Sonic boom

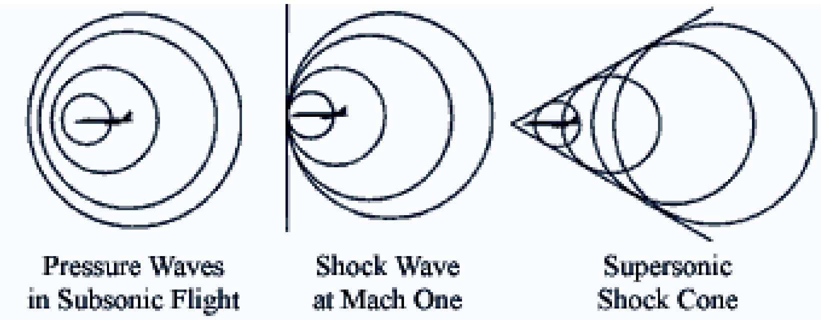
F/A-18C passing the sound barrier.

A **sonic boom** is the audible component of a shock wave in air. The term is commonly used to refer to the air shocks caused by the supersonic flight of military aircraft or passenger transports such as Concorde (Mach 2.03, no longer flying) and the Space Shuttle (Mach 27, has only flown once since the 2003 crash). Sonic booms generate enormous amounts of sound energy, sounding much like an explosion; typically the shock front may approach 167 megawatts per square meter, and may exceed 200 decibels.

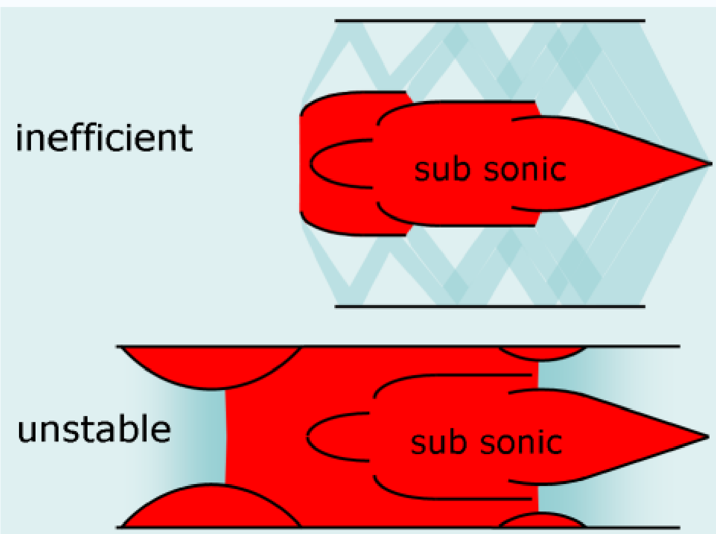
When an aircraft is near the sound barrier, an unusual cloud sometimes forms in its wake. A Prandtl-Glauert Singularity results from a drop in pressure, because of shock wave formation. This pressure change causes a sharp drop in temperature, which in humid conditions leads the water vapor in the air to condense into droplets and form the cloud.

Cause

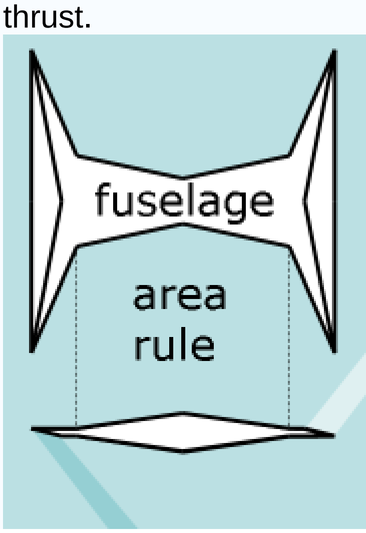
As an object moves through the air it creates a series of pressure waves in front of it and behind it, similar to the bow and stern waves created by a boat. These waves travel at the speed of sound, and as the speed of the aircraft increases the waves are forced together or 'compressed' because they cannot "get out of the way" of each other, eventually merging into a single shock wave at the speed of sound. This critical speed is known as Mach 1 and is approximately 1,225 kilometers per hour (761 mph) at sea level.



In smooth flight, the shock wave starts at the nose of the aircraft and ends at the tail. There is a sudden rise in pressure at the nose, decreasing steadily to a negative pressure at the tail, where it suddenly returns to normal. This "overpressure profile" is known as the N-wave because of its shape. The "boom" is experienced when there is a sudden rise in pressure, so the N-wave causes two booms, one when the initial pressure rise from the nose hits, and another when the tail passes and the pressure suddenly returns to normal. This leads to a distinctive "double boom" from supersonic aircraft. When maneuvering the pressure distribution changes into different forms, with a characteristic U-wave shape. Since the boom is being generated continually as long as the aircraft is supersonic, it traces out a path on the ground following the aircraft's flight path, known as the **boom carpet**.



A nacelle around the engine reflects any shock waves. A spike behind the engine converts them into thrust.



To generate lift a supersonic airplane has to produce at least two shock waves: One over-pressure downwards wave, and one under-pressure upwards wave. Whitcomb area rule states air displacement can be reused without generating additional shock waves. In this case the fuselage reuses some displacement of the wings.

A sonic boom or "tunnel boom" can also be caused by high-speed trains in tunnels (such as the Japanese Shinkansen). In order to reduce the sonic boom effect, a special shape of the traincar and a widened opening of the tunnel entrance is necessary. When a high speed train enters a tunnel, the sonic boom effect occurs at the tunnel exit. In contrast to the (super)sonic boom of an aircraft, this "tunnel boom" is caused by a rapid change of subsonic flow (from the sudden narrowing of the surrounding space) rather than by a shock wave. Close to the tunnel exit this phenomenon can cause disturbances to residents.

Characteristics

The power, or volume, of the shock wave is dependent on the quantity of air that is being accelerated, and thus the size and weight of the aircraft. As the aircraft increases speed the shocks grow "tighter" around the craft and do not become much "louder". At very high speeds and altitudes the cone does not intersect the ground and no boom is heard. The "length" of the boom from front to back is dependent on the length of the aircraft to a factor of 3:2. Longer aircraft therefore "spread out" their booms more than smaller ones, which leads to a less powerful boom.

The nose shockwave compresses and pulls the air along with the aircraft so that the aircraft behind its shockwave is in subsonic airflow.

However, this means that several smaller shock waves can, and usually do, form at other points on the aircraft, primarily any convex points or curves, the leading wing edge and especially the inlet to engines. These secondary shockwaves are caused by the subsonic air behind the main shockwave being forced to go supersonic again by the shape of the aircraft (for example, the air's acceleration over the top of a curved wing).

