Shock wave applications

Last time we showed that when gas is compressed at supersonic speeds a thin transition layer is formed. Across this layer the flow of mass, momentum and energy are conserved: the Rankine–Hugoniot equations. Dissipation (collisions) is ultimately responsible for limiting the thickness of this region, and produces the entropy required from conservation laws.

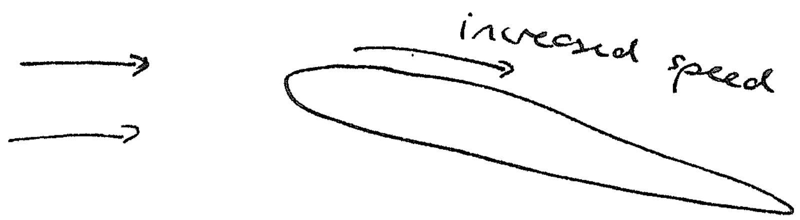
We will look at two applications

1. Supersonic flight

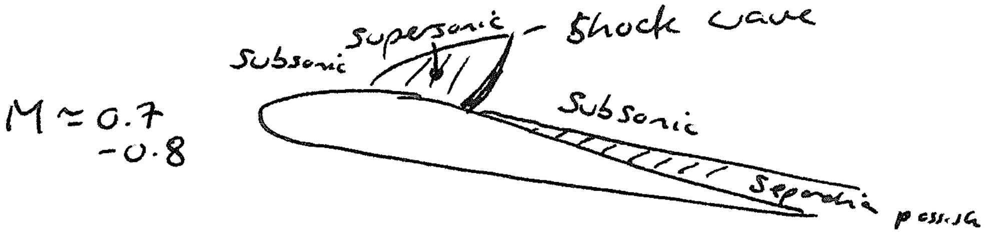
2. Blast waves

Transonic and supersonic flight

In subsonic flight the air flow speed varies around a wing (or cylinder)

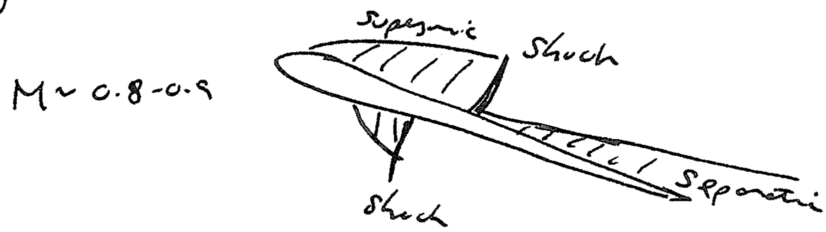


As the speed of airflow increases, the maximum flow speed becomes supersonic before the free stream becomes supersonic.

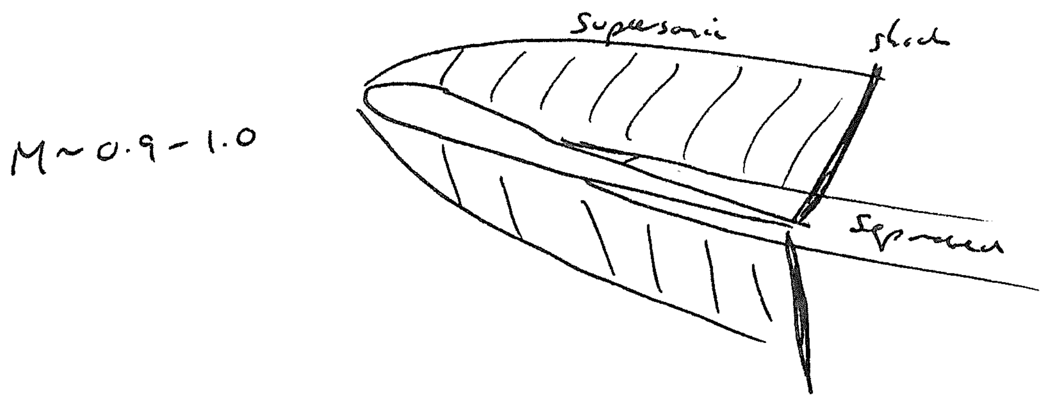


A shock first forms on the top surface where the flow first goes supersonic then slows to subsonic. The jump in pressure across the shock can lead to boundary layer separation

