DOCUMENT
GSM-G-CPL.004

DOCUMENT TITLE
AERODYNAMICS 3

HIGH SPEED FLIGHT

CHAPTER 1 – Approaching the Speed of Sound

Version 1.0
February 2015

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INTRODUCTION

NATURE OF COMPRESSIBILITY

At low flight speeds the study of aerodynamics is greatly simplified by the fact that air may experience relatively small changes in pressure with only negligible changes in density. Subsonic airflow is therefore termed **incompressible**. Such a condition of airflow is analogous to the flow of water, hydraulic fluid, or any other incompressible fluid. However, at high flight speeds the pressure changes that take place are quite large and significant changes in air density occur. The study of airflow at high speeds must account for these changes in air density and must consider that the air is compressible and that there will be "compressibility effects."

A factor of great importance in the study of high speed airflow is the speed of sound. The speed of sound is the rate at which small pressure disturbances will be propagated through the air and this propagation speed is solely a function of air temperature.

Evidence of this "pressure warning" is seen in the typical subsonic flow pattern around an aerofoil of where there is up wash and flow direction change well ahead of the leading edge. The aircraft really “telegraphs” its presence to the air ahead. f the object is travelling at some speed above the speed of sound the airflow ahead of the object will not be influenced by the pressure field on the object since pressure disturbances cannot be propagated ahead of the object. Thus, as the flight speed nears the speed of sound a compression wave will form at the leading edge and all changes in velocity and pressure will take place quite sharply and suddenly. The airflow ahead of the object is not influenced until the air particles are suddenly forced out of the way by the concentrated pressure wave set up by the object.

When an aircraft is flying in the transonic flight range, significant changes in the flow and pressure distributions take place, which result in a loss of lift and an increase in drag. This is caused by the formation of shock waves, which in turn adversely affect the stability and control characteristics of an aircraft. Aircraft designed to fly at high Mach numbers therefore incorporate features which are designed to minimise these effects. It is however the speed of sound which leads to these problems.

The first aircraft to exceed the speed of sound was the **Bell X1** in 1947. Flown by Chuck Yeager, it was dropped from a Boeing B29 at altitude and powered by rocket engines. Refer to Figures 1.1 and 1.2.

Figure 1-1 Bell X1 and B 29 Mother Ship

Figure 1-2 Bell X1

The first jet aircraft to be able to fly supersonic in straight and level flight was the North American **F100 Super Sabre** in 1954. Refer to Figure 1.3

Figure 1-3 F 100

THE SPEED OF SOUND

The speed of sound is defined as the rate at which small pressure disturbances are propagated through the air, which is solely a function of air temperature Refer to Figure 1.4.

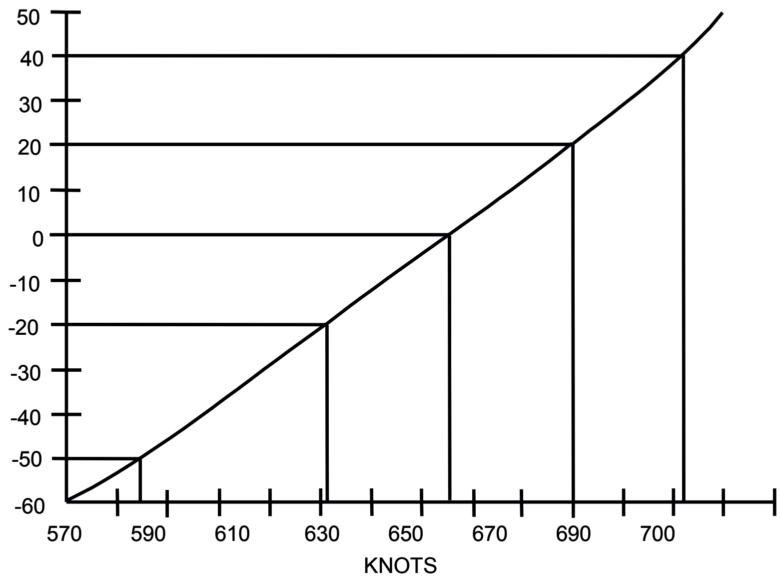


Figure 1-4 Variation of Speed of Sound and Temperature

- The speed of sound is **therefore dependent only on the ambient air temperature** and varies with altitude as illustrated in the following table.
- ***LOCAL SONIC SPEED (knots) = 38.94 X SQUARE ROOT OF THE KELVIN TEMPERATURE***

Notably the speed of sound at **sea level is approximately 660 knots** and steadily reduces up to the base of the tropopause, where after it remains constant.