The later shock waves are somehow faster than the first one, travel faster and add to the main shockwave at some distance away from the aircraft to create a much more defined N-wave shape. This maximizes both the magnitude and the "rise time" of the shock which makes the boom seem louder. On most designs the characteristic distance is about 40,000 feet (12,000 m), meaning that below this altitude the sonic boom will be "softer". However, the drag at this altitude or below makes supersonic travel particularly inefficient, which poses a serious problem.

Abatement

In the late 1950s when supersonic transport (SST) designs were being actively pursued, it was thought that although the boom would be very large, the problems could be avoided by flying higher. This premise was proven false when the North American B-70 *Valkyrie* started flying, and it was found that the boom was a problem even at 70,000 feet (21,000m). It was during these tests that the N-wave was first characterized.

Richard Seebass and his colleague Albert George at Cornell University studied the problem extensively and eventually defined a "figure of merit" (FM) to characterize the sonic boom levels of different aircraft. FM is proportional to the aircraft weight divided by three-halves of the aircraft length, FM = W/(3/2·L) = 2W/3L. The lower this value, the less boom the aircraft generates, with figures of about 1 or lower being considered acceptable. Using this calculation, they found FM's of about 1.4 for

Concorde and 1.9 for the Boeing 2707. This eventually doomed most SST projects as public resentment mixed with politics eventually resulted in laws that made any such aircraft impractical (flying only over water for instance).

Seebass-George also worked on the problem from another angle, examining ways to reduce the "peaks" of the N-wave and therefore smooth out the shock into something less annoying. Their theory suggested that body shaping might be able to use the secondary shocks to either "spread out" the N-wave, or interfere with each other to the same end. Ideally this would raise the characteristic altitude from 40,000 feet to 60,000 feet (from 12,000 m to 18,000 m), which is where most SST aircraft fly. The design required some fairly sophisticated shaping in order to achieve the dual needs of reducing the shock and still leaving an aerodynamically efficient shape, and therefore had to wait for the advent of computer-aided design before being able to be built.

This remained untested for decades, until DARPA started the **Quiet Supersonic Platform** project and funded the **Shaped Sonic Boom Demonstration** (SSBD) aircraft to test it. SSBD used an F-5 Freedom Fighter modified with a new body shape and was tested over a two year period in what has become the most extensive study on the sonic boom to date. After measuring the 1,300 recordings, some taken inside the shock wave by a chase plane, the SSBD demonstrated a reduction in boom by about one-third. Although one-third is not a huge reduction, it could have reduced Concorde below the FM = 1 limit for instance.

There are theoretical designs that do not appear to create sonic booms at all, such as the Busemann's Biplane. Nobody has been able to suggest a practical implementation of this concept, as yet.

Perception and noise

The sound of a sonic boom depends largely on the distance between the observer and the aircraft producing the sonic boom. A sonic boom is usually heard as a deep double "boom" as the aircraft is usually some distance away. However, as those who have witnessed landings of space shuttles have heard, when the aircraft is nearby the sonic boom is a sharper "bang" or "crack". The sound is much like the "aerial bombs" used at firework displays.

In 1964, NASA and the Federal Aviation Administration began the Oklahoma City sonic boom tests, which caused eight sonic booms per day over a period of six months. Valuable data was gathered from the experiment, but 15,000 complaints were generated and ultimately entangled the government in a class action lawsuit, which it lost on appeal in 1969.

In late October 2005, Israel used F-16 jet planes to create sonic booms over the Gaza Strip [1] as a method of psychological warfare. The practice was condemned by the United Nations. A senior Israeli army intelligence source said the tactic was intended to break civilian support for armed Palestinian groups, especially those firing Qassam rockets into Israeli population centers. [2]

Media

These videos include jets achieving supersonic speeds.

- First supersonic flight (file info)
  - Chuck Yeager broke the sound barrier on October 14, 1947 in the Bell X-1.
- F-14 Tomcat sonic boom flyby (with audio) (file info)
  - F-14 Tomcat flies at Mach 1 over the water, creating a sonic boom as it passes.

- F-14A Tomcat supersonic flyby (file info)
  - Supersonic F-14A Tomcat flying by the USS Theodore Roosevelt CVN-71 in 1986 for the tiger cruise.
- Shuttle passes sound barrier (file info)
  - Space shuttle Columbia crosses the sound barrier at 45 seconds after liftoff.
- *Problems seeing the videos? See media help.*

See also

- Bullwhip
- Mach number
- Sound barrier

Sound barrier

U.S. Navy F/A-18 at transonic speed. The cloud is due to the Prandtl-Glauert singularity.

In aerodynamics, the **sound barrier** is the apparent physical boundary stopping large objects from becoming supersonic. The term came into use during World War II when a number of aircraft started to encounter the effects of compressibility, a grab-bag of unrelated aerodynamic effects, and fell out of use in the 1950s when aircraft started to routinely "break" the sound barrier.

[edit]

First person to break the sound barrier

Hans Guido Mutke claimed to have broken the sound barrier on April 9, 1945 in a Messerschmitt Me 262. However, this claim is disputed by most experts and lacks a scientific foundation.

George Welch apparently broke the sound barrier on October 1, 1947 while diving the subsonic XP-86 Sabre. 13 days later and 30 minutes before Yeager's historic flight, Welch apparently repeated his supersonic flight. Although evidence from witnesses and instruments strongly imply that Welch achieved supersonic speed, the flights were not properly monitored and cannot be officially recognized. (The XP-86 officially achieved supersonic speed on April 26, 1948.)

Chuck Yeager (then a Captain in the US Air Force, later a Brigadier General who was promoted in 2005 to Major General, 30 years after his official retirement) was the first person to break the sound barrier in level flight on October 14, 1947, flying the experimental Bell X-1 rocket plane to Mach 1 at an altitude of 45,000 feet. Yeager's flight was part of a test program with the goal of achieving supersonic flight so proper monitoring was in-place for the flight.

Chuck Yeager is officially credited with being the first person to break the sound barrier "in level flight" (see the video below). This leaves the door open for claims of previous supersonic flights made while diving.

The sound barrier was first broken on land in 1948 by a rocket train in California. It was powered by 50,000 pounds of thrust, reaching 1,019 mph.

Jackie Cochran was the first woman to break the sound barrier on May 18, 1953 in a Canadair F-86 Sabre.

Compressibility

Material Properties	
Specific heat	$c = \frac{T}{N}\left(\frac{\partial S}{\partial T}\right)$
Compressibility	$\beta = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)$
Thermal expansion	$\alpha = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)$
	edit

In thermodynamics and fluid mechanics, **compressibility** is a measure of the relative volume change of fluid or solid as a response to a pressure (or mean stress) change.

$$\beta = -\frac{1}{V}\frac{\partial V}{\partial P}$$

where *V* is volume and *P* is pressure. The above statement is incomplete, because for any object or system the magnitude of the compressibility depends strongly on whether the process is adiabatic or isothermal. Accordingly we define the isothermal compressibility as:

$$\beta_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T$$

where the subscript *T* indicates that the partial differential is to be taken at constant temperature. The adiabatic compressibility as:

$$\beta_S = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_S$$

where *S* is entropy. For a solid, the distinction between the two is usually negligible.

