High Speed Flow

High-speed flow around objects

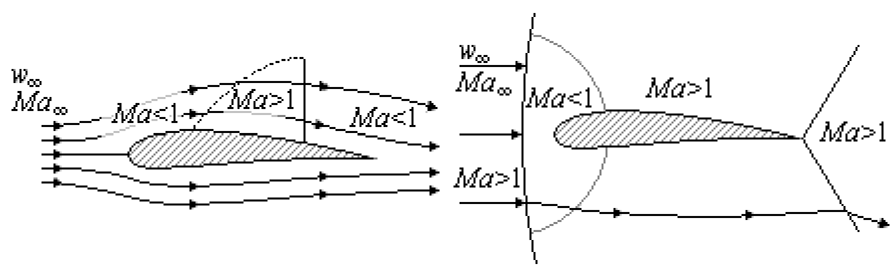
Flight can be roughly classified in six categories:

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.

Critical Mach number

In aerodynamics, the **critical Mach number (Mcr)** of an aircraft is the lowest Mach number at which the airflow over a small region of the wing reaches the speed of sound.[1]

For all aircraft in flight, the airflow around the aircraft is not exactly the same as the airspeed of the aircraft due to the airflow speeding up and slowing down to travel around the aircraft structure. At the Critical Mach number, local airflow in some areas near the airframe reaches the speed of sound, even though the aircraft itself has an airspeed lower than Mach 1.0. This creates a weak shock wave. At speeds faster than the Critical Mach number:

- drag coefficient increases suddenly, causing dramatically increased drag
- in aircraft not designed for transonic or supersonic speeds, changes to the airflow over the flight control surfaces lead to deterioration in control of the aircraft.

In aircraft not designed to fly at the Critical Mach number, shock waves in the flow over the wing and tailplane were sufficient to stall the wing, make control surfaces ineffective or lead to loss of control such as Mach tuck. The phenomena associated with problems at the Critical Mach number became known as compressibility. Compressibility led to a number of accidents involving high-speed military and experimental aircraft in the 1930s and 1940s.

Although unknown at the time, compressibility was the cause of the phenomenon known as the sound barrier. Subsonic aircraft such as the Supermarine Spitfire, BF 109, P-51 Mustang, Gloster Meteor, Me 262, P-80 have relatively thick, unswept wings and are incapable of reaching Mach 1.0. In 1947, Chuck Yeager flew the Bell X-1 to Mach 1.0 and beyond, and the sound barrier was finally broken.

Early transonic military aircraft such as the Hawker Hunter and F-86 Sabre were designed to fly satisfactorily faster than their Critical Mach number. They did not possess sufficient engine thrust to reach Mach 1.0 in level flight but could be dived to Mach 1.0 and beyond, and remain controllable. Modern passenger-carrying jet aircraft such as Airbus and Boeing aircraft have Maximum Operating Mach numbers slower than Mach 1.0.

Supersonic aircraft, such as Concorde, the English Electric Lightning, Lockheed F-104, Dassault Mirage III, and MiG 21 are designed to exceed Mach 1.0 in level flight. They have very thin wings. Their Critical Mach numbers are higher than those of subsonic and transonic aircraft but less than Mach 1.0.

The actual Critical Mach number varies from wing to wing. In general a thicker wing will have a lower Critical Mach number, because a thicker wing accelerates the airflow to a faster speed than a thinner one. For instance, the fairly thick wing on the P-38 Lightning led to a Critical Mach number of about .69, a speed it could reach with some ease in dives, which led to a number of crashes. The much thinner wing on the Supermarine Spitfire caused this aircraft to have a Critical Mach number of about 0.89

Effects of Mach number and compressibility

We study the effects of Mach number and compressibility on strain-rate and vorticity dynamics in decaying isotropic turbulence employing direct numerical simulations. Since local Mach number and dilatation are two direct indicators of compressibility of a fluid element, we use these quantities as conditioning parameters to examine the various aspects of turbulence dynamics. Several interesting observations along with the underlying physics pertaining to the inertial (vortex stretching and self-straining) and pressure (pressure Hessian and baroclinic) terms in the budget of strain-rate and vorticity dynamics will be presented in the talk. The contrasting nature of these physical effects in expanding vs. contracting and supersonic vs. subsonic fluid elements will be highlighted.

Source : http://nprcet.org/e%20content/Misc/e-Learning/Mechanical/III%20year/ME1303-GAS%20DYNAMICS%20AND%20JET%20PROPULSION.pdf