At higher speeds a shock also forms on the lower surface:

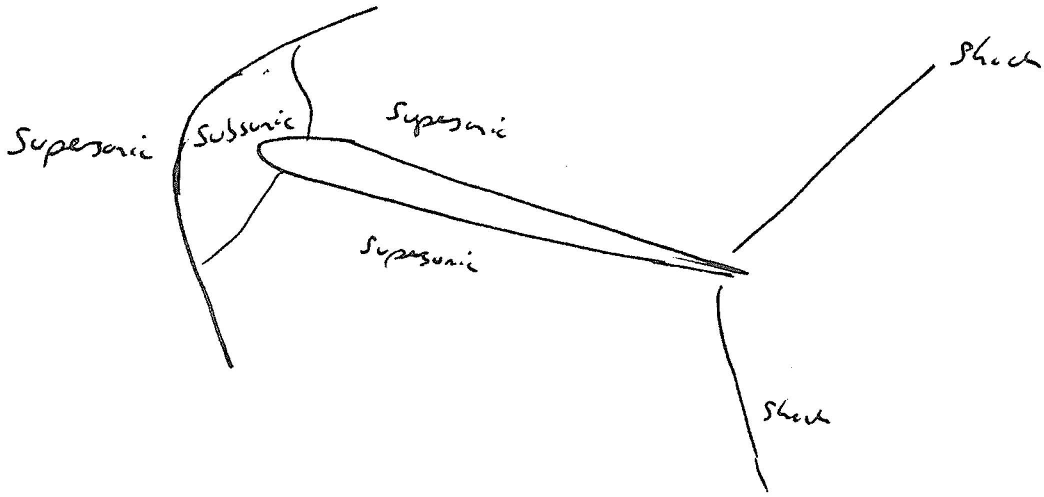


As the speed is increased these shocks move towards the rear of the aerofoil



15.2

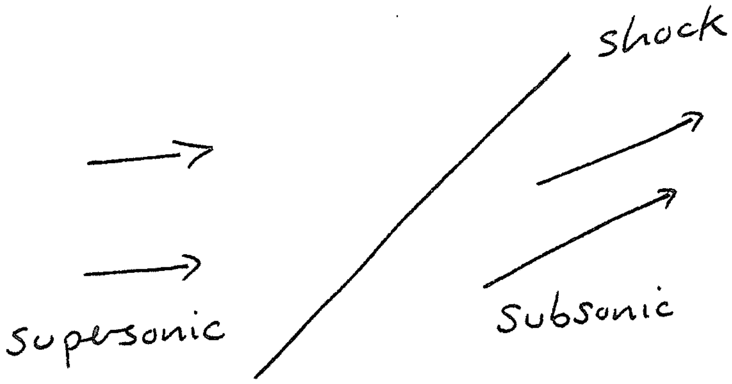
Once the airflow (aircraft speed) exceeds Mach 1 a bow wave forms at the front



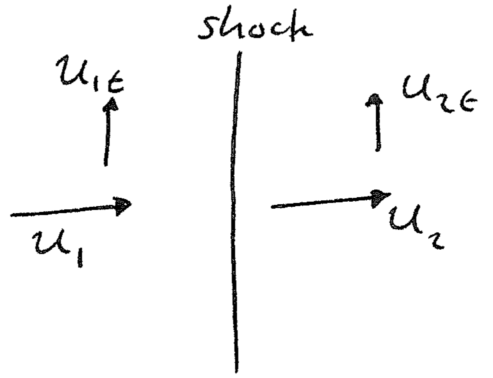
This formation and motion of shock waves around the wing (and body) of aircraft, and the resulting boundary layer separation, resulted in often violent pitching or shaking of early aircraft approaching the speed of sound.