In practice, fully subsonic aircraft can be heard approaching because they produce pressure waves which travel at the speed of sound, and are transmitted to ones ears by way of these pressure waves. Conversely, aircraft travelling supersonically can not be heard because the air ahead gets no warning of their approach, and consequently the aircraft arrives before the sound pressure wave does.

MACH NUMBER

Mach number is named after **Ernst Mach**, an Austrian physicist, and is the ratio of the speed of a body or flow to the speed of sound in the surrounding atmosphere, so that for example, if an aircraft is travelling at half the speed of sound the Mach number is 0.5. Below is ***a shadowgraph picture taken by Ernst Mach in 1888*** of a bullet travelling supersonically. Refer to Figure 1.5.

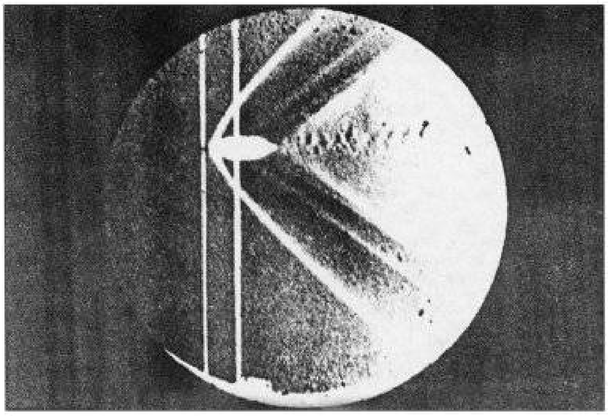
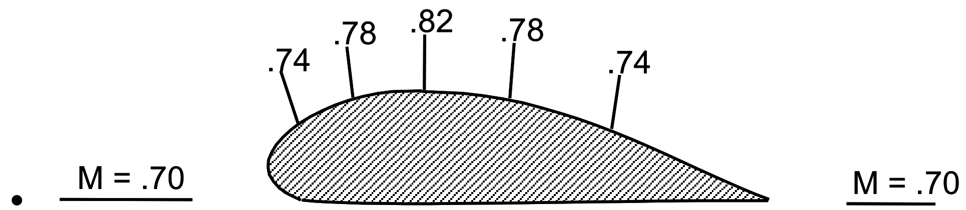


Figure 1-5 A Shadow Graph Picture

From the basic Mach number the following definitions can be derived:

- ***Free Stream Mach Number (M_{FS}):*** This is the Mach number of the airflow sufficiently remote from the aircraft so as not to be affected by it.
- ***Local Mach Number (M_L):*** This is the actual speed of flow over a surface. For example the airflow accelerates as it passes over a wings surface, so that the local Mach number on top of the wing is always greater than the free stream Mach number. Additionally, for a given aerofoil section and free stream Mach number the local Mach number varies directly with changes in the angle of attack. Refer to Figure1.6.



- Figure 1-6 Local Velocity Less than Sonic

- ***Critical Mach Number (M_{CRIT}):*** This is the value of the free stream Mach number when the local Mach number first becomes sonic anywhere on an aircraft, which normally initially occurs on the upper surface of an aircraft's wing near to the point of maximum thickness. Refer to Figure 1.7.