The inverse of the compressibility is called the bulk modulus, often denoted *K*. That page also contains some examples for different materials.

Fluid Dynamics

Compressibility is an important notion in aerodynamics. At low speeds, the compressibility of air is not important for aircraft design, but as the airflow nears and exceeds the speed of sound, a host of new aerodynamic effects become important in the design of aircraft. These effects, often several of them at a time, made it very difficult for World War II era aircraft to reach speeds much beyond 500mph.

Some of the minor effects include changes to the airflow that lead to problems in control. For instance, the P-38 Lightning had a particular problem in high speed dives that led to a nose-heavy condition. Pilots would enter dives, and then find that they could no longer control the plane, which continued to nose over until it crashed. Adding a "dive flap" beneath the wing to upset the airflow cured the problem.

A similar problem effected some models of the Supermarine Spitfire. At high speeds the ailerons could apply more torque than the Spitfire's thin wings could handle, and the entire wing would twist in the opposite direction. This meant that the plane would roll in the direction opposite to what the pilot expected, and led to a number of accidents. This wasn't noticed until later model Spitfires like the Mk.IX started to appear, because earlier models weren't fast enough. This was mitigated by adding considerable strength to the wings, and was wholly cured when the Mk.XIV was introduced.

The Messerschmitt Bf 109 and Mitsubishi Zero had the exact opposite problem, the controls were too weak. At higher speeds the pilot simply couldn't move the controls because there was too much airflow over the control surfaces. The planes would become difficult to manoeuvre, and at high enough speeds even less manoeuvrable aircraft could out-turn them.

Finally, another common problem that fits into this category is flutter. At some speeds the airflow over the control surfaces will become turbulent, and the controls will start to flutter. If the speed of the fluttering is close to a harmonic of the control's movement, the resonance could break the control off completely. This was a serious problem on the Zero. When they first encountered problems with the poor control at high speed they addressed it with a new style of control surface with more power. However this introduced a new resonant mode, and a number of planes disappeared before this was discovered.

All of the items above are often talked about when the term "compressibility" is used, but in a manner of speaking, they are all incorrectly used. From a strictly aerodynamic point of view, the term should refer only to those effects arising as a side effect of the changes in airflow from an incompressible fluid (similar in effect to water) to compressible fluid (acting as a gas) as you approach the speed of sound. There are two effects in particular, wave drag and critical mach.

Wave drag is a sudden rise in drag on the aircraft, caused by air building up in front of it. At lower speeds this air has time to "get out of the way", guided by the air in front of it that is in contact with the aircraft. But at the speed of sound this can no longer happen. Air which was previously following the streamline around the aircraft now hits it directly. The amount of power needed to overcome this effect is considerable.

At the speed of sound the way that lift is generated changes dramatically, from being dominated by Bernoulli's principle to forces generated by shock waves. Since the air on the top of the wing is travelling faster than on the bottom, due to Bernoulli effect, at speeds close to the speed of sound the air on the top of the wing will be accelerated to supersonic. When this happens the distribution of lift changes dramatically, typically causing a powerful nose-down trim. Since the aircraft normally approached these speeds only in a dive, pilots would report the aircraft attempting to nose over into the ground.

All of these effects have adverse effects on the control or performance of the plane. For this reason it's common to see references to aircraft that suffer from compressibility. The P-38 and Zero are particularly common examples, although in fact they are both bad ones.

Thermodynamics

The term "compressibility" is also used in thermodynamics to describe the deviance in the thermodynamic properties of a real gas from those expected from an ideal gas. The **compressibility factor** is defined as

$$Z = \frac{P\tilde{V}}{RT}$$

where *P* is the pressure of the gas, *T* is its temperature, and $\tilde{V}$ is its molar volume. In the case of an ideal gas, the compressibility factor *Z* is equal to unity, and the familiar ideal gas law is recovered:

$$P = \frac{RT}{\tilde{V}}$$

Z can, in general, be either greater or less than unity for a real gas.

The deviation from ideal gas behavior tends to become particularly significant (or, equivalently, the compressibility factor strays far from unity) near the critical point, or in the case of high pressure or low temperature. In these cases, an alternative equation of state better suited to the problem must be utilized to produce accurate results.

Geology

Compressibility is a geological term used to quantify the ability of a soil to reduce in volume with applied pressure. It is an important concept in geotechnical engineering in the design of certain structural foundations. For example, the construction of high-rise structures over underlying layers of highly compressible bay mud poses a considerable desgn constraint, and often leads to use of driven piles or other innovative techniques.

Shock wave

A **shock wave** (or simply "**shock**") is a type of propagating disturbance. Like a normal wave, a shock wave carries energy and can propagate through a medium or, in special cases, through a field such as the electromagnetic field in the absence of a physical medium. Shock waves are characterized by a sudden change in the characteristics of the medium (such as pressure, temperature, or speed) as a positive step function. The counterpart to a shock wave is an expansion wave. A shock wave travels through the medium at a higher speed than a normal wave.

Unlike solitons (another kind of nonlinear wave), the energy of a shock wave dissipates relatively quickly with distance. Additionally, the companion expansion wave from a shock approaches, and eventually merges with the shock, partially cancelling it out. Thus the sonic boom associated with the passage of an aircraft is the sound wave resulting from the degradation and merging of the shock wave-expansion wave pair produced by the passage of a supersonic aircraft.

Shock waves in supersonic flows

The **shock wave** is one of several different ways in which a gas in a supersonic flow can be compressed. Two other methods are isentropic and Prandtl-Meyer compressions. The method of compression of a gas results in different temperatures and densities for a given pressure ratio, which can be analytically calculated for a non-reacting gas. A shock wave compression results in a loss of total pressure, meaning that it is a less efficient method of compressing gases for some purposes, for instance in the intake of a scramjet. The appearance of pressure-drag on supersonic aircraft is mostly due to the effect of shock compression on the flow.

When an object (or disturbance) moves faster than the information about it can be propagated into the surrounding fluid, fluid near the disturbance cannot react or "get out of the way" before the disturbance arrives. In a shock wave the properties of the fluid (density, pressure, temperature, velocity, Mach number) change almost instantaneously. Measurements of the thickness of shock waves have resulted in values approximately one order of magnitude greater than the mean free path of the gas investigated.

Shock waves are not sound waves; a shock wave takes the form of a very sharp change in the gas properties on the order of a few mean free paths (roughly micro-meters at atmospheric conditions) in thickness. Shock waves in air are heard as a loud "crack" or "snap" noise. Over time a shock wave can change from a nonlinear wave into a linear wave, degenerating into a conventional sound wave as it heats the air and loses energy. The sound wave is heard as the familiar "thud" or "thump" of a sonic boom, commonly created by the supersonic flight of aircraft.