Oblique shocks

Many of the features of transonic or supersonic aircraft can be understood by considering shocks at an angle to the flow



The velocity of the flow can be decomposed into a flow parallel and perpendicular to the shock

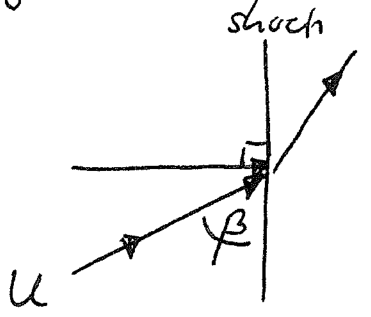


Moving into a frame moving along the shock at speed u_{1t} we can recover a "normal" shock as before.

The velocity along the shock is therefore not affected by the shock: $u_{2t} = u_{1t}$

Since $u_2 < u_1$ the flow is refracted towards the shock.

If the flow makes an angle β to the shock



The velocity into the shock is $u \sin\beta$ and so the effective Mach number of the shock is reduced by a $\sin\beta$ factor

e.g. 30° → Reduces by ×2

The pressure ratio

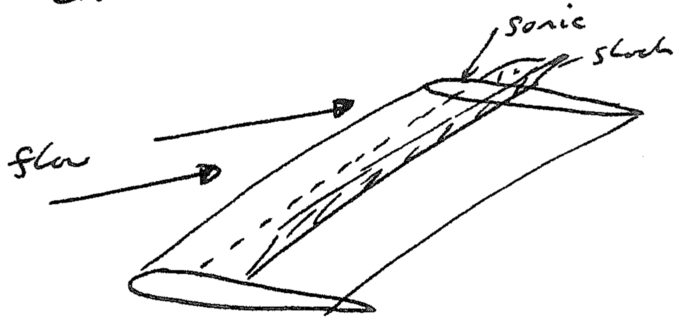
$$\frac{P_2}{P_1} = \frac{2\gamma M_1^2 - \gamma + 1}{\gamma + 1}$$

goes like the square of the Mach number, as does the amount of kinetic energy dissipated as heat in the shock ⟹ Shocks should be as oblique as possible.

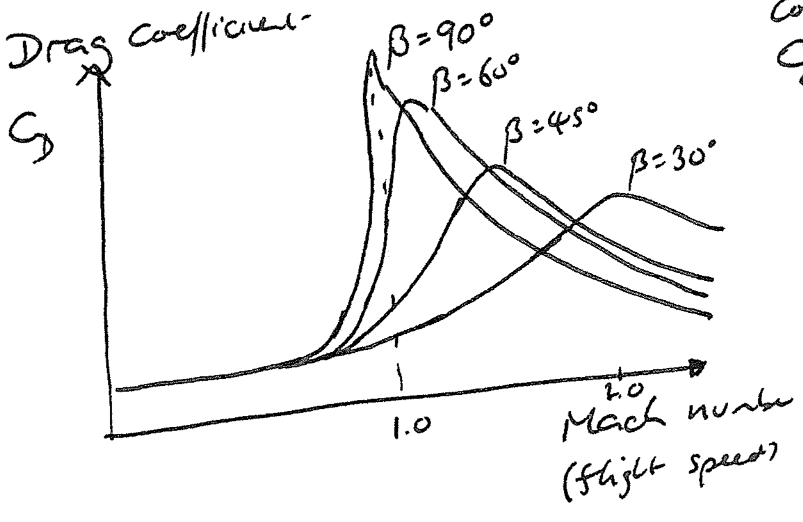
15.3 Trans-sonic aircraft

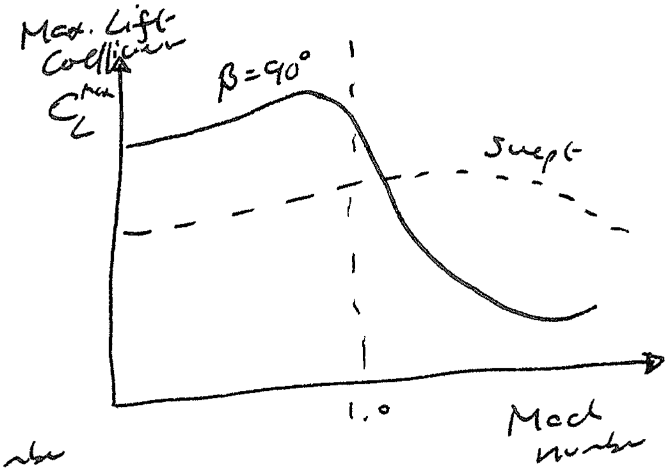
1. Swept-back wings

When shocks start to form on a wing they will do so at the same point along its chord