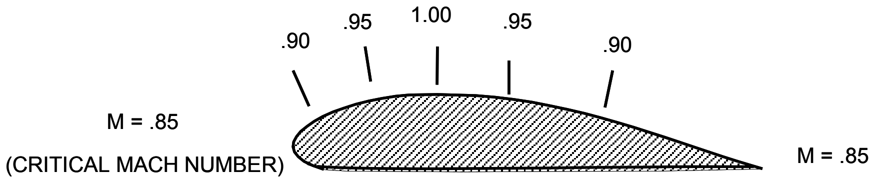


Figure 1-7 Local Velocity Equal to Sonic

FLIGHT SPEED CLASSIFICATIONS

In flight the airspeed of an aircraft determines whether the airflow is travelling subsonic or supersonic around an aircraft. These can be classified as:

- ***Subsonic:*** Aircraft speeds approximately **Mach 0.8 or less**, where the total airflow around an aircraft is travelling at a speed less than the speed of sound.
- ***Transonic:*** Aircraft speeds between **Mach 0.8 and Mach 1.3,** where the airflow around an aircraft is partly subsonic, and partly supersonic.
- ***Supersonic:*** Aircraft speeds between Mach **1.3 and Mach 5.0**, where the total airflow around an aircraft is travelling at a speed greater than the speed of sound.
- ***Hypersonic:*** Aircraft speeds **greater than Mach 5.** Serious skin friction and airframe heating problems occur.

DEVELOPMENT OF SHOCK WAVES

When an aircraft flies through the air every part of it sets up tiny pressure disturbances which radiate outwards at the speed of sound in all directions. This is similar to the ripples produced when a stone is dropped into a pool of water, when the resulting pressure waves travel outwards from the source in expanding spheres, each travelling at the speed of sound Refer to Figure 1.8.

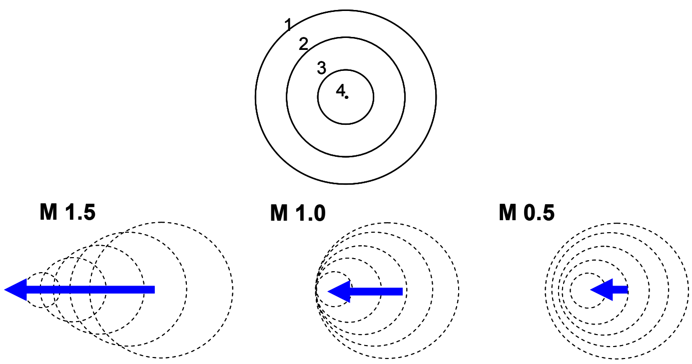


Figure 1-8 Pressure Waves

At low subsonic airspeeds, (Mach 0.6), the disturbances travel forward faster than the oncoming flow. This warns the air ahead of the aircrafts approach. As the air flows over the wing it accelerates, but remains subsonic, and no shock waves exist. Refer to Figure 1.9.

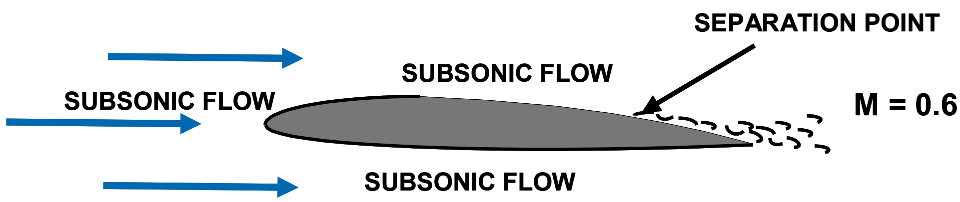


Figure 1-9 Aerofoil Travelling at M 0.6

With an increasing Mach number the flow over the wing continues to accelerate and eventually reaches a sonic value at a particular point on the wing, normally the point of maximum thickness. Refer to Figure 1.10 (Diagram 1.6).

