynamic pressure.

(this equation requires a consistent system of measurement)

EAS can also be obtained from the aircraft mach number and static pressure.

$$EAS = a_0 M \sqrt{\frac{P}{P_0}}$$

Where:

a_0 is the standard speed of sound at 15 °C (661.47 knots)

M is Mach number

P is static pressure

P_0 is standard sea level pressure (1013.25 hPa)

Combining the above with the expression for Mach number gives EAS as a function of impact pressure and static pressure (valid for subsonic flow):

$$EAS = a_0 \sqrt{\frac{5P}{P_0}[(\frac{q_c}{P} + 1)^{\frac{2}{7}} - 1]}$$

Where:

q_c is impact pressure.

At standard sea level EAS is the same as calibrated airspeed (CAS) and true airspeed (TAS). At high altitude, EAS may be obtained from CAS by correcting for compressibility error.

A simplified formula can be used that allows calculation of CAS from EAS.

$$CAS = EAS \times [1 + \frac{1}{8}(1 - \delta)M^2 + \frac{3}{640}(1 - 10\delta + 9\delta^2)M^4]$$

where:

Pressure ratio: $\delta = \frac{P}{P_0}$

CAS & EAS the airspeeds in either knots, km/h, mph or any other appropriate unit

Above formula is accurate within 1% up to Mach 1.2 and useful with acceptable error up to Mach 1.5. The 4th order Mach term can be neglected for speeds below Mach 0.85.

Calibrated Airspeed

Calibrated airspeed (CAS) is the speed shown by a conventional airspeed indicator after correction for instrument error and position error. Most civilian EFIS displays also show CAS. At high speeds and altitudes, calibrated airspeed is further corrected for compressibility errors and becomes equivalent airspeed (EAS).

When flying at sea level under International Standard Atmosphere conditions (15°C, 1013 hPa, 0% humidity) calibrated airspeed is the same as equivalent airspeed and true airspeed (TAS). If there is no wind it is also the same as ground speed (GS). Under any other conditions, CAS may differ from the aircraft's TAS and GS.

Calibrated airspeed in knots is usually abbreviated as *KCAS*, while indicated airspeed is abbreviated as *KIAS*.

Practical applications of CAS

CAS has two primary applications in aviation:

- for navigation, CAS is traditionally calculated as one of the steps between indicated airspeed and true airspeed;
- for aircraft control, CAS (and EAS) are the primary reference points, since they describe the dynamic pressure acting on aircraft surfaces regardless of density altitude, wind, and other conditions. EAS is used as a reference by aircraft designers, but EAS cannot be displayed correctly at varying altitudes by a simple (single capsule) airspeed indicator. CAS is therefore a standard for calibrating the airspeed indicator such that CAS equals EAS at sea level pressure and approximates EAS at higher altitudes.

With the widespread use of GPS and other advanced navigation systems in cockpits, the first application is rapidly decreasing in importance – pilots are able to read groundspeed (and often true airspeed) directly, without calculating calibrated airspeed as an intermediate step. The second application remains critical, however – for example, at the same weight, an aircraft will rotate and climb at approximately the same calibrated airspeed at any elevation, even though the true airspeed and groundspeed may differ significantly. These V speeds are usually given as IAS rather than CAS, so that a pilot can read them directly from the airspeed indicator.

Calculation from impact pressure

Since the airspeed indicator capsule responds to impact pressure, CAS is defined as a function of impact pressure alone. Static pressure and temperature appear as fixed coefficients defined by convention as standard sea level values. It so happens that the speed of sound is a direct function of temperature, so instead of a standard temperature, we can define a standard speed of sound.

For subsonic speeds, CAS is calculated as:

$$CAS = a_0\sqrt{5\left[\left(\frac{q_c}{P_0}+1\right)^{\frac{2}{7}}-1\right]}$$

where:

- q_c = impact pressure
- P_0 = standard pressure at sea level
- a_0 is the standard speed of sound at 15 °C

For supersonic airspeeds, where a normal shock forms in front of the pitot probe, the Rayleigh formula applies:

$$CAS = a_0\left[\left(\frac{q_c}{P_0}+1\right)\times\left(7\left(\frac{CAS}{a_0}\right)^2-1\right)^{2.5}/\left(6^{2.5}\times 1.2^{3.5}\right)\right]^{(1/7)}$$

The supersonic formula must be solved iteratively, by assuming an initial value for *CAS* equal to a_0.

These formulae work in any units provided the appropriate values for P_0 and a_0 are selected. For example P_0 = 1013.25 hPa, a_0 = 661.48 knots. The ratio of specific heats for air is assumed to be 1.4.

These formulae can then be used to calibrate an airspeed indicator when impact pressure (q_c) is measured using a water manometer or accurate pressure gauge. If using a water manometer to measure millimeters of water the reference pressure (P_0) may be entered as 10333 mm $H_2 0$.

At higher altitudes CAS can be corrected for compressibility error to give equivalent airspeed (EAS). In practice compressibility error is negligible below about 10,000 feet and 200 knots.

Chapter 3

True Airspeed

True airspeed (**TAS**) of an aircraft is the speed of the aircraft relative to the airmass in which it is flying. True airspeed is important information for accurate navigation of an aircraft.

Performance

TAS is the true measure of aircraft performance in cruise, thus listed in aircraft specs, manuals, performance comparisons, pilot reports, and every situation when actual performance needs to be measured. It is the speed normally listed on the flight plan, also used in flight planning, before considering the effects of wind.

Airspeed sensing errors

The airspeed indicator (ASI), driven by the Pitot tube, shows what is called indicated airspeed (IAS). The ASI is calibrated so that IAS corresponds to TAS at sea level in the International Standard Atmosphere (ISA).

When the air around the aircraft differs from standard sea level conditions, IAS will no longer correspond to TAS, thus it will no longer reflect aircraft performance. The ASI will indicate less than TAS when the air density decreases due to increase in altitude or temperature.

For this reason, TAS cannot be measured directly. In flight, it can be calculated either by using an E6B flight calculator or its equivalent. The data required are static air temperature, Pressure altitude and calibrated airspeed (CAS). Modern aircraft instrumentation use an Air Data Computer to perform this calculation in real time and display the TAS reading directly on the EFIS.

Since temperature variations are of a smaller influence, the ASI error can be roughly estimated as indicating about 2% less than TAS per 1,000ft of altitude above sea level. For example, an aircraft flying at 15,000ft in the international standard atmosphere with an IAS of 100kt, is actually flying at 126kt TAS.

Use in Navigation Calculations

To maintain a desired ground track whilst flying in the moving airmass, the pilot of an aircraft must use knowledge of wind speed, wind direction, and true air speed to determine the required heading.