Shock waves due to nonlinear steepening

Shock waves can form due to steepening of ordinary waves. The best-known example of this phenomenon is ocean waves that form breakers on the shore. In shallow water, the speed of surface waves is dependent on the depth of the water. An incoming ocean wave has a slightly higher wave speed near the crest of each wave than near the troughs between waves, because the wave height is not infinitesimal compared to the depth of the water. The crests overtake the troughs until the leading edge of the wave forms a vertical face and spills over to form a turbulent shock (a breaker) that dissipates the wave's energy as sound and heat.

Similar phenomena affect strong sound waves in gas or plasma, due to the dependence of the sound speed on temperature. Strong waves heat the medium near each pressure front, due to adiabatic compression of the air itself, so that high pressure fronts outrun the corresponding pressure troughs. While shock formation by this process does not normally happen to sound waves in Earth's atmosphere, it is though to be one mechanism by which the solar chromosphere and corona are heated, via waves that propagate up from the solar interior.

Analogies

A shock wave may be described as the furthest point upstream of a moving object which "knows" about the approach of the object. In this description, the shock wave position is defined as the boundary between the zone having no information about the shock-driving event, and the zone aware of the shock-driving event, analogous with the light cone described in the theory of general relativity.

To get a shockwave something has to be travelling faster than the local speed of sound. In that case some parts of the air around the aircraft are travelling at exactly the speed of sound with the aircraft, so that the soundwaves leaving the aircraft pile up on each other, sort of like a tailback on a road, and a shockwave forms, the pressure goes up and up and up there, and then spreads out sideways. Because of this amplification effect, a shockwave is very intense, more like an explosion when you hear it (not coincidentally, since explosions create shockwaves).

Analogous phenomena are known outside fluid mechanics. For example, particles accelerated beyond the speed of light in a refractive medium (where the speed of light is less than that in a vacuum, such as water) create visible shock effects, a phenomenon known as Cherenkov radiation.

Types of shock wave

There are several types of shock wave:

1. Shock propagating into a stationary flow
   - This shock is generally generated by the interaction of two bodies of gas at different pressure, with a shock wave propagating into the lower pressure gas, and an expansion wave propagating into the higher pressure gas.
   - Examples: Balloon bursting, Shock tube, shock wave from explosion
   - In this case, the gas ahead of the shock is stationary (in the laboratory frame), and the gas behind the shock is supersonic in the laboratory frame. The shock propagates normal to the oncoming flow. The speed of the shock is a function of the original pressure ratio between the two bodies of gas.
2. Shock in a pipe flow
   - This shock appears when supersonic flow in a pipe is decelerated.
   - Examples: Supersonic Ramjet, Scramjet, needle valve
   - In this case the gas ahead of the shock is supersonic (in the laboratory frame), and the gas behind the shock system is either supersonic (oblique shocks) or subsonic (normal shock) (Although for some oblique shocks very close to the deflection angle limit, the downstream Mach number is subsonic.) The shock is the result of the deceleration of the gas by a converging duct, or by the growth of the boundary layer on the wall of a parallel duct.
3. Recompression shock on a transonic body
   - These shocks appear when the flow over a transsonic body is decelerated to subsonic speeds.
   - Examples: Transonic wings, Turbines,shockwave at mach1

- Where the flow over the suction side of a transonic wing is accelerated to a supersonic speed, the resulting recompression can be by either Prandtl-meyer compression or by the formation of a normal shock. This shock is of particular interest to makers of transonic devices because it can cause separation of the boundary layer at the point where it touches the transonic profile. This can then lead to full separation and stall on the profile, higher drag, or shock-buffet, a condition where the separation and the shock interact in a resonance condition, causing resonating loads on the underlying structure.

4. Attached shock on a supersonic body
   - These shocks appear as "attached" to the tip of a sharp body moving at supersonic speeds.
   - Examples: Supersonic wedges and cones with small apex angles.
   - The attached shock wave is a classic structure in aerodynamics because, for a perfect gas and inviscid flowfield, an analytic solution is available, such that the pressure ratio, temperature ratio, angle of the wedge and the downstream Mach number can all be calculated knowing the upstream Mach number and the shock angle. Smaller shock angles are associated with higher downstream Mach numbers, and the special case where the shock wave is at 90 degrees to the oncoming flow (Normal shock), is associated with a downstream Mach number of one. These follow the "weak-shock" solutions of the analytic equations.
5. Detached shock on a supersonic body (see also bow shock)
   - Such a shock occurs about a supersonic body that is too blunt for the shock to attach to the tip.
   - Examples: Space return vehicles (Apollo, Space shuttle), bullets. The boundary of a magnetosphere.
   - These shocks are curved, and form a small distance in front of the body. Directly in front of the body, they stand at 90 degrees to the oncoming flow, and then curve around the body. Detached shocks allow the same type of analytic calculations as for the attached shock, for the flow near the shock. They are a topic of continuing interest, because the rules governing the shock's distance ahead of the blunt body are complicated, and are a function of the body's shape. Additionally, the shock standoff distance varies drastically with the temperature for a non-ideal gas, causing large differences in the heat transfer to the thermal protection system of the vehicle. See the extended discussion on this topic at Atmospheric reentry. These follow the "strong-shock" solutions of the analytic equations, meaning that for some oblique shocks very close to the deflection angle limit, the downstream Mach number is subsonic.
6. Detonation wave

A detonation wave is essentially a shock within which an exothermic reaction takes place. It involves a wave travelling through a highly combustible or chemically unstable medium, such as an oxygen-methane mixture or a high explosive. The chemical reaction of the medium occurs within the wave, and the chemical energy of the reaction drives the wave forward.
It is also possible for a shock wave in a reactive mixture to initiate combustion (shock-induced combustion), but in this case the shock proceeds at a velocity indicated by the noncombusted mixture, since the actual combustion occurs in the region behind the shock wave, rather than within the wave. The velocity of a shock wave is independant of what is happening after it passes.
A detonation wave follows slightly different rules from an ordinary shock since it is driven by the chemical reaction occurring inside the wave front itself. This change from a shock-induced combustion to detonation happens as the time for the exothermic reaction to occur approaches the time for the shock-wave to pass the reacting particles. Detonation waves proceed at the Chapman-Jouguet velocity, which is a function of the nature of the chemical reaction occurring.

A detonation will also cause a shock of type 1, above to propagate into the surrounding air due to the overpressure induced by the explosion.

External links

- Photo Gallery
- eFluids gallery
- NACA 1135: Equations, Tables, and Charts for Compressible Flow
- Bomb Shock Wave Estimation
- NASA Glenn Research Center information on:
  - Oblique Shocks
  - Multiple Crossed Shocks
  - Expansion Fans

Critical mach

Critical mach is a aeronautics term that refers to the speed at which some of the airflow on a wing becomes supersonic. When this occurs the distribution of forces on the wing changes suddenly and dramatically, typically leading to a strong nose-down force on the aircraft. This effect led to a number of accidents in the 1930s and 1940s, when aircraft in a dive would hit critical mach and continue to push over into a steeper and steeper dive. This problem is often lumped in with the catch-all phrase compressibility.

