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AERODYNAMICS 3

HIGH SPEED FLIGHT

CHAPTER 3 – Supersonic Flight

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INTRODUCTION

We have examined the Transonic Flight region where shock wave troubles are at their worst. We will now look at the much simpler and straight forward supersonic flight range, where the main flow everywhere is supersonic. To understand supersonic flight, it is necessary to examine the nature of supersonic airflow which behaves much more simply than subsonic flow.

Look at a point travelling supersonically. The pressure waves sent out continuously form a MACH CONE. The lines forming it are called mach lines. Refer to Figure 3-1.

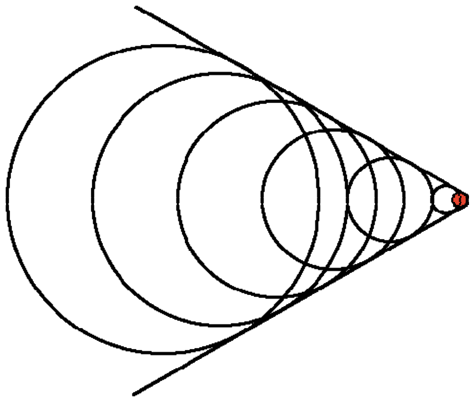


Figure 3-1 Mach Cone and Pressure Waves

The half angle of the cone is called the Mach angle. The size of this angle is the ratio of the forward speed to the speed of sound. If we place 1 over the Sine of the Mach angle we get the speed of the object. As the Mach number is increased the Mach angle grows smaller.

At Mach 1 the Mach angle is 90 degrees. So 30 degrees is 1/ Sin 30 degrees .which equals Mach 2.

A similar effect can be seen by driving a boat faster than the speed of the waves. Only the region inside the wave is influenced by the boat. The water outside this region is undisturbed. Refer to Figure 3-2.

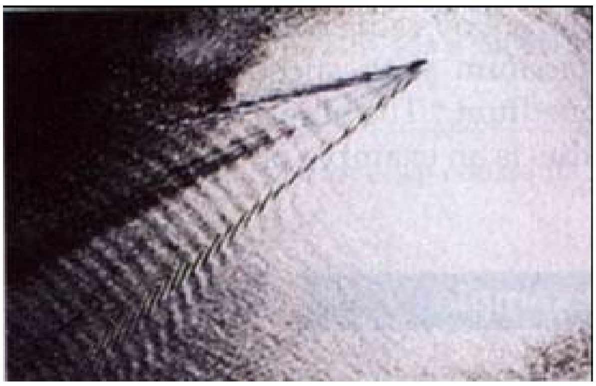


Figure 3-2 Mach bow waves from a boat

In the same way the supersonic point can only affect the air inside the Mach lines. Ahead of the Mach lines the air is undisturbed.

SONIC BOOM

This shock wave will also be heard on the ground as a sonic boom. Anyone inside this Mach cone will hear a loud “boom, boom” as the shock waves pass by them at the speed of the generating aircraft. Refer to Figure 3-3. At low level they are sufficient to shatter windows. It does pose an environmental issue in regards noise pollution.