- Wind triangle

Calculating true airspeed

Low-speed flight

At low speeds and altitudes IAS and CAS are close to equivalent airspeed (EAS). TAS can be calculated as a function of EAS and air density:

$$TAS = EAS\sqrt{\frac{\rho_0}{\rho}}$$

where

TAS is true airspeed

EAS is equivalent airspeed

ρ_0 is the air density at standard sea level (1.225 kg/m^3)

ρ is the density of the air in which the aircraft is flying

High-speed flight

TAS can be calculated as a function of Mach number and static air temperature:

$$TAS = a_0 M\sqrt{\frac{T}{T_0}}$$

Where

a_0 is the speed of sound at standard sea level (661.47 knots)

M is Mach number,

T is static air temperature in kelvin,

T_0 is the temperature at standard sea level (288.15 K)

For manual calculation of TAS in knots where Mach number and static air temperature are known the expression may be simplified to:

$$\mathrm{TAS} = 39M\sqrt{T}$$

(remembering temperature is in kelvin)

Combining the above with the expression for Mach number gives an expression for TAS as a function of impact pressure, static pressure and static air temperature (valid for subsonic flow):

$$TAS = a_0 \sqrt{\frac{5T}{T_0} \left[\left(\frac{q_c}{P} + 1 \right)^{\frac{2}{7}} - 1 \right]}$$

Where

q_c is impact pressure

P is static pressure

Electronic Flight Instrument Systems (EFIS) contain an air data computer with inputs of impact pressure, static pressure and total air temperature. In order to compute TAS the air data computer must convert total air temperature to static air temperature. This is also a function of Mach number:

$$T = \frac{T_t}{1 + 0.2M^2}$$

Where

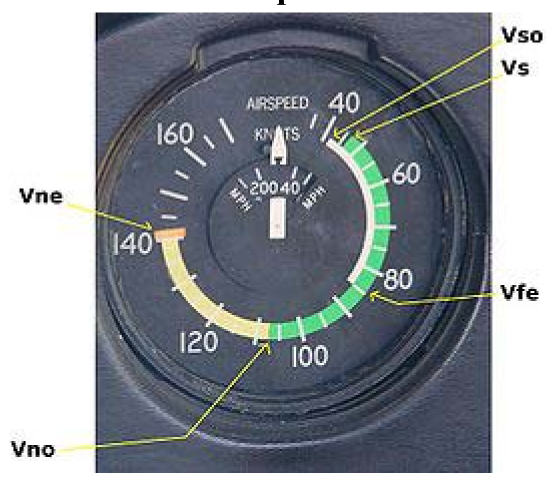
T_t = total air temperature

In simple aircraft, without an air data computer or Machmeter, true airspeed can be calculated as a function of calibrated airspeed and local air density (or static air temperature and pressure altitude which determine density). Some airspeed indicators incorporate a slide rule mechanism to perform this calculation. Otherwise, it can be performed using this applet or a device such as the E6B (a handheld circular slide rule).

Chapter 4

V Speeds

V speeds



A single-engine Cessna 150L's airspeed indicator indicating its V speeds.

In aviation, **V-speeds** are standard terms used to define airspeeds important or useful to the operation of all aircraft including fixed-wing aircraft, gliders, autogiros, helicopters, and dirigibles. These speeds are derived from data obtained by aircraft designers and manufacturers during flight testing and verified in most countries by government flight inspectors during aircraft type-certification testing. Using them is considered a best practice to maximize aviation safety, aircraft performance or both.

The actual speeds represented by these designators are specific to a particular model of aircraft, and are expressed in terms of the aircraft's indicated airspeed, so that pilots may use them directly, without having to apply correction factors.

In general aviation aircraft, the most commonly-used and most safety-critical airspeeds are displayed as color-coded arcs and lines located on the face of an aircraft's airspeed indicator. The lower ends of the green arc and the white arc are the stalling speed with wing flaps retracted, and stalling speed with wing flaps fully extended, respectively. These are the stalling speeds for the aircraft at its maximum weight.

Proper display of V speeds is an airworthiness requirement for type-certificated aircraft in most countries.

Regulation

The most common V-speeds are often defined by a particular government's aviation regulations. In the United States, these are defined in title 14 of the United States Code of Federal Regulations, known as the Federal Aviation Regulations or FARs. In Canada, the regulatory body, Transport Canada, defines 26 commonly-used V-speeds in their Aeronautical Information Manual (AIM).

Regulatory V-speeds

These V-speeds are defined by regulations.

V-speed designator	Description
V_1	Critical engine failure recognition speed.
V_2	Takeoff safety speed. The speed at which the aircraft may safely become airborne with one engine inoperative.
V_{2min}	Minimum takeoff safety speed.
V_3	Flap retraction speed.
V_4	Steady initial climb speed. The all engines operating take-off climb speed used to the point where acceleration to flap retraction speed is initiated. Should be attained by a gross height of 400 feet.
V_A	Design maneuvering speed, also known as the "Speed for maximum control deflection." This is the speed above which it is unwise to make full application of any single flight control (or "pull to the stops") as it may generate a force greater than the aircraft's structural limitations. The heavier an aircraft is loaded the faster this speed.
V_B	Design speed for maximum gust intensity.
V_C	Design cruising speed, also known as the optimum cruise speed, is the most efficient speed in terms of distance, speed and fuel usage.
V_{cef}	See V_1; generally used in documentation of military aircraft performance.
V_D	Design diving speed.
V_{DF}	Demonstrated flight diving speed.
V_{EF}	The speed at which the Critical engine is assumed to fail during takeoff.
V_F	Designed flap speed.
V_{FC}	Maximum speed for stability characteristics.
V_{FE}	Maximum flap extended speed.
V_{FTO}	Final takeoff speed.

V_H	Maximum speed in level flight at maximum continuous power.
V_{LE}	Maximum landing gear extended speed. This is the maximum speed at which it is safe to fly a retractable gear aircraft with the landing gear extended.
V_{LO}	Maximum landing gear operating speed. This is the maximum speed at which it is safe to extend or retract the landing gear on a retractable gear aircraft.
V_{LOF}	Lift-off speed.
V_{MC}	Minimum control speed with Critical engine inoperative.
V_{mca}	Minimum control speed in the take-off configuration – the minimum calibrated airspeed at which the aircraft is directionally controllable in flight with a sudden Critical engine failure and takeoff power on the operative engine(s).
V_{mcg}	Minimum control speed on the ground - the minimum airspeed at which the aircraft is directionally controllable during acceleration along the runway with one engine inoperative, takeoff power on the operative engine(s), and with nose wheel steering assumed inoperative.
V_{mcl}	Minimum control speed in the landing configuration with one engine inoperative.
V_{MO}	Maximum operating limit speed.
V_{MU}	Minimum unstick speed.
V_{NE}	Never exceed speed.
V_{NO}	Maximum structural cruising speed or maximum speed for normal operations.
V_R	Rotation speed. The speed at which the aircraft's nosewheel leaves the ground.
V_{rot}	Used instead of V_R (in discussions of the takeoff performance of military aircraft) to denote **rotation speed** in conjunction with the term V_{ref} *(refusal speed).*
V_{Ref}	Landing reference speed or threshold crossing speed. In discussions of the **takeoff** performance of military aircraft, the term V_{ref} stands for **refusal speed**. Refusal speed is the maximum speed during takeoff from which the air vehicle can stop within the available remaining runway length for a specified altitude, weight, and configuration. Incorrectly, or as an abbreviation, some documentation refers to V_{ref} and/or V_{rot} speeds as "V_r."
V_S	Stall speed or minimum steady flight speed for which the aircraft is still controllable.
V_{S0}	Stall speed or minimum flight speed in landing configuration.
V_{S1}	Stall speed or minimum steady flight speed for which the aircraft is still controllable in a specific configuration.