Wings generate much of their lift due to Bernoulli's principle: by speeding up the airflow over the top of the wing, the air has less pressure on top than on the bottom, leading to a net upward force. The relative difference in speed is due largely to the wing's shape (although symmetrical wings can also generate lift), so the difference in speed remains a fairly constant ratio over a wide range of speeds.

But if the air speed on the top of the wing is faster than on the bottom, there will be some speed where the air on top reaches the speed of sound. This is the critical mach. When this happens shock waves form on the upper wing at the point where the flow becomes supersonic, typically behind the midline of the chord. Shock waves generate lift of their own, so the lift of the wing suddenly moves rearward, twisting it down. This effect is known as **mach tuck**.

The actual speed of critical mach varies from wing to wing. In general a thicker wing will have a lower critical mach, because a thicker wing accelerates the airflow more than a thinner one. For instance, the fairly thick wing on the P-38 Lightning led to a critical mach of about .69 Mach, a speed it could reach with some ease in dives, which lead to a number of crashes. The much thinner wing on the Supermarine Spitfire was deliberately chosen to avoid this problem, and had a critical mach of about .89 Mach.

Today a compromise design is used, the swept-wing. This design "fools" the air into thinking it's flowing over a thin wing, which is in fact fairly thick. Swept-wings are used on almost all aircraft that fly in the transonic, and is a common feature of almost all airliners and modern fighter aircraft.

It is possible to see the mach line on an airliner visually, as these aircraft fly beyond the critical mach in crusing flight. The shock wave extends vertically from the wing, and the change in density is enough to make it operate as a lens. By looking at straight lines running parallel to the wing you can often spot a discontinuity where the line "jumps". Roads are an excellent marker for this.

Waverider

A **waverider** is a hypersonic aircraft design that improves its supersonic lift-to-drag ratio by producing a lifting surface built out of the shock waves being generated by its own flight, a technique known as compression lift. To date the only aircraft to use the technique is the Mach 3 supersonic XB-70 Valkyrie, which was waverider-like with its drooping wingtips. The waverider remains a well-studied design for high-speed aircraft in the Mach 5 and higher hypersonic regime, although no production design has used the concept to date.

History

The waverider concept was first developed by Terence Nonweiler of the Queen's University of Belfast, and first described in print in 1951 as a re-entry vehicle. It consisted of a delta-wing platform with a low wing loading to provide considerable surface area to dump the heat of re-entry. At the time he was forced to use a greatly simplified 2D model of airflow around the aircraft, which he realized would not be accurate due to spanwise flow across the wing. While attempting to develop simplified 3D equations to model the aircraft, he noticed that the shock wave would lead to high pressure under the wing, which could be used for lift. This is the basic principle of the waverider, and was more fully developed in later research.

In the 1950s, the British started a space program based around the Blue Streak missile, which was, at some point, to include a manned vehicle. Armstrong-Whitworth were contracted to develop the re-entry vehicle, and unlike the US space program they decided to stick with a winged vehicle instead of a ballistic capsule. Between 1957 and 1959, they contracted Nonweiler to develop his concepts further. This work produced a pyramid-shaped design with a flat underside and short wings. Heat was conducted through the wings to the upper cool surfaces, where it was dumped into the turbulent air on the top of the wing.

In 1960, work on the Blue Streak was canceled as the missile was seen as being obsolete before it could enter service. Work on waverider then moved to the Royal Aircraft Establishment (RAE), where it continued until 1965 as a research program into high-speed (Mach 6) civilian airliners. During this period at least one waverider was tested at the Woomera Rocket Range, mounted on the nose of an air-launched Blue Steel missile, and a number of airframes were tested in the wind tunnel at NASA's Ames Research Center.

In 1962 Nonweiler moved to Glasgow University to became Professor of Aerodynamics and Fluid Mechanics. That year his *Delta Wings of Shapes Amenable to Exact Shock-Wave Theory* was published by the *Journal of the Royal Aeronautical Society*, and earned him that society's Gold Medal. In this paper the "classic" waverider is described, a modification of the original Armstrong-Whitworth design. In the new design the wings were angled down towards the tips, and the shock waves being generated from their leading edges interacted to form a single flat "plate" shock under the fuselage. The shock wave itself was a lifting surface, generating the needed lift with little physical interaction with the airframe, and dramatically lowering heating. Two to three years later the concept briefly came into the public eye, due to the airliner work at the RAE that led to the prospect of reaching Australia in 90 minutes. Newspaper articles lead to an appearance on Scottish Television.

Hawker-Siddeley examined the waverider in the later 1960s as a part of a three-stage lunar rocket design. The first stage was built on an expanded Blue Steel, the second a waverider, and the third a nuclear-powered manned stage. This work was generalized in 1971 to produce a two-staged reusable spacecraft. The 121-foot (36.9 m) long first stage was designed as a classical waverider, with airbreathing propulsion for return to the launch site. The upper stage was designed as a lifting body, and would have carried an 8000-pound (3.6 t) payload to low Earth orbit.

During the 1970s most work in hypersonics disappeared, and the waverider along with it.

In 1981, Rasmussen at the University of Maryland started a waverider renaissance by publishing a paper on a new 3D underside shape riding the shock wave from a conical projection, as opposed to Nonweiler's simple 2D 'caret' design riding the shock from a flat nose. These shapes have superior lifting performance and less drag. Since then, whole families of cone-derived waveriders have been designed using more and more complex conic shocks, based on more complex software. This work eventually led to a conference in 1989, the *First International Hypersonic Waverider Conference*, held at the University of Maryland.

One last development of the waverider is the **Hypersonic Sail Waverider**, which uses a rogallo wing as the lifting surface. The primary purpose for this design is to create a light-weight disposable lifting surface for interplanetary spacecraft to use while maneuvering over planets with an atmosphere. If used over Venus for instance, the spacecraft could aeromaneuver with the lift provided by the waverider to a degree that no gravitational slingshot could hope to achieve.

Design

During re-entry, hypersonic vehicles generate lift only from the underside of the fuselage. The underside, which is inclined to the flow at a high angle of attack, creates lift in reaction to the vehicle wedging the airflow downwards. The amount of lift is not particularly high, compared to a traditional wing, but more than enough to maneuver given the amount of distance the vehicle covers.

The problem is to dump the heat generated in this process. Put simply, the energy used to place the vehicle into orbit is returned to it when it comes back to Earth. Consider that the vehicle likely used a very large rocket to get into space and you get some indication of the magnitude of the forces involved.