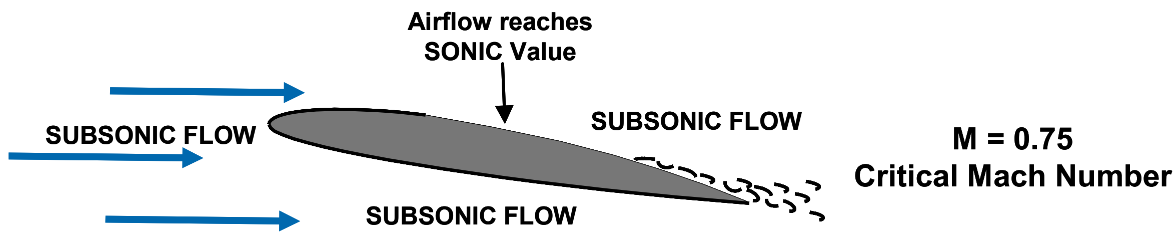


Figure 1-10 Aerofoil Travelling at M 0.75

The aircraft is now travelling at its **critical Mach number** with the airflow either side of this point remaining subsonic.

With increasing Mach number this point grows into an area of supersonic flow, so that the air over the upper surface is now moving rearwards faster than the pressure disturbances can move forwards. The disturbances consequently pile up on each other and form a shock wave. Refer to Figure 1.11.

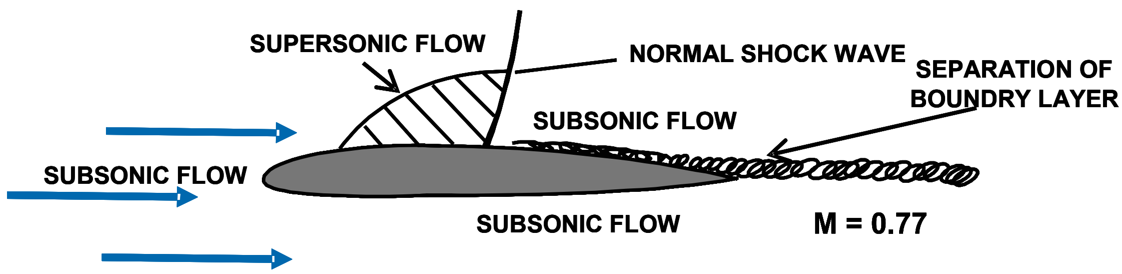


Figure 1-11 Aerofoil Travelling at M 0.77

The shock wave acts perpendicular or normal to the surface, and is more commonly referred to as **normal shock wave.** A normal shock wave has supersonic airflow in front of it and subsonic behind it. With increasing Mach number the shock wave grows in intensity and moves rearwards with a greater portion of the upper surface being covered by supersonic flow. The overall direction of the airflow however remains the same, but as it passes through the shock wave the following changes take place:

- **The flow is rapidly decelerated to a subsonic mach number**
- **The static pressure is substantially increased**
- **The density of the air is suddenly increased**
- **The kinetic energy of the boundary layer is substantially reduced**.

At Mach 0.82 a weak shock wave also forms on the lower surface of the wing. Refer to Figure 1.12.

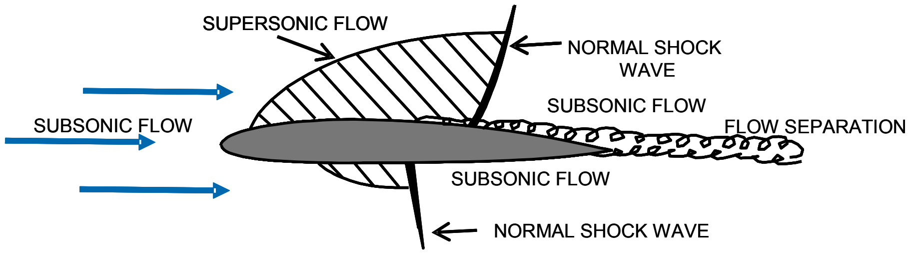


Figure 1-12 Aerofoil Travelling at M 0.82

As the free stream Mach number approaches the speed of sound the areas of supersonic flow continue to grow as both shock waves increase in intensity and move rearwards. Refer to Figure 1.13.