V_{SR}	Reference stall speed.
V_{SR0}	Reference stall speed in landing configuration.
V_{SR1}	Reference stall speed in a specific configuration.
V_{SW}	Speed at which the stall warning will occur.
V_{TOSS}	Category A rotorcraft takeoff safety speed.
V_X	Speed that will allow for best angle of climb.
V_Y	Speed that will allow for the best rate of climb.

Other V-speeds

Some of these V-speeds are specific to particular types of aircraft and are not defined by regulations.

V-speed designator	Description
V_{BE}	Best endurance speed – the speed that gives the greatest airborne time for fuel consumed. This may be used when there is reason to remain aloft for an extended period, such as waiting for a forecast improvement in weather on the ground.
V_{BG}	Best power-off glide speed – the speed that provides maximum lift-to-drag ratio and thus the greatest gliding distance available.
V_{BR}	Best range speed – the speed that gives the greatest range for fuel consumed - often identical to V_{md}.
V_{FS}	Final segment of a departure with one powerplant failed.
V_{imd}	Minimum drag
V_{imp}	Minimum power
V_{LLO}	Maximum landing light operating speed – for aircraft with retractable landing lights.
V_{mbe}	Maximum brake energy speed
V_{md}	Minimum drag (per lift) - often identical to V_{BR}. (alternatively same as V_{imd})
V_{min}	Minimum speed for instrument flight (IFR) for helicopters
V_{mp}	Minimum power
V_p	Aquaplaning speed
V_{PD}	Maximum speed at which whole-aircraft parachute deployment has been demonstrated
V_{ra}	Rough air speed (turbulence penetration speed).
V_{SL}	stall speed in a specific configuration
V_{s1g}	stall speed at maximum lift coefficient
V_{sse}	Safe single engine speed
V_t	Threshold speed

V_{tocs}	Take-off climbout speed (helicopters)
V_{tos}	Minimum speed for a positive rate of climb with one engine inoperative
V_{tmax}	Max threshold speed
V_{wo}	Maximum window or canopy open operating speed
V_{XSE}	Best angle of climb speed with a single operating engine in a light, twin-engine aircraft – the speed that provides the most altitude gain per unit of horizontal distance following an engine failure.
V_{YSE}	Best rate of climb speed with a single operating engine in a light, twin-engine aircraft – the speed that provides the most altitude gain per unit of time following an engine failure.
V_{ZRC}	Zero rate of climb speed in a twin-engine aircraft

Mach numbers

Whenever a limiting speed is expressed in terms of Mach number, it is expressed as an "M speed", e.g. V_{MO}: Maximum operating limit speed (in knots), M_{MO}: Maximum operating limit Mach.

V_1 definitions

V_1 is the critical engine failure recognition speed or takeoff decision speed. It is the decision speed nominated by the pilot which satisfies all safety rules, and above which the takeoff will continue even if an engine fails. The speed will vary between aircraft types and also due to aircraft weight, runway length, wing flap setting, engine thrust used, runway surface contamination and other factors.

V_1 is defined differently in different jurisdictions:

- The US Federal Aviation Administration defines it as: *V1 means the maximum speed in the takeoff at which the pilot must take the first action (e.g., apply brakes, reduce thrust, deploy speed brakes) to stop the airplane within the accelerate-stop distance. V1 also means the minimum speed in the takeoff, following a failure of the critical engine at VEF, at which the pilot can continue the takeoff and achieve the required height above the takeoff surface within the takeoff distance.*

- Transport Canada defines it as: *Critical engine failure recognition speed* and adds: *This definition is not restrictive. An operator may adopt any other definition outlined in the aircraft flight manual (AFM) of TC type-approved aircraft as long as such definition does not compromise operational safety of the aircraft.*

Chapter 5

Mach Number

An F/A-18 Hornet at transonic speed and displaying the Prandtl–Glauert singularity just before reaching the speed of sound

Mach number (Ma or *M*) is the speed of an object moving through air, or any other fluid substance, divided by the speed of sound as it is in that substance for its particular physical conditions, including those of temperature and pressure. It is commonly used to represent the speed of an object when it is traveling close to or above the speed of sound.

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

where

M is the Mach number
V is the relative velocity of the source to the medium and
a is the speed of sound in the medium

The Mach number is named after Austrian physicist and philosopher Ernst Mach, a designation proposed by aeronautical engineer Jakob Ackeret. Because the Mach number is often viewed as a dimensionless quantity rather than a unit of measure, with Mach, the number comes *after* the unit; the second Mach number is "Mach 2" instead of "2 Mach" (or Machs). This is somewhat reminiscent of the early modern ocean sounding unit "mark" (a synonym for fathom), which was also unit-first, and may have influenced the use of the term Mach. In the decade preceding faster-than-sound human flight, aeronautical engineers referred to the speed of sound as *Mach's number*, never "Mach 1."

In French, the Mach number is sometimes called the "nombre de Sarrau" ("Sarrau number") after Émile Sarrau, researching on explosions in the 1870s and 1880s.

Overview

The Mach number is commonly used both with objects traveling at high speed in a fluid, and with high-speed fluid flows inside channels such as nozzles, diffusers or wind tunnels. As it is defined as a ratio of two speeds, it is a dimensionless number. At Standard Sea Level conditions (corresponding to a temperature of 15 degrees Celsius), the speed of sound is 340.3 m/s (1225 km/h, or 761.2 mph, or 661.5 knots, or 1116 ft/s) in the Earth's atmosphere. The speed represented by Mach 1 is not a constant; for example, it is mostly dependent on temperature and atmospheric composition and largely independent of pressure. In the stratosphere, where the temperatures are constant, it does not vary with altitude even though the air pressure changes significantly with altitude.

Since the speed of sound increases as the temperature increases, the actual speed of an object traveling at Mach 1 will depend on the fluid temperature around it. Mach number is useful because the fluid behaves in a similar way at the same Mach number. So, an aircraft traveling at Mach 1 at 20°C or 68°F will experience shock waves in much the same manner as when it is traveling at Mach 1 at 11,000 m (36,000 ft) at -50°C or -58F, even though it is traveling at only 86% of its speed at higher temperature like 20°C or 68°F.

High-speed flow around objects

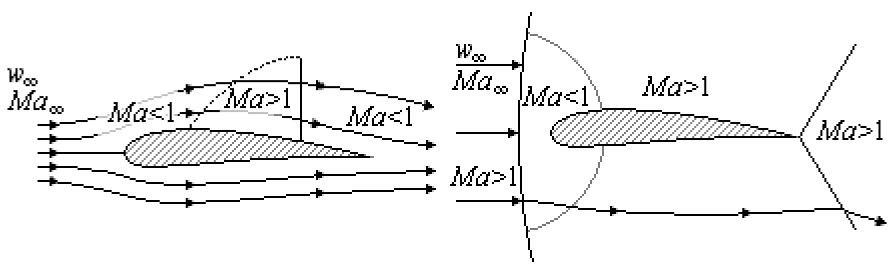
Flight can be roughly classified in six categories:

Regime	Subsonic	Transonic	Sonic	Supersonic	Hypersonic	High-hypersonic
Mach	<0.75	0.75–1.2	1.0	1.2–5.0	5.0–10.0	>10.0

For comparison: the required speed for low Earth orbit is approximately 7.5 km/s = Mach 25.4 in air at high altitudes. The speed of light in a vacuum corresponds to a Mach number of approximately 881,000 (relative to air at sea level).