By changing the angle of the wing with respect to the flow, the formation of these shocks can be delayed, and their effects reduced, because the upstream Mach number across the shock is reduced.

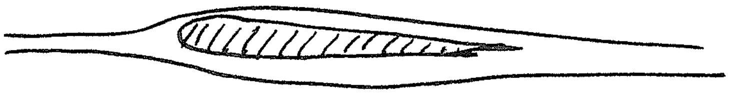




Airliners operate at high (subsonic) speeds in the transonic regime e.g. Airbus A340 has a maximum Mach number of 0.86, so has a 30° sweep ($\beta=60°$) partly to reduce and suppress the formation of shock waves at these high speeds.

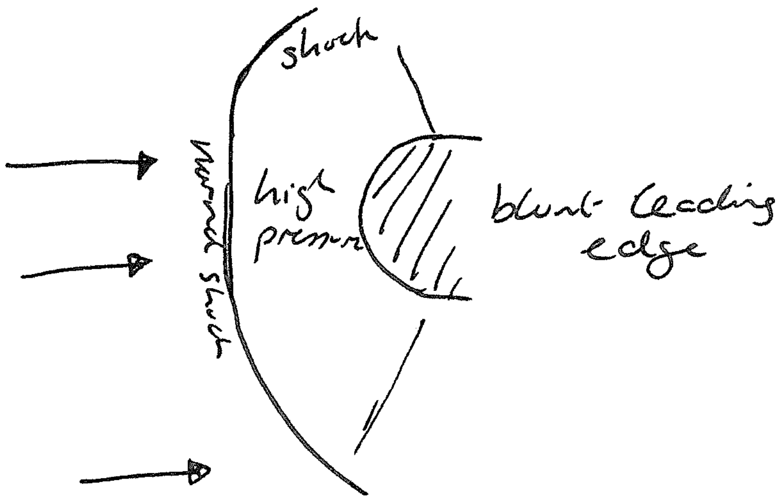
2. Pointed leading edges

For subsonic flows the most streamlined shapes have a blunt leading edge and tapering trailing edge

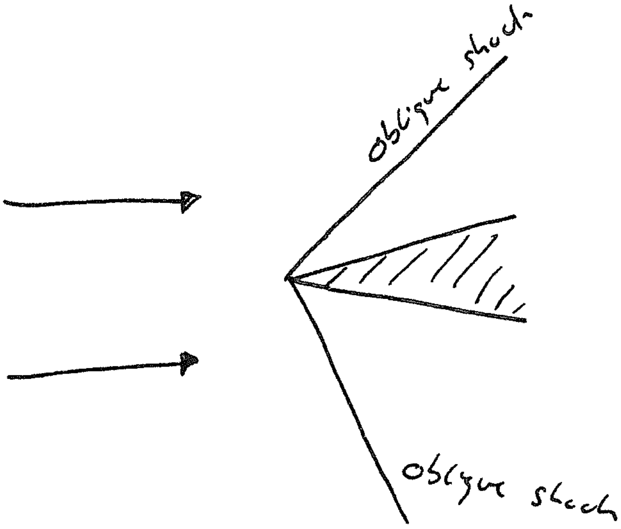


pressure perturbations due to the wing propogate ahead of the wing at the speed of sound, pushing air aside so that a smooth flow occurs.

At supersonic speeds the pressure 'information' cannot propogate ahead of the wing since the wing is moving faster than the speed of sound.



A high pressure region forms in front of the leading edge, created by a normal "bow" shock.



A pointed leading edge leads to the formation of oblique shocks, which dissipate less energy so have lower drag.