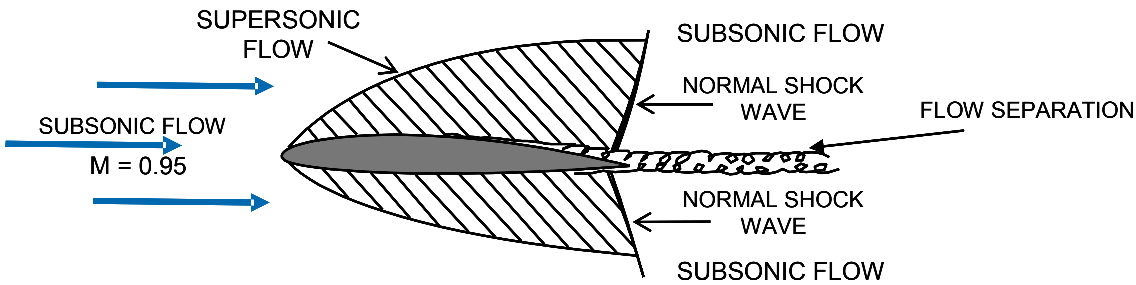


Figure 1-13 Aerofoil Travelling at M 0.95

At speeds just above the speed of sound another shock wave appears ahead of the wing, which is known as a bow wave, and the original shock waves move to the trailing edge. Refer to Figure 1.14.

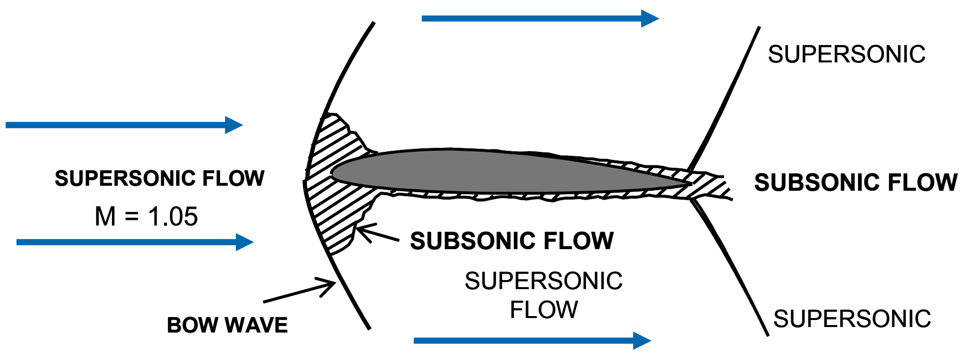


Figure 1-14 Aerofoil Travelling at M 1.05

Behind this shock wave a small region of subsonic flow exists, but everywhere else the flow is supersonic.

Finally when the flow is fully supersonic, fully developed bow and tail waves firmly attach themselves at the leading and trailing edges respectively. These are called ***OBLIQUE SHOCK WAVES***. These have supersonic airflow on both sides. Airflow behind is still slower than in front but still supersonic. Refer to Figure 1-15.

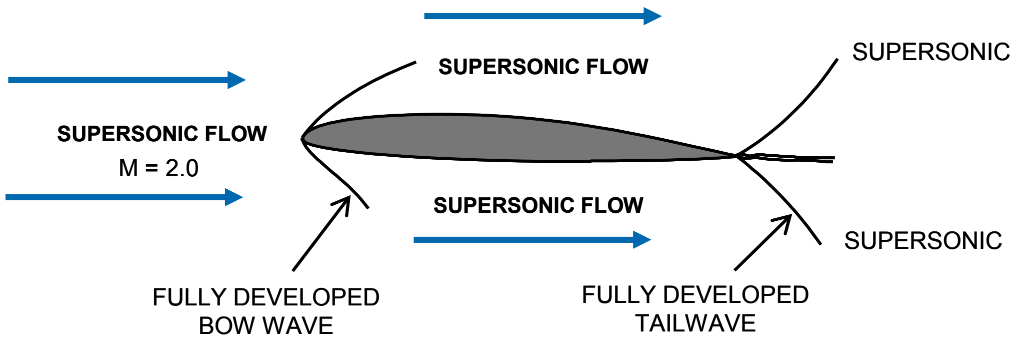


Figure 1-15 Aerofoil Travelling at M 2.0

The Mach number at which this occurs is known as the shock attachment Mach number **(M_{SA}).** This can also be called ***M_{det},*** or shock detachment Mach number.