At transonic speeds, the flow field around the object includes both sub- and supersonic parts. The transonic period begins when first zones of M>1 flow appear around the object. In case of an airfoil (such as an aircraft's wing), this typically happens above the wing. Supersonic flow can decelerate back to subsonic only in a normal shock; this typically happens before the trailing edge. (Fig.1a)

As the speed increases, the zone of $M>1$ flow increases towards both leading and trailing edges. As $M=1$ is reached and passed, the normal shock reaches the trailing edge and becomes a weak oblique shock: the flow decelerates over the shock, but remains supersonic. A normal shock is created ahead of the object, and the only subsonic zone in the flow field is a small area around the object's leading edge. (Fig.1b)



(a) (b)

Fig. 1. *Mach number in transonic airflow around an airfoil; M<1 (a) and M>1 (b).*

When an aircraft exceeds Mach 1 (i.e. the sound barrier) a large pressure difference is created just in front of the aircraft. This abrupt pressure difference, called a shock wave, spreads backward and outward from the aircraft in a cone shape (a so-called Mach cone). It is this shock wave that causes the sonic boom heard as a fast moving aircraft travels overhead. A person inside the aircraft will not hear this. The higher the speed, the more narrow the cone; at just over $M=1$ it is hardly a cone at all, but closer to a slightly concave plane.

At fully supersonic speed, the shock wave starts to take its cone shape and flow is either completely supersonic, or (in case of a blunt object), only a very small subsonic flow area remains between the object's nose and the shock wave it creates ahead of itself. (In the case of a sharp object, there is no air between the nose and the shock wave: the shock wave starts from the nose.)

As the Mach number increases, so does the strength of the shock wave and the Mach cone becomes increasingly narrow. As the fluid flow crosses the shock wave, its speed is reduced and temperature, pressure, and density increase. The stronger the shock, the greater the changes. At high enough Mach numbers the temperature increases so much over the shock that ionization and dissociation of gas molecules behind the shock wave begin. Such flows are called hypersonic.

It is clear that any object traveling at hypersonic speeds will likewise be exposed to the same extreme temperatures as the gas behind the nose shock wave, and hence choice of heat-resistant materials becomes important.

High-speed flow in a channel

As a flow in a channel crosses M=1 becomes supersonic, one significant change takes place. The conservation of mass flow rate leads one to expect that contracting the flow channel would increase the flow speed (i.e. making the channel narrower results in faster air flow) and at subsonic speeds this holds true. However, once the flow becomes supersonic, the relationship of flow area and speed is reversed: expanding the channel actually increases the speed.

The obvious result is that in order to accelerate a flow to supersonic, one needs a convergent-divergent nozzle, where the converging section accelerates the flow to M=1, sonic speeds, and the diverging section continues the acceleration. Such nozzles are called de Laval nozzles and in extreme cases they are able to reach incredible, hypersonic speeds (Mach 13 at 20°C).

An aircraft Machmeter or electronic flight information system (EFIS) can display Mach number derived from stagnation pressure (pitot tube) and static pressure.

Calculating Mach Number

Assuming air to be an ideal gas, the formula to compute Mach number in a subsonic compressible flow is derived from Bernoulli's equation for M<1:

$$M = \sqrt{\frac{2}{\gamma - 1}\left[\left(\frac{q_c}{p} + 1\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

where:

M is Mach number

q_c is impact pressure and
p is static pressure
γ is the ratio of specific heat of a gas at a constant pressure to heat at a constant volume (1.4 for air).

The formula to compute Mach number in a supersonic compressible flow is derived from the Rayleigh Supersonic Pitot equation:

$$\frac{q_c}{p} = \left[\left(\frac{\gamma+1}{2}\right) M^2\right]^{\left(\frac{\gamma}{\gamma-1}\right)} \cdot \left[\frac{\gamma+1}{(1-\gamma+2\gamma\cdot M^2)^{\left(\frac{1}{\gamma-1}\right)}}\right]^{\left(\frac{1}{\gamma-1}\right)} - 1$$

or for air, a simplfied formula:

$$M = 0.88128485\sqrt{\left[\left(\frac{q_c}{p}+1\right)\left(1-\frac{1}{[7M^2]}\right)^{2.5}\right]}$$

where:

q_c is now impact pressure measured behind a normal shock.

The Mach number at which an aircraft is flying at can be calculated by

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

where:

M is Mach number
V is velocity of the moving aircraft and
a is the speed of sound at the given altitude

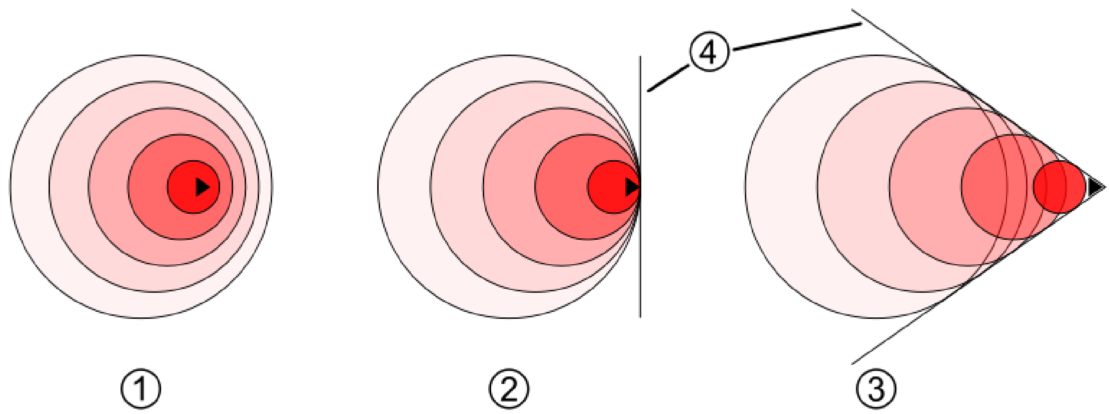
Note that the dynamic pressure can be found as:

$$q = \frac{\gamma}{2} p M^2$$

Chapter 6

Sound Barrier

U.S. Navy F/A-18 breaking the sound barrier. The white halo formed by condensed water droplets is thought to result from a drop in air pressure around the aircraft at transonic speeds.



1. Subsonic
2. Mach 1
3. Supersonic
4. Shock wave

In aerodynamics, the **sound barrier** usually refers to the point at which an aircraft moves from transonic to supersonic speed. The term came into use during World War II when a number of aircraft started to encounter the effects of compressibility, a collection of several unrelated aerodynamic effects that "struck" their planes like an impediment to further acceleration. By the 1950s, new aircraft designs started to routinely "break" the sound barrier.