Most re-entry vehicles have been based on the blunt-nose reentry design pioneered by Theodore von Kármán. He demonstrated that a shock wave is forced to "detatch" from a curved surface, forced out into a larger configuration that requires considerable energy to form. Energy expended in forming this shock wave is no longer available as heat, so this shaping can dramatically reduce the heat load on the spacecraft. Such a design has been the basis for almost every re-entry vehicle since, found on the blunt noses of the early ICBM warheads, the bottoms of the various NASA capsules, and the large nose of the Space Shuttle.

The problem with the blunt-nose system is that the resulting design creates very little lift, meaning the vehicle has problems maneuvering during re-entry. If the spacecraft is meant to be able to return to its point of launch "on command", then some sort of maneuvering will be required to counteract the fact that the Earth is turning under the spacecraft as it flies. After a single low-earth orbit, the launching point will be over 1000 km to the east of the spacecraft by the time it flies over again after one full orbit. A considerable amount of research was dedicated to combining the blunt-nose system with wings, leading to the development of the lifting body designs in the U.S.

It was while working on exactly one such design that Nonweiler developed the waverider. He noticed that the detachment of the shock wave over the blunt leading edges of the wings of the Armstrong-Whitworth design would allow the air on the bottom of the craft to flow spanwise and escape to the upper part of the wing through the gap between the leading edge and the detached shock wave. This loss of airflow dramatically reduced the amount of lift being generated by the waverider (up to a quarter), which led to studies on how to avoid this problem and keep the flow trapped under the wing.

Nonweiler's resulting design is a delta-wing with some amount of negative dihedral — the wings are bent down from the fuselage towards the tips. When viewed from the front, the wing resembles a caret symbol (^) in cross-section, and these designs are often referred to as carets. The more modern 3D version typically looks like a rounded letter M. Theoretically, a star-shaped waverider with a frontal cross-section of a "+" or "×" could reduce drag by another 20%. The disadvantage of this design is that it has more area in contact with the shock wave and therefore has more pronounced heat dissipation problems.

Waveriders generally have sharp noses and sharp leading edges on their wings. The underside shock-surface remains attached to this. Air flowing in through the shock surface is trapped between the shock and the fuselage, and can only escape at the rear of the fuselage. With sharp edges, all the lift is retained.

Even though sharp edges get much hotter than rounded ones at the same air density, the improved lift means that waveriders can glide on re-entry at much higher altitudes where the air density is lower. A list ranking various space vehicles in order of heating applied to the airframe would have capsules at the top (re-entering quickly with very high heating loads), waveriders at the bottom (extremely long gliding profiles at high altitude), and the Space Shuttle somewhere in the middle.

Simple waveriders have substantial design problems. First, the obvious designs only work at a particular Mach number, and the amount of lift captured will change dramatically as the vehicle changes speed. Another problem is that the waverider depends on radiative cooling, possible as long as the vehicle spends most of its time at very high altitudes. However these altitudes also demand a very large wing to generate the needed lift in the thin air, and that same wing can become rather unwieldy at lower altitudes and speeds.

Because of these problems, waveriders have not found favor with practical aerodynamic designers, despite the fact that they might make long-distance hypersonic vehicles efficient enough to carry air freight.

It is controversial, but some researchers claim that there are designs that overcome these problems. One candidate for a multi-speed waverider is a "caret wing", operated at different angles of attack. A caret wing is a delta wing with longitudinal conical or triangular slots or strakes. It strongly resembles a paper airplane or rogallo wing. The correct angle of attack would become increasingly precise at higher mach numbers, but this is a control problem that is theoretically soluble. The wing is said to perform even better if it can be constructed of tight mesh, because that reduces its drag, while maintaining lift. Such wings are said to have the unusual attribute of operating at a wide range of mach numbers in different fluids with a wide range of Reynolds numbers.

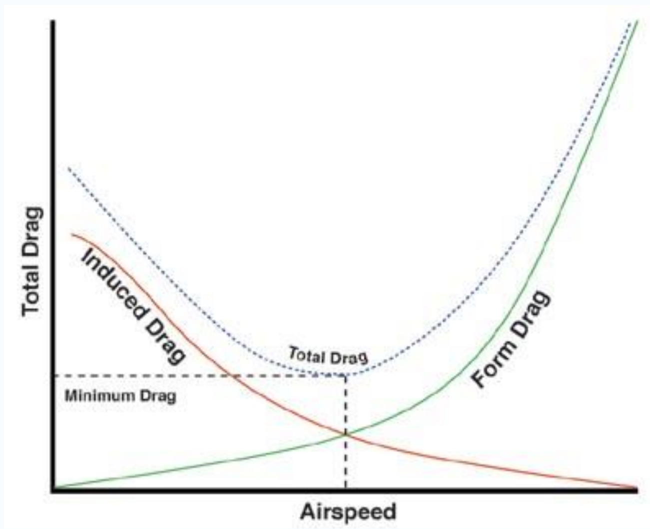
The temperature problem can be solved with some combination of a transpiring surface, exotic materials, and possibly heat-pipes. In a transpiring surface, small amounts of a coolant such as water are pumped through small holes in the aircraft's skin (see transpiration and perspiration). This design works for Mach-25 spacecraft re-entry shields, and therefore should work for any aircraft that can carry the weight of the coolant. Exotic materials such as carbon-carbon composite do not conduct heat but endure it, and they tend to be brittle. Although they are not widely used at present, heatpipes may be an excellent, unexplored solution: they are passive (no pumps), they conduct heat better than most exotic solid materials, and they would disperse heat away from the active parts of the wing.

Popular fictional use

Due to the pratically non-existant use of waverider designs on actual real life aircraft (past or present), waveriders have become the norm in transatmospheric spacecraft, spaceships, mecha and other vehicles or machines in many works of science-fiction.

Lift-to-drag ratio

In aerodynamics, the **lift-to-drag ratio**, or **L/D ratio** ("ell-over-dee", as opposed to "ell-dee"), is the amount of lift generated by a wing, compared to the drag it creates by moving through the air. A "better" L/D ratio is one of the major goals in wing design, since a particular aircraft's needed lift doesn't change, delivering that lift with lower drag leads directly to better fuel economy, climb performance and glide ratio.



The drag curve

The term is calculated for any particular speed by measuring the lift generated, then dividing by the drag it causes. These vary with speed, so the results are typically plotted on a 2D graph. In almost all cases the graph forms a U-shape, due to the two main components of drag on the wing.

Induced drag is caused by the generation of lift by the wing. Lift generated by a wing is directed straight up from the wing, but since wings typically fly at some small angle of attack, this means the force is directed both up and to the rear. The rearward component of this force is seen as drag. At low speeds an aircraft has to generate lift with a higher angle of attack, thereby leading to greater induced drag. This term dominates the low-speed side of the L/D graph, the left side of the U.