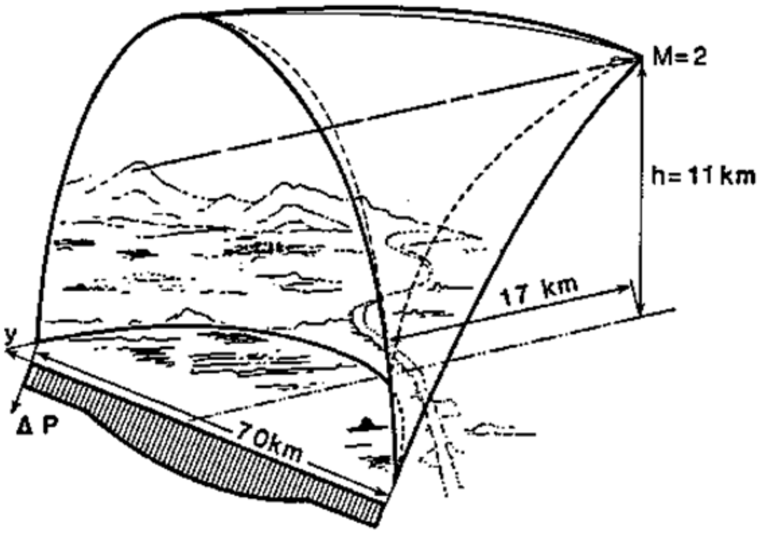
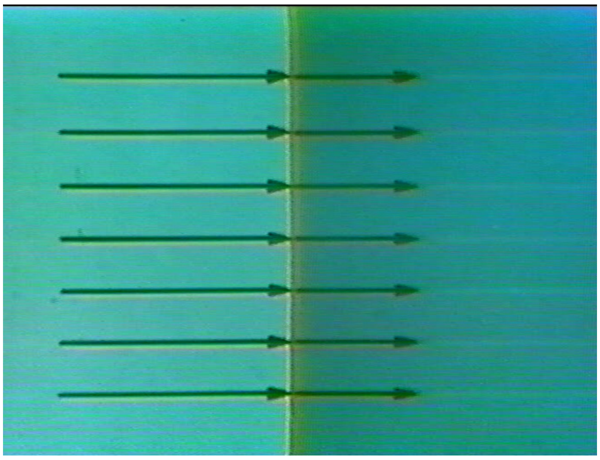


Figure 3-3 Sonic Boom

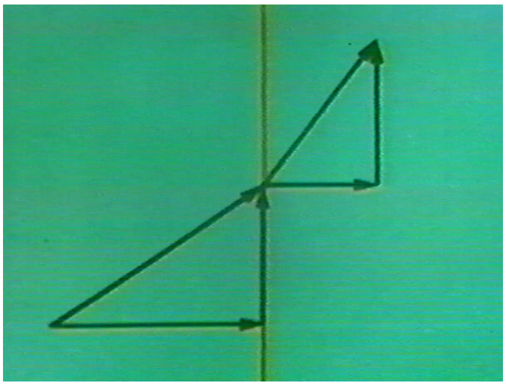
OBLIQUE SHOCKWAVES

If a large disturbance is formed, such as the leading edge of a supersonic wing, an **oblique shock wave** is formed. How does the flow behave as it passes through such a shock wave?

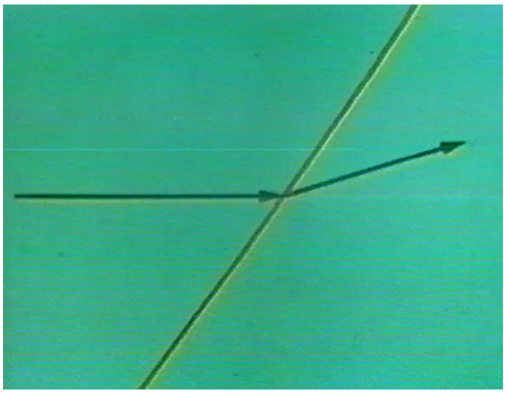


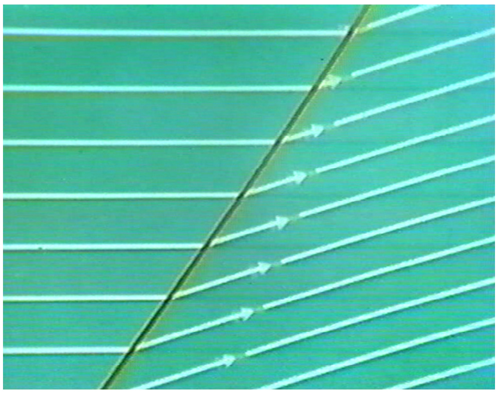
If we look again at a normal shock wave, we see that it always slows the airflow from supersonic down to subsonic. The speed is represented by the length of the arrows.