History

Some common whips such as the bullwhip or sparewhip are able to move faster than sound: the tip of the whip breaks the sound barrier and causes a sharp crack—literally a sonic boom. Firearms since the 19th century have generally had a supersonic muzzle velocity.

The sound barrier may have been first breached in nature some 150 million years ago. Some paleobiologists report that, based on computer models of their biomechanical capabilities, certain long-tailed dinosaurs such as apatosaurus and diplodocus may have possessed the ability to flick their tails at supersonic velocities, possibly used to generate an intimidating booming sound. This finding is theoretical and disputed by others in the field.

Early problems

The tip of the propeller on many early aircraft may reach supersonic speeds, producing a noticeable buzz that differentiates such aircraft. This is particularly noticeable on the Stearman, and noticeable on the T-6 Texan when it enters a sharp-breaking turn. This is undesirable, as the transonic air movement creates disruptive shock waves and turbulence. It is due to these effects that propellers are known to suffer from dramatically decreased performance as they approach the speed of sound. It is easy to demonstrate that the power needed to improve performance is so great that the weight of the required engine grows faster than the power output of the propeller. This problem was one of the issues that led to early research into jet engines, notably by Frank Whittle in England and Hans von Ohain in Germany, who were led to their research specifically in order to avoid these problems in high-speed flight.

Propeller aircraft were, nevertheless, able to approach the speed of sound in a dive. This led to numerous crashes for a variety of reasons. These included the rapidly increasing forces on the various control surfaces, which led to the aircraft becoming difficult to control to the point where many suffered from powered flight into terrain when the pilot was unable to overcome the force on the control stick. The Mitsubishi Zero was infamous for this problem, and several attempts to fix it only made the problem worse. In the case of the Supermarine Spitfire, the wings suffered from low torsional stiffness, and when ailerons were moved the wing tended to flex such that they counteracted the control input, leading to a condition known as *control reversal*. This was solved in later models with changes to the wing. The P-38 Lightning suffered from a particularly dangerous interaction of the airflow between the wings and tail surfaces in the dive that made it difficult to "pull out", a problem that was later solved with the addition of a "dive flap" that upset the airflow under these circumstances. Flutter due to the formation of shock waves on curved surfaces was another major problem, which led most famously to the breakup of de Havilland Swallow and death of its pilot, Geoffrey de Havilland, Jr.

All of these effects, although unrelated in most ways, led to the concept of a "barrier" that makes it difficult for an aircraft to break the speed of sound.

Early claims

There are, however, several claims that the sound barrier was broken during World War II. Hans Guido Mutke claimed to have broken the sound barrier on 9 April 1945 in a Messerschmitt Me 262. Mutke reported not just transonic buffeting but the resumption of normal control once a certain speed was exceeded, then a resumption of severe buffeting once the Me 262 slowed again. He also reported engine flame out. However, this claim is widely disputed by various experts believing the Me 262's structure could not support high transonic, let alone supersonic flight. The lack of area ruled fuselage and 10 percent thick wings did not prevent other aircraft from exceeding Mach 1 in dives. Chuck Yeager's Bell X-1, the North American F-86 Sabre (with Me-262 profile) and the Convair Sea Dart seaplane exceeded Mach 1 without area rule fuselages. Computational tests carried out by Professor Otto Wagner of the Munich Technical University in 1999 suggest the Me 262 was capable of supersonic flight during steep dives. Recovering from the dive and the resumption of severe buffeting once subsonic flight was resumed would have been very likely to damage the craft terminally.

On page 13 of the "Me 262 A-1 Pilot's Handbook" issued by Headquarters Air Materiel Command, Wright Field, Dayton, Ohio as Report No. F-SU-1111-ND on January 10, 1946:

Speeds of 950 km/h (590 mph) are reported to have been attained in a shallow dive 20° to 30° from the horizontal. No vertical dives were made. At speeds of 950 to 1,000 km/h (590 to 620 mph) the air flow around the aircraft reaches the speed of sound, and it is reported that the control surfaces no longer affect the direction of flight. The results vary with different airplanes: some wing over and dive while others dive gradually. It is also reported that once the speed of sound is exceeded, this condition disappears and normal control is restored.

The comments about restoration of flight control and cessation of buffeting above Mach 1 are very significant in a 1946 document.

In his book *Me-163*, former Messerschmitt Me 163 "Komet" pilot Mano Ziegler claims that his friend, test pilot Heini Dittmar, broke the sound barrier when steep diving the rocket plane and that several on the ground heard the sonic booms. Heini Dittmar had been accurately and officially recorded at 1,004.5 km/h (623.8 mph) in level flight on 2 October 1941 in the prototype Me 163 V4. He reached this speed at less than full throttle, as he was concerned by the transonic buffeting. The craft's Walter RII-203 cold rocket engine produced 7.34 kN (750 kgp / 1,650 lbf) thrust. The flight was made after a drop launch from a carrier plane to conserve fuel, a record that was kept secret until the war's end. The craft's potential performance in a powered dive is unknown, but the Me 163B test version of the series rocket plane had an even more powerful engine (HWK 109-509 A-2) and a greater wing sweep than the Me 163A. Ziegler claims that on 6 July 1944, Heini Dittmar, flying a test Me 163 B V18 VA + SP, was measured traveling at a speed of 1,130 km/h.

Similar claims for the Spitfire and other propeller aircraft are more suspect. It is now known that traditional airspeed gauges using a pitot tube give inaccurately high readings in the transonic regime, apparently due to shock waves interacting with the tube or the static source. This led to problems then known as "Mach jump".

Attempts to break the sound barrier

The first powered flight faster than sound may have been the Soviet ramjet experiments of Yuri Pobedonostsev in 1933. Phosphorus-powered ramjets achieved speeds of 600–680 meters/second (Mach 2) . Another early vehicle to break the sound barrier was probably the first successful test launch of the German V-2 ballistic missile on 3 October 1942, at Peenemünde in Germany. By September 1944, the V-2s routinely achieved Mach 4 (1,200 m/s) during terminal descent.

In 1942 the United Kingdom's Ministry of Aviation began a top secret project with Miles Aircraft to develop the world's first aircraft capable of breaking the sound barrier. The project resulted in the development of the prototype Miles M.52 jet aircraft, which was designed to reach 1,000 mph (417 m/s; 1,600 km/h) at 36,000 ft (11 km) in 1 minute 30 sec.

The aircraft's design introduced many innovations which are still used on today's supersonic aircraft. The single most important development was the all-moving tailplane, giving extra control to counteract the Mach tuck which allowed control to be maintained to and beyond supersonic speeds. This was wind-tunnel tested at Mach 0.86 in 1944 in the UK. In the immediate postwar era new data from captured German records suggested that major savings in drag could be had through a variety of means such as swept wings, and Director of Scientific Research, Sir Ben Lockspeiser, decided to cancel the project in light of this new information. Later experimentation with the Miles M.52 design proved that the aircraft would indeed have broken the sound barrier, with an unpiloted 3/10 scale replica of the M.52 achieving Mach 1.5 in October 1948. By that time, the sound barrier had been broken by the Americans, and also by the British De Havilland DH 108.