Profile drag is caused by air hitting the wing itself. This form of drag, simply another name for wind resistance, varies with the square of speed (see drag equation). For this reason profile drag is only a real factor at higher speeds, forming the right side of the L/D graph's U shape. Profile drag is lowered primarily by using thinner wings, but such a shape often leads to less low-speed lift, and thus higher induced drag.

It is the bottom point of the graph, the point where the combined drag is at its lowest, that the wing is performing at its best. For this reason designers will typically select a wing with its L/D peak at the chosen cruising speed of the aircraft, thereby maximizing economy. Like all things in aeronautical engineering, the lift-to-drag ratio is not the only consideration for wing design. Performance at high angle of attack and a gentle stall are often considered more important, and for this reason easy-to-fly wing designs like the **Clark-Y** continue to be used even though many more efficient wings have since been designed.

As the aircraft fuselage and control surfaces will also add drag it is fair to consider the L/D of the aircraft as a whole. As it turns out, the glide ratio, which is the ratio of an (unpowered) aircraft's descent to its forward motion, is exactly equal to the aircraft's L/D. This is especially of interest in the design and operation of high performance gliders (called sailplanes), which can have glide ratios approaching 60 to 1 (60 units of distance forward for each unit of descent) in the extreme cases, but with 30:1 being considered good performance for general recreational use. Achieving a sailplane's best L/D in practice requires precise control of airspeed and smooth and restrained operation of the controls to reduce drag from deflected control surfaces. In zero wind conditions, L/D will equal altitude lost divided by distance traveled. Achieving the maximum distance for altitude lost in wind conditions requires further modification of the best airspeed, as does alternating cruising and thermaling.

Mathematically, the maximum lift-to-drag ratio can be estimated as:

$$(L/D)_{max} = \frac{1}{2}\sqrt{\frac{\pi A \epsilon}{C_{D,0}}}$$ [1],

where A is the aspect ratio, ε is the aircraft's efficiency factor, and $C_{D,0}$ is the zero-lift drag coefficient.

Lift-induced drag

In aerodynamics, **lift-induced drag**, or **induced drag**, is a drag force which occurs whenever a lifting body or a wing of finite span generates lift.

Source of Induced Drag

There is no practical wing of infinite span. However, the characteristics of such a wing can be measured on a section of wing spanning the width of a wind tunnel, since the walls block spanwise flow and create an effectively 2-D flow. By definition, the reaction force is resolved into two components. That parallel to the incident airflow is the drag and that normal to the incident airflow is the lift. At practical angles of incidence the lift greatly exceeds the drag.

An aerofoil produces lift by generating an area of high pressure on the under surface and an area of low pressure over the upper surface. On a wing of finite span some air 'leaks' around the wingtip from the lower surface towards the upper surface producing a wingtip vortex. The vortices then create a down flow or 'downwash' behind the wing. This modifies the airflow around the wing, relative to that on a wing of infinite span, tilting the total reaction force rearwards. The angular deflection is small and has little effect on the lift as defined above. However, there is an increase in the drag equal to the product of the lift force and the angle through which it is deflected. Since the deflection is itself a function of the lift the additional drag is proportional to the square of the lift. Unlike parasitic drag, induced drag is inversely proportional to the square of the airspeed.

Reducing Induced Drag

Induced drag can be minimized by the following means:

- **Increase the wing span.** The effect of the wingtip vortices is greatest near the wing tips. With increased wingspan a lesser portion of the wing is in the most affected region. Increasing span with no other change would increase wing area. In practice, the wing area is kept constant by increasing the aspect ratio rather than the span.

- **Optimise the spanwise load distribution.** If the lift is diminished towards the wingtips there is less pressure differential near the wingtips to create wingtip vortices. Minimum induced drag is achieved when the spanwise lift distribution is elliptical. The parameter with greatest effect on lift distribution is the wing planform. Thus, a wing with elliptical planform would have low induced drag. Few aircraft have this planform because of manufacturing complications — the most famous example is the World War II Spitfire. Tapered wings with straight leading and trailing edges can approximate to elliptical lift distribution. Typically, straight wings produce between 5–15% more induced drag than an elliptical wing. The lift distribution may also be modified by the use of washout, a spanwise twist of the wing to reduce the incidence towards the wingtips, and by changing the airfoil section near the wingtips.

- **Provide a physical barrier to vortex formation.** Such a barrier might take several forms. Some early aircraft had fins mounted on the tips of the tailplane which served as endplates. More recent aircraft have wingtip mounted winglet to oppose the formation of vortices. Wingtip mounted fuel tanks may also provide some benefit.

Calculation of Induced Drag

Induced drag is calculated as follows:

$$D_i = \frac{1}{2}\rho V^2 S C_{Di} = \frac{1}{2}\rho_0 V_e^2 S C_{Di}$$

where

$C_{Di} = \dfrac{kC_L^2}{\pi A}$ and

$$C_L = \frac{L}{\frac{1}{2}\rho_0 V_e^2 S}$$

Thus

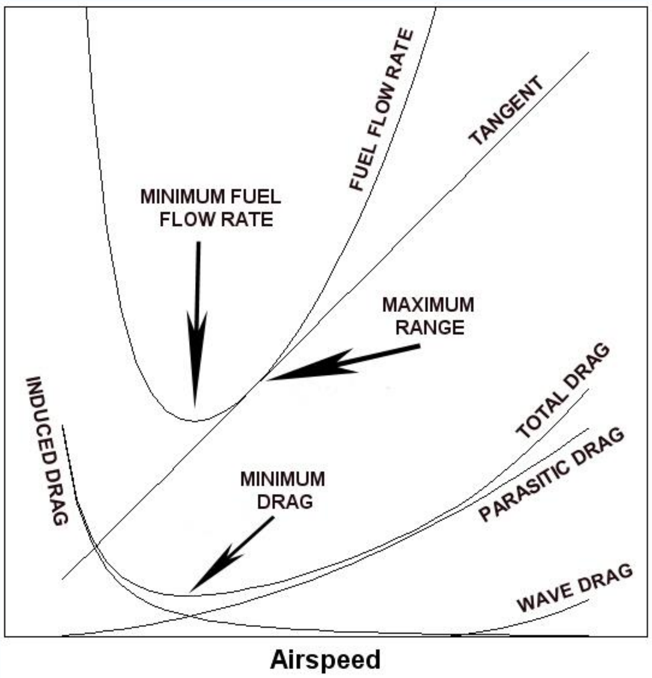
$$D_i = \frac{kL^2}{\frac{1}{2}\rho_0 V_e^2 S \pi A}$$

Where:

A is the aspect ratio,

C_{Di} is the induced drag coefficient,
C_L is the lift coefficient,
D_i is the induced drag,
k is the factor by which the induced drag exceeds that of an elliptical lift distribution, typically 1.05 to 1.15,
L is the lift,
S is the gross wing area,
V is the true airspeed,
V_e is the equilavent airspeed,
ρ is the air density and
ρ_0 is 1.225 kg/m³, the air density at sea level, ISA conditions.