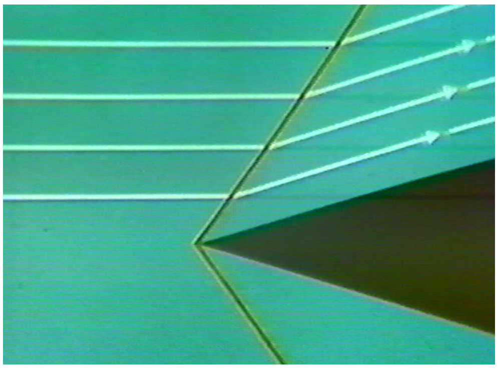
As speed increases, the Mach angle gets smaller and the shock wave leans back. There is now a uniform sideways movement imposed on the shock wave, which is not affected by the shock wave and it the same on both sides of it. So as the speed of the flow reduces, the sideways force causes the airflow to change direction slightly.



The shock wave is now **oblique** to the airflow and has slowed the airflow down and deflected it slightly. Pressure always increases when velocity is lower. If streamlines are drawn, they are closer together behind the shock wave than in front of them.







This is called a **compression wave** and allows the supersonic flow to follow the new surface with ease.

This supersonic wing section has another kind of sharp corner. This is called a double wedge. Refer to Figure 3-4.It can only be used on a supersonic flying machine such as a missile or a rocket as airflow would separate over it subsonically, so sharp corners are avoided on subsonic aircraft. Refer to Figure 3-5.