Sound barrier officially broken

U.S. efforts progressed apace soon after Britain had disclosed all its research and designs to the U.S. government on the promise that U.S. information would be shared the other way - a promise that the Americans did not keep. They took the technological information provided by the British and began work on the Bell XS-1. The final version of the Bell XS-1 has many design similarities to the original Miles M.52 version. Also featuring the all-moving tail, the XS-1 was later known as the X-1. It was in the X-1 that Chuck Yeager was credited with being the first man to break the sound barrier in level flight on 14 October 1947, flying at an altitude of 45,000 ft (13.7 km). George Welch made a plausible but officially unverified claim to have broken the sound barrier on 1 October 1947, while flying an XP-86 Sabre. He also claimed to have repeated his supersonic flight on 14 October 1947, 30 minutes before Yeager broke the sound barrier in the Bell X-1. Although evidence from witnesses and instruments strongly imply that Welch achieved supersonic speed, the flights were not properly monitored and are not officially recognized. The XP-86 officially achieved supersonic speed on 26 April 1948.

On 14 October 1947, just under a month after the United States Air Force had been created as a separate service, the tests culminated in the first manned supersonic flight, piloted by Air Force Captain Charles "Chuck" Yeager in aircraft #46-062, which he had christened *Glamorous Glennis*. The rocket-powered aircraft was launched from the bomb bay of a specially modified B-29 and glided to a landing on a runway. XS-1 flight number 50 is the first one where the X-1 recorded supersonic flight, at Mach 1.06 (361 m/s, 1,299 km/h, 807.2 mph) peak speed; however, Yeager and many other personnel believe Flight #49 (also with Yeager piloting), which reached a top recorded speed of Mach 0.997 (339 m/s, 1,221 km/h), may have, in fact, exceeded Mach 1. (The measurements were not accurate to three significant figures and no sonic boom was recorded for that flight.)

As a result of the X-1's initial supersonic flight, the National Aeronautics Association voted its 1948 Collier Trophy to be shared by the three main participants in the program.

Honored at the White House by President Harry S. Truman were Larry Bell for Bell Aircraft, Captain Yeager for piloting the flights, and John Stack for the NACA contributions.

Jackie Cochran was the first woman to break the sound barrier on May 18, 1953, in a Canadair Sabre, with Yeager as her wingman.

The sound barrier fades

Chuck Yeager broke the sound barrier on October 14, 1947 in the Bell X-1, as shown in this newsreel.

As the science of high-speed flight became more widely understood, a number of changes led to the eventual disappearance of the "sound barrier". Among these were the introduction of swept wings, the area rule, and engines of ever-increasing performance. By the 1950s many combat aircraft could routinely break the sound barrier in level flight, although they often suffered from control problems when doing so, such as Mach tuck. Modern aircraft can transit the "barrier" without it even being noticeable.

By the late 1950s the issue was so well understood that many companies started investing in the development of supersonic airliners, or SSTs, believing that to be the next "natural" step in airliner evolution. History has proven this not to be the case, at least yet, but Concorde and the Tupolev Tu-144 both entered service in the 1970s regardless.

Although Concorde and the Tu-144 were the first aircraft to carry commercial passengers at supersonic speeds, they were not the first or only commercial airliners to break the sound barrier. On 21 August 1961, a Douglas DC-8 broke the sound barrier at Mach 1.012 or 1,240 km/h (776.2 mph) while in a controlled dive through 41,088 feet (12,510 m). The purpose of the flight was to collect data on a new leading-edge design for the wing. A China Airlines 747 may have broken the sound barrier in an unplanned descent from 41,000 ft (12,500 m) to 9,500 ft (2,900 m) after an in-flight upset on 19 February 1985. It also reached over 5g.

Breaking the sound barrier on land

On 15 October 1997, in a vehicle designed and built by a team led by Richard Noble, British driver (and Royal Air Force pilot) Andy Green became the first person to break the sound barrier in a land vehicle in compliance with Fédération Internationale de l'Automobile rules. The vehicle, called the ThrustSSC ("Super Sonic Car"), captured the record exactly 50 years and one day after Yeager's flight.

Chapter 7

Indicated Airspeed & Position Error

Indicated Airspeed

Indicated airspeed (IAS) is the airspeed read directly from the airspeed indicator on an aircraft, driven by the pitot-static system. IAS is directly related to calibrated airspeed (CAS), which is the IAS corrected for instrument and installation errors.

An aircraft's indicated airspeed in knots is typically abbreviated *KIAS* for "Knots-Indicated Air Speed" (vs. *KCAS* for calibrated airspeed and *KTAS* for true airspeed).

The IAS is an important value for the pilot because it directly indicates stall speed and various airframe structurally limited speeds, regardless of density altitude. Furthermore the IAS is specified in regard to airspeed restrictions below certain altitudes since it is the primary speed indicator in an aircraft when operated below transonic or supersonic speeds.

IAS and V speeds

Unless an aircraft is at sea level under International Standard Atmosphere conditions (15°C, 1013 hPa, 0% humidity) and no wind, the IAS bears little relation to how fast an aircraft is moving in reference to the ground; however, because the air density affects IAS/CAS and an aircraft's flight characteristics in exactly the same way, IAS and CAS are extremely useful for controlling an aircraft, and the critical V speeds are usually given as IAS.

In aneroid instruments the indicated airspeed drops-off with increasing altitude as air density decreases. This leads to an apparent falling-off of airspeed at higher altitudes. For this and other reasons never exceed speeds (abbreviated V_{NE}) are often given at several differing altitudes in some aircraft's operating manuals, the V_{NE} IAS figure falling as height is increased, as shown in the sample table below.

Diving below	mph IAS
30,000 ft	370
25,000 ft	410
20,000 ft	450
15,000 ft	490
10,000 ft	540

Ref: *Pilot's Notes for Tempest V Sabre IIA Engine* - Air Ministry A.P.2458C-PN

IAS and navigation

For navigation, it is necessary to convert IAS to TAS and/or ground speed (GS) using the following method:

- correct IAS to calibrated airspeed (CAS) using an aircraft-specific correction table;
- correct CAS to true airspeed (TAS) by using Outside Air Temperature (OAT), Pressure-altitude and CAS on an E6B flight computer or equivalent functionality on most GPSs;
- convert TAS to ground speed (GS) by allowing for the effect of wind.

With the advent of Doppler radar navigation and, more recently, GPS receivers, with other advanced navigation equipment that allows pilots to read ground speed directly, the TAS calculation in-flight is becoming unnecessary for the purposes of navigation estimations.

TAS is the primary method to determine aircraft's cruise performance in manufacturer's specs, speed comparisons and pilot reports.

Other Airspeeds

From IAS, the following speeds can also be calculated:

- convert CAS to equivalent airspeed (EAS) by allowing for compressibility effects (not necessary at slow speed or low altitude); EAS is used by aircraft engineers and some very high-altitude flying aircraft such as the U-2 and the SR-71;
- convert EAS to true airspeed (TAS) by allowing for differences in density altitude.

Position Error

Position error is one of the errors affecting the systems in an aircraft for measuring airspeed and altitude. It is not practical or necessary for an aircraft to have an airspeed indicating system and an altitude indicating system that are exactly accurate. A small amount of error is tolerable.