Combined Effect with other Drag Sources



Curves showing induced, parasitic, and combined drag vs. airspeed

Induced drag must be added to the parasitic drag to find the total drag. Since induced drag is inversely proportional to the square of the airspeed whereas parasitic drag is proportional to the square of the airspeed, the combined overall drag curve shows a minimum at some airspeed - the minimum drag speed. An aircraft flying at this speed is at its optimal aerodynamic efficiency. The minimum drag speed occurs at the speed where the induced drag is equal to the parasitic drag. This is the speed at which the best gradient of climb, or for unpowered aircraft, minimum gradient of descent (minimum sink rate), is achieved.

The speed for best endurance, i.e. time in the air, is the speed for minimum fuel flow rate. The fuel flow rate is calculated as the product of the drag or power required and the engine specific fuel consumption. The engine specific fuel consumption will be expressed in units of fuel flow rate per unit of thrust or per unit of power depending on whether the engine generates thrust e.g. a jet engine, or power e.g. a turbo-prop engine.

The speed for best range, i.e. distance travelled, occurs at the speed at which a tangent from the origin touches the fuel flow rate curve. The curve of range versus airspeed is normally very flat and it is customary to operate at the speed for 99% best range since this gives about 5% greater speed for only 1% less range.

See also

- Drag equation

Vortex

Vortex created by the passage of an aircraft wing, revealed by coloured smoke

A **vortex** is a spinning, often turbulent, flow (or any spiral motion) with closed streamlines. The shape of media or mass rotating rapidly around a center forms a vortex. It is a flow involving rotation about an axis (vertical or horizontal).

Dynamics

A vortex can be any circular or rotary flow that possesses *vorticity*.[1] Vorticity is a mathematical concept used in fluid dynamics. It can be related to the amount of "circulation" or "rotation" in a fluid. In fluid dynamics, vorticity is the circulation per unit area at a point in the flow field. It is a vector quantity, whose direction is (roughly speaking) along the axis of the swirl. Also in fluid dynamics, the movement of a fluid can be said to be *vortical* if the fluid moves around in a circle, or in a helix, or if it tends to spin around some axis. Such motion can also be called solenoidal. In the atmospheric sciences, vorticity is a property that characterizes large-scale rotation of air masses. Since the atmospheric circulation is nearly horizontal, the (3 dimensional) vorticity is nearly vertical, and it is common to use the vertical component as a scalar vorticity.

Mathematically, it is defined as,

$$\omega = \nabla \times u$$

where u = ui + vj + wk is the *fluid velocity*.

The properties of vorticity in 2 and 3 dimensions are treated in some depth in George Batchelor's famous textbook (ch 5 & ch 7 et seq.). Of particular importance in practical situations is the intensification of vorticity which takes place in three dimensions when a vortex-line is extended (p270 et seq).

Two types of vortex

In fluid mechanics, a distinction is often made between two limiting vortex cases. One is called the free (irrotational) vortex, and the other is the forced (rotational) vortex. These are considered as below:

Free (irrotational) vortex

When fluid is drawn down a plug-hole, one can observe the phenomenon of a **free vortex**. The tangential velocity v varies inversely as the distance r from the centre of rotation, so the angular momentum, rv, is constant; the vorticity is zero everywhere (except for a singularity at the centre-line) and the circulation about a contour containing r=0 has the same value everywhere. The free surface (if present) dips sharply (as r^{-2}) as the centre line is approached.

The tangential velocity is given by:

$$v_\theta = \frac{\Gamma}{2\pi r} \qquad (2.1)$$

where Γ is the vortex strength and r is the radial distance from the center of the vortex.

Forced (Rotational) Vortex

In a **forced vortex** the fluid essentially rotates as a solid body (there is no shear). The motion can be realised by placing a dish of fluid on a turntable rotating at T radians/sec; the fluid has vorticity of 2 T everywhere, and the free surface (if present) is a parabola.

The tangential velocity is given by:

$$v_\theta = \omega r \qquad (2.2)$$

where ω is the angular velocity and r is the radial distance from the center of the vortex.

Observations

A vortex can be seen in the spiraling motion of air or liquid around a center of rotation. Circular current of water of conflicting tides form vortex shapes. Turbulent flow makes many vortices. A good example of a vortex is the atmospheric phenomenon of a whirlwind or a tornado or dust devil. This whirling air mass mostly takes the form of a helix, column, or spiral. Tornadoes develop from severe thunderstorms, usually spawned from squall lines and supercell thunderstorms, though they sometimes happen as a result of a hurricane.

A *mesovortex* is on the scale of a few miles (smaller than a hurricane but larger than a tornado). [2] On a much smaller scale, a vortex is usually formed as water goes down a drain, as in a sink or a toilet. This occurs in water as the revolving mass forms a whirlpool. This whirlpool is caused by water flowing out of a small opening in the bottom of a basin or reservoir. This swirling flow structure within a region of fluid flow opens downward from the water surface.

Instances

- In the hydrodynamic interpretation of the behaviour of electromagnetic fields, the acceleration of electric fluid in a particular direction creates a positive vortex of magnetic fluid. This in turn creates around itself a corresponding negative vortex of electric fluid.
- Smoke ring : A ring of smoke in the air.
- Lift-induced drag of a wing on an aircraft.
- The primary cause of drag in the sail of a sloop.
- Whirlpool : a swirling body of water produced by ocean tides or by a hole underneath the vortex, where water drains out, as in a bathtub. In popular imagination, but only rarely in reality, can they have the dangerous effect of destroying boats.
- Tornado : a violent windstorm characterized by a twisting, funnel-shaped cloud. A less violent version of a tornado, over water, is called a waterspout.
- Hurricane : a much larger, swirling body of clouds produced by evaporating warm ocean water and influenced by the Earth's rotation. Similar, but far greater, vortices are also seen on other planets, such as the permanent Great Red Spot on Jupiter and the intermittent Great Dark Spot on Neptune.
- Polar vortex : a persistent, large-scale cyclone centered near the Earth's poles, in the middle and upper troposphere and the stratosphere.
- Sunspot : dark region on the Sun's surface (photosphere) marked by a lower temperature than its surroundings, and intense magnetic activity.
- The accretion disk of a black hole or other massive gravitational source.
- Spiral galaxy : a type of galaxy in the Hubble sequence which is characterized by a thin, rotating disk. Our galaxy, the Milky Way is of this type.

See also

Water vortex

- Cyclonic separation
- Eddy
- Fan death
- Oregon Vortex
- Optical Vortex
- Viktor Schauberger
- Shower-curtain effect
- Spiral
- Strouhal number
- Vile Vortices
- Von Kármán vortex street
- Vortex Healing
- Vortex ring
- Vortex tube
- Vortex cooler