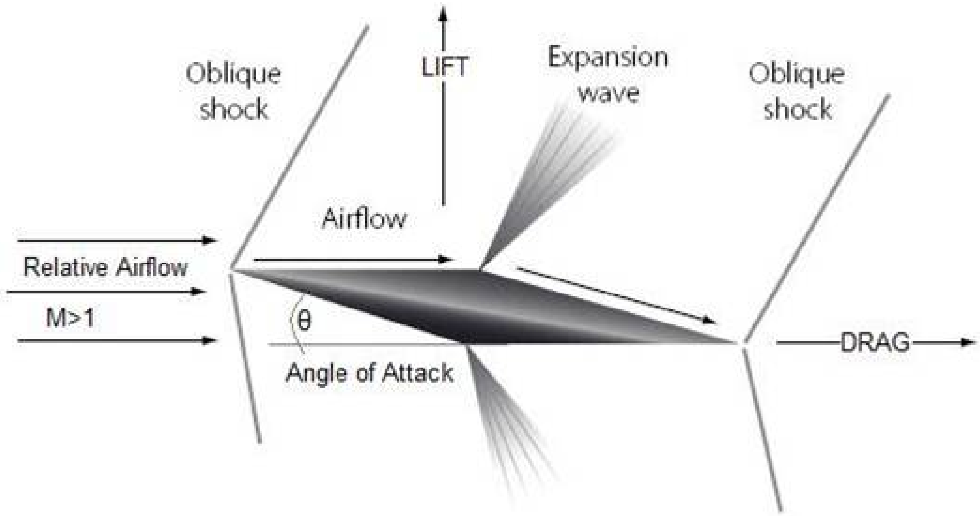


Figure 3-4 Double wedge wing

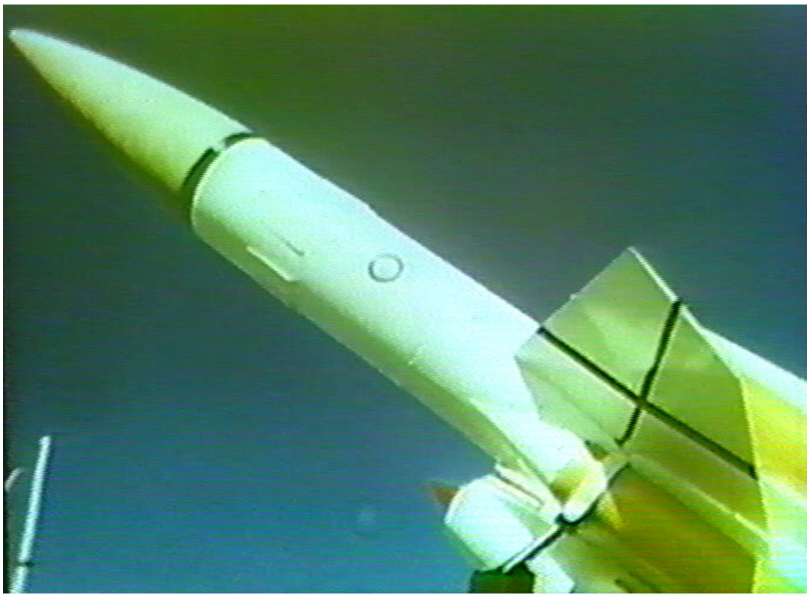


Figure 3-5 Double wedge wing section on a Bloodhound Missile

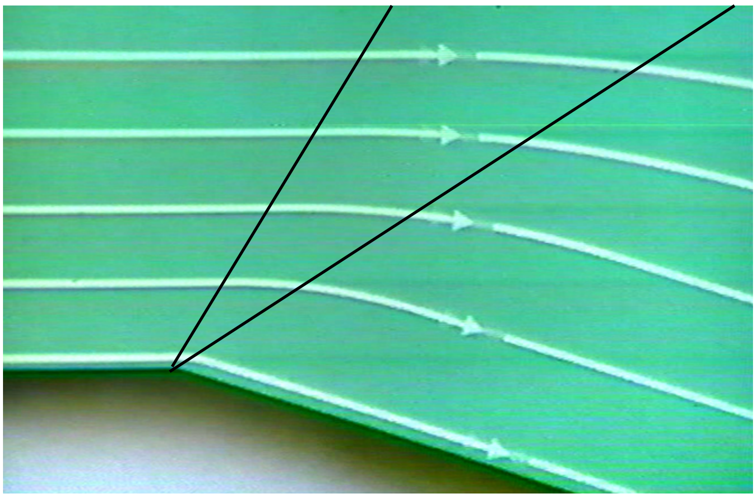


Figure 3-6 Expansion Wave

Here the opposite happens. The streamlines move further apart and are speeded up. This is called an **expansion wave** and is caused by the air being deflected as they reach the Mach lines caused by the sharp corner. Refer to Figure 3-6 above. The angle depends on the speed. They bend slightly and follow the new surface with relative ease. An expansion can be looked on as a series of tiny changes in direction pressure and speed. The expansion finishes at the Mach angle corresponding to the final direction and speed of the flow. So it is confined to a fan shaped region between the first and last Mach lines. Inside this area, direction, speed and pressure change smoothly, unlike the previous shock wave where the change of direction is sudden. In either case the supersonic airflow follows the new surface with little disturbance. So as we can see, supersonic airflow behaves much more simply and smoothly.

As stated before, this wing section could not be used on a subsonic aircraft, so a Bi convex section is used as shown below. Refer to Figure 3-7.