Static system

All aircraft are equipped with a small hole in the surface of the aircraft called the static port. The air pressure in the vicinity of the static port is conveyed by a conduit to the altimeter and the airspeed indicator. This static port and the conduit constitute the aircraft's static system. The objective of the static system is to sense the pressure of the air at the altitude at which the aircraft is flying. In an ideal static system the air pressure fed to the altimeter and airspeed indicator is equal to the pressure of the air at the altitude at which the aircraft is flying.

As the air flows past an aircraft in flight, the streamlines are affected by the presence of the aircraft and the speed of the air relative to the aircraft is different at different positions on the aircraft's outer surface. In consequence of Bernoulli's principle, the different speeds of the air result in different pressures at different positions on the aircraft's surface. The ideal position for a static port is a position where the local air pressure in flight is always equal to the pressure remote from the aircraft, however there is no position on an aircraft where this ideal situation exists for all angles of attack. When deciding on a position for a static port aircraft designers attempt to find a position where the error between static pressure and free-stream pressure is a minimum across the operating range of angle of attack of the aircraft. The residual error at any given angle of attack is called the **position error**.

PART III—OPERATING DATA

(iii) *Maximum weights:*

Take off and straight flying ..	65,000 lb., provided that the following mods. are incorporated: Mod. 505 or 518 ,, 588 or 598 ,, 811 or SI/RDA.660 ,, 1004 63,000 lb., if these mods. are not incorporated.
Landing and all forms of flying ..	55,000 lb.

Flying should be restricted to straight and level until weight is reduced to 63,000 lb.

(iv) *Bomb clearance angles:*

Dive	30°
Climb	20°
Bank	10° (with S.B.C. 25°)

47. **Position error corrections**

All handling speeds are quoted for aircraft with the pilot's A.S.I. connected to the static vent, in the port side of the fuselage. The position error for the static vent connection is −1 m.p.h. at all speeds from 140 m.p.h. I.A.S. upward.

The position error correction for aircraft on which the static vent connection has not been made is as follows:—

From To	120 140	140 160	160 180	180 200	200 250	} m.p.h. I.A.S.
Add	12	10	8	6	4	m.p.h.

With bomb doors open, the correction is 2 m.p.h. higher between 160 and 200 m.p.h. I.A.S.

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The **position error** correction table from a WWII aircraft's *Pilot's Notes*

Position error affects the indicated airspeed and the indicated altitude. Aircraft manufacturers use the aircraft flight manual to publish details of the error in indicated airspeed and indicated altitude across the operating range of speeds. In many aircraft, the effect of position error on airspeed is shown as the difference between indicated airspeed and calibrated airspeed. In some low-speed aircraft, the position error is shown as the difference between indicated airspeed and equivalent airspeed.

Pitot system

Bernoulli's principle states that total pressure (or stagnation pressure) is constant along a streamline. There is no variation in stagnation pressure, regardless of the position on the streamline where it is measured. There is no position error associated with stagnation pressure.

The Pitot tube supplies pressure to the airspeed indicator. Pitot pressure is equal to stagnation pressure providing the Pitot tube is aligned with the local airflow, it is located outside the boundary layer, and outside the wash from the propeller. Pitot pressure can suffer alignment error but it is not vulnerable to position error.

Aircraft design standards

Aircraft design standards specify a maximum amount of Pitot-static system error. The error in indicated altitude must not be excessive because it is important for pilots to know their altitude with reasonable accuracy for the purpose of traffic separation. US Federal Aviation Regulations, Part 23, §23.1325(e) includes the following requirement for the static pressure system:

- The system error, in indicated pressure altitude, ..., may not exceed ±30 feet per 100 knot speed for the [operating speed range for the aircraft].

The error in indicated airspeed must also not be excessive. Part 23, §23.1323(b) includes the following requirement for the airspeed indicating system:

- The system error, including position error, ..., may not exceed three percent of the calibrated airspeed or five knots, whichever is greater, throughout the [operating speed range for the aircraft].

Measuring position error

For the purpose of complying with an aircraft design standard that specifies a maximum permissible error in the airspeed indicating system it is necessary to measure the position error in a representative aircraft. There are many different methods for measuring position error. Some of the more common methods are:

- use of a GNSS receiver while flying a triangular course
- trailing conduit with static source, stabilized by a plastic cone
- tower fly-by with photographs of the passing aircraft taken from the tower to accurately show the height of the aircraft above or below the tower
- trailing bomb with both Pitot and static sources

Chapter 8

Supersonic Airfoils & Wind Speed

Supersonic Airfoils

A United States Navy F/A-18E/F Super Hornet in transonic flight

A supersonic airfoil is a cross-section geometry designed to generate lift efficiently at supersonic speeds. The need for such a design arises when an aircraft is required to operate consistently in the supersonic flight regime.

Supersonic airfoils generally have a thin section formed of either angled planes or opposed arcs (called "double wedge airfoils" and "biconvex airfoils" respectively), with very sharp leading and trailing edges. The sharp edges prevent the formation of a detached bow shock in front of the airfoil as it moves through the air.. This shape is in contrast to subsonic airfoils, which often have rounded leading edges to reduce flow separation over a wide range of angle of attack. A rounded edge would behave as a blunt body in supersonic flight and thus would form a bow shock, which greatly increases wave drag. The airfoils' thickness, camber, and angle of attack are varied to achieve a design that will cause a slight deviation in the direction of the surrounding airflow.

However, since a round leading edge decreases an airfoil's susceptibility to flow separation, a sharp leading edge implies that the airfoil will be more sensitive to changes in angle of attack. Therefore, to increase lift at lower speeds, aircraft that employ supersonic airfoils also use high-lift devices such as leading edge and trailing edge flaps.

Lift and Drag

At supersonic conditions, aircraft drag is originated due to:

- Skin-friction drag.
- The wave drag due to thickness (or volume) or zero-lift wave drag.
- Drag due to lift

Therefore the Drag coefficient on a supersonic airfoil is described by the following expression:

$\mathbf{C}_D = \mathbf{C}_{D,friction} + \mathbf{C}_{D,thickness} + \mathbf{C}_{D,lift}$

Experimental data allow us to reduce this expression to:

$\mathbf{C}_D = \mathbf{C}_{D,O} + \mathbf{KC}_L^2$ Where $\mathbf{C}_{DO}$ is the sum of $\mathbf{C}_{(D,friction)}$ and $\mathbf{C}_{D,thickness}$, and **k** for supersonic flow is a function of the Mach number. Whereas the skin-friction component is derived from the presence of a viscous boundary layer which is infinitely close to the surface of the aircraft body. At the boundary wall, the normal component of velocity is zero; therefore an infinitesimal area exists where there is no slip. The zero-lift wave drag component can be obtained based on the supersonic area rule which tells us that the wave-drag of an aircraft in a steady supersonic flow is identical to the average of a series of equivalent bodies of revolution. The bodies of revolution are defined by the cuts through the aircraft made by the tangent to the fore Mach cone from a distant point of the aircraft at an azimuthal angle. This average is over all azimuthal angles.. The drag due-to lift component is calculated using lift-analysis programs. The wing design and the lift-analysis programs are separate lifting-surfaces methods that solve the direct or inverse problem of design and lift analysis.

Supersonic Wings Design

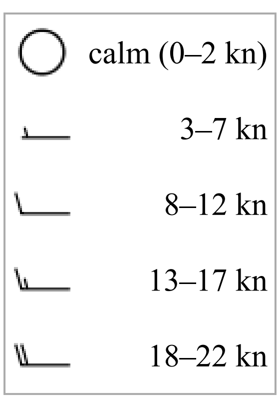
Supersonic flow resembles bizarre conditions to engineers, physicists and designers, years of research and experience lead to some interesting conclusions about wings in a supersonic flow.Considering a rectangular wing, the pressure at a point P with coordinates (x,y) on the wing is only being defined by pressure disturbances originated at points within the upstream Mach cone emanating from point P. As result, the wing tips modify the flow. The remaining area of the wing does not suffer any modification by the tips and can be analyzed with two-dimensional theory. For an arbitrary planform the supersonic leading and trailing are those portions of the wing edge where the components of the freestream velocity normal to the edge are supersonic. Similarly the subsonic leading and trailing are those portions of the wing edge where the components of the free stream velocity normal to the edge are subsonic.

Delta wings have supersonic leading and trailing edges; in contrast arrow wings have a subsonic leading edge and a supersonic trailing edge.

Summary

Aerodynamic efficiency for supersonic aircraft increases with thin section airfoils with sharp leading and trailing edges. Swept wings where the leading edge is subsonic have the advantage of reducing the wave drag component at supersonic flight speeds; however experiments show that the theoretical benefits are not always attained due to separation of the flow over the surface of the wing; however this can be corrected with design factors. Double-Wedge and Bi-convex airfoils are the most common designs used in supersonic flights. Wave drag is the simplest and most important component of the drag in supersonic flow flight regions. For the optimized aircraft nearly 60% of its drag is skin friction drag, little over 20% is induced drag, and slightly under 20% is wave drag, hence less than 30% of the drag is due to lift.

Wind Speed



23–27 kn
28–32 kn
33–37 kn
38–42 kn
43–47 kn
48–52 kn
53–57 kn
58–62 kn
63–67 kn
98–102 kn
103–107 kn

Wind speed (or magnitude) of the vector of motion. wind speed, or **wind velocity** (when directionality is considered), is a fundamental abiotic factor that affects the growth and metabolism of many plant species.

Wind speed has always meant the movement of air in an outside environment, but the speed of air movement inside is important in many areas, including weather forecasting, aircraft and maritime operations, building and civil engineering. High wind speeds can cause unpleasant side effects, and strong winds often have special names, including gales, hurricanes, and typhoons.

Wind speed is measured with an anemometer.

Factors affecting wind speed

Wind speed is affected by a number of factors and situations, operating on varying scales (from micro to macro scales). These include the pressure gradient, Rossby waves and jet streams, and local weather conditions. There are also links to be found between wind speed and wind direction, notably with the pressure gradient and surfaces over which the air is found.

Pressure gradient is a term to describe the difference in air pressure between two points in the atmosphere or on the surface of the Earth. It is vital to wind speed, because the greater the difference in pressure, the faster the wind flows (from the high to low pressure) to balance out the variation. The pressure gradient, when combined with the Coriolis Effect and friction, also influences wind direction.

Rossby waves are strong winds in the upper troposphere. These operate on a global scale and move from West to East (hence being known as Westerlies). The Rossby waves are themselves a different wind speed from what we experience in the lower troposphere.

Local weather conditions play a key role in influencing wind speed, as the formation of hurricanes, monsoons and cyclones as freak weather conditions can drastically affect the velocity of the wind.

Highest speed

During the passage of Tropical Cyclone Olivia on 10 April 1996, an automatic weather station on Barrow Island, Australia, registered a maximum wind gust of 408 km/h (220 kn; 253 mph). The wind gust was evaluated by the WMO Evaluation Panel who found that the anemometer was mechanically sound and the gust was within statistical probability and ratified the measurement in 2010. The anemometer was mounted 10 m above ground level and so 64 m above sea level. During the cyclone, several extreme gusts of greater than 300 km/h (160 kt) were recorded, with a maximum 5-minute mean speed of 176 km/h (95 kt), the extreme gust factor was in the order of 2.27–2.75 times the mean wind speed. The pattern and scales of the gusts suggests that a mesovortex was embedded in the already strong eyewall of the cyclone.

The second-highest surface wind speed ever officially recorded is 372 km/h (231 mph) at the Mount Washington (New Hampshire) Observatory in the US on 12 April 1934, using a heated anemometer. The anemometer, specifically designed for use on Mount Washington, was later tested by the US National Weather Bureau and confirmed to be accurate. The highest surface wind speed ever officially recorded in Asia was recorded in Afghanistan on 14 August 2008: 328 km/h (204 mph) in Ab-Paran, Ghowr.

Wind speeds within certain atmospheric phenomena (such as tornadoes) may greatly exceed these values but have never been accurately measured. The figure of 509 km/h (316 mph) during the F5 tornado in Moore, Oklahoma is often quoted as the highest surface wind speed but was measured 30 m (90 feet) above ground.

In 1991, a chase team from the University of Oklahoma chased a tornado in Red Rock, Oklahoma and used a portable Doppler weather radar to measure a wind speed of 460 km/h (286 mph).

According to Alan F. Arbogast ("Discovering Physical Geography") wind direction and speed are affected by three main factors:

1. Pressure gradient - the difference in barometric pressure between adjacent zones of high and low pressure.

2. Frictional forces - features on the Earth's surface which oppose the wind; e.g.: mountains, trees, buildings, etc.
3. Coriolis effect - the Earth's rotation causes winds to be deflected to the right in the Northern Hemisphere, and in the Southern Hemisphere to the left.

All three of these combined result in the spiral motion of air in both high and low pressure systems.

Design of structures

Wind speed is a common factor in the design of structures and buildings around the world. The wind speed is often the governing factor in the "lateral" design of a structure and is used by professional engineers and designers. In the United States, the wind speed used in design is often referred to as a "3-second gust" which is the highest sustained gust over a 3 second period having a probability of being exceeded per year of 1 in 50 (ASCE 7-latest edition). Windspeedbyzip maps out the design wind speed as suggested by ASCE 7-05 for the United States. This design wind speed is accepted by most building codes in the United States and often times governs the lateral design of buildings and structures. In Canada, reference wind pressures are used in design and are based on the "mean hourly" wind speed having a probability of being exceeded per year of 1 in 50. The reference wind pressure (q) is calculated in Pascals using the following equation (ref: NBC 2005 Structural Commentaries - Part 4 of Div. B, Comm. I): q=(1/2)pV**2 where p is the air density in kg/m**3 and V is wind speed in m/s. Historically, wind speeds have been reported with a variety of averaging times (fastest mile, 3-second gust, 1-minute and mean hourly for example) which designers may have to take into account. To convert wind speeds from one averaging time to another, the Durst Curve (Ref: ASCE 7-05 commentary Figure C6-2) was developed which defines the relation between probable maximum wind speed averaged over t seconds, V(t), and mean wind speed over one hour V(3600).