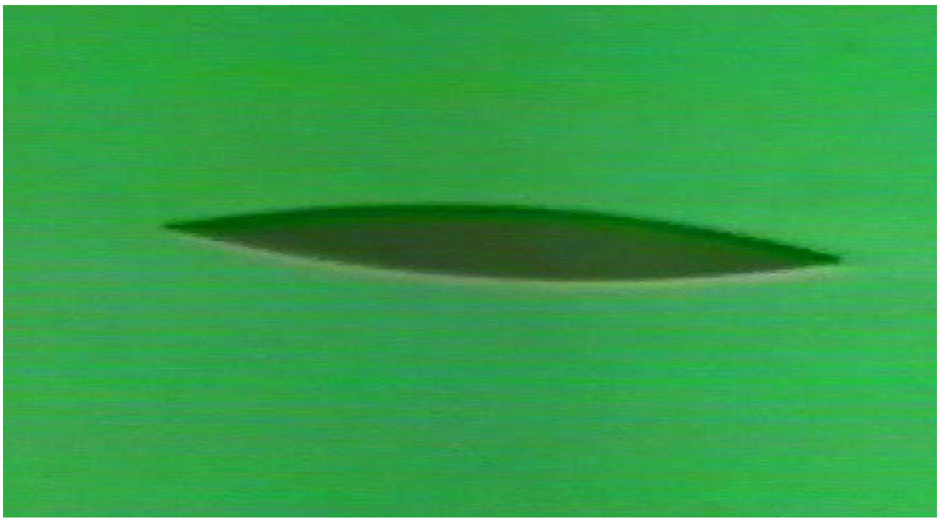


Figure 3-7 Bi Convex Aerofoil

The Bi Convex section will give a similar CL and drag to the double wedge aerofoil but is suitable for subsonic flight. Refer to Figure 3-8.

Both of these sections shown apply to straight wings without sweepback. They must therefore have sharp leading edges and thin sections which seriously affect the low speed characteristics of the wing.

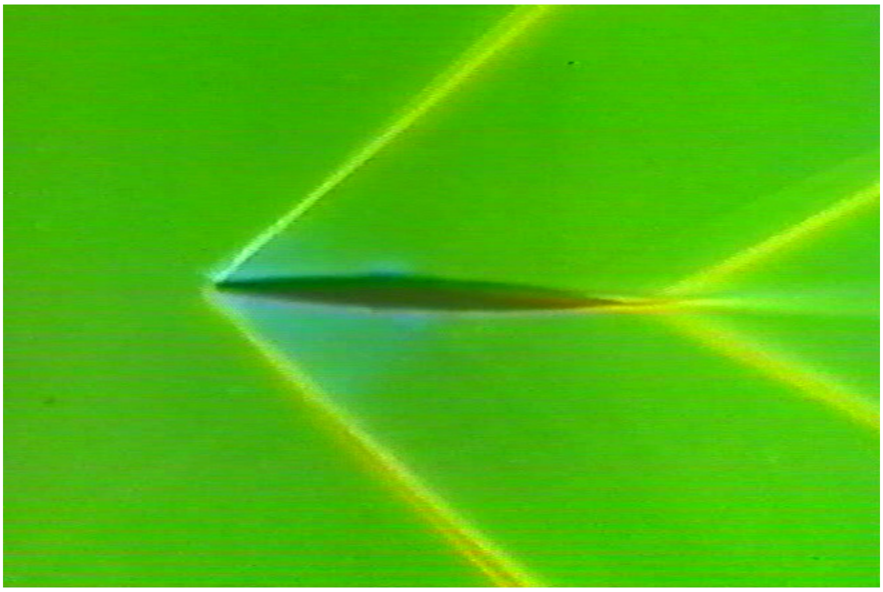


Figure 3-8 Bi Convex section at Mach 1.8

Imagine the Mach line originating at the wing root of a straight wing. The air in front of the Oblique shock wave has no notice of the wings approach. It must therefore have a sharp leading edge. Refer to Figure 3-9.

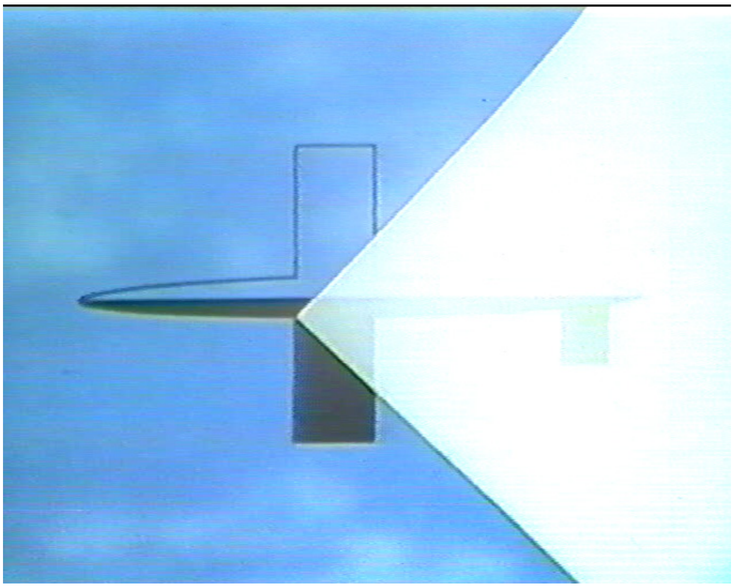


Figure 3-9 Straight wing Mach line

What if we sweep the wing back so that it lies within the Mach lines? Refer to Figure3-10. The air ahead of the wing now has warning of the wings approach, so it behaves as if it was subsonic so it can therefore have a subsonic section. The wing can have a thicker section and a relatively blunt leading edge. This solves some of our low speed handling and structural strength problems. Leading edge slats and flaps and other high lift devices help even more.

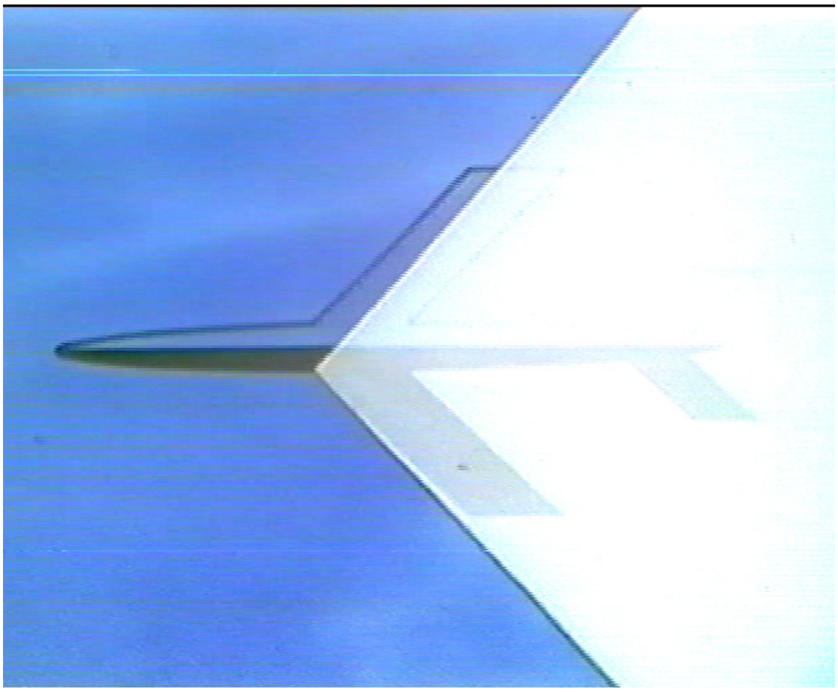


Figure 3-10 Swept wing Mach line

SUPERSONIC DESIGN

How does this affect the actual design of a supersonic aircraft? The higher the speed an aircraft is designed to fly, the more highly swept it must be so that the wing leading edge remains inside the Mach lines. But there are limits beyond which the aircraft becomes difficult to handle both at low speed and supersonic speeds. The choices are:

- ***Straight wings*** are usually short and of low aspect ratio for sufficient strength. Most modern fighters are like this now; or
- ***Highly swept or delta wings.***

What decides the plan form for a particular supersonic aircraft? It's a compromise between many factors, an important one of which is transonic and supersonic drag.

Refer to the following diagram, Figure 3-11.Take a delta shape and plot its drag against Mach number. A swept plan form will give a similar curve. A straight wing giving a similar landing speed will give a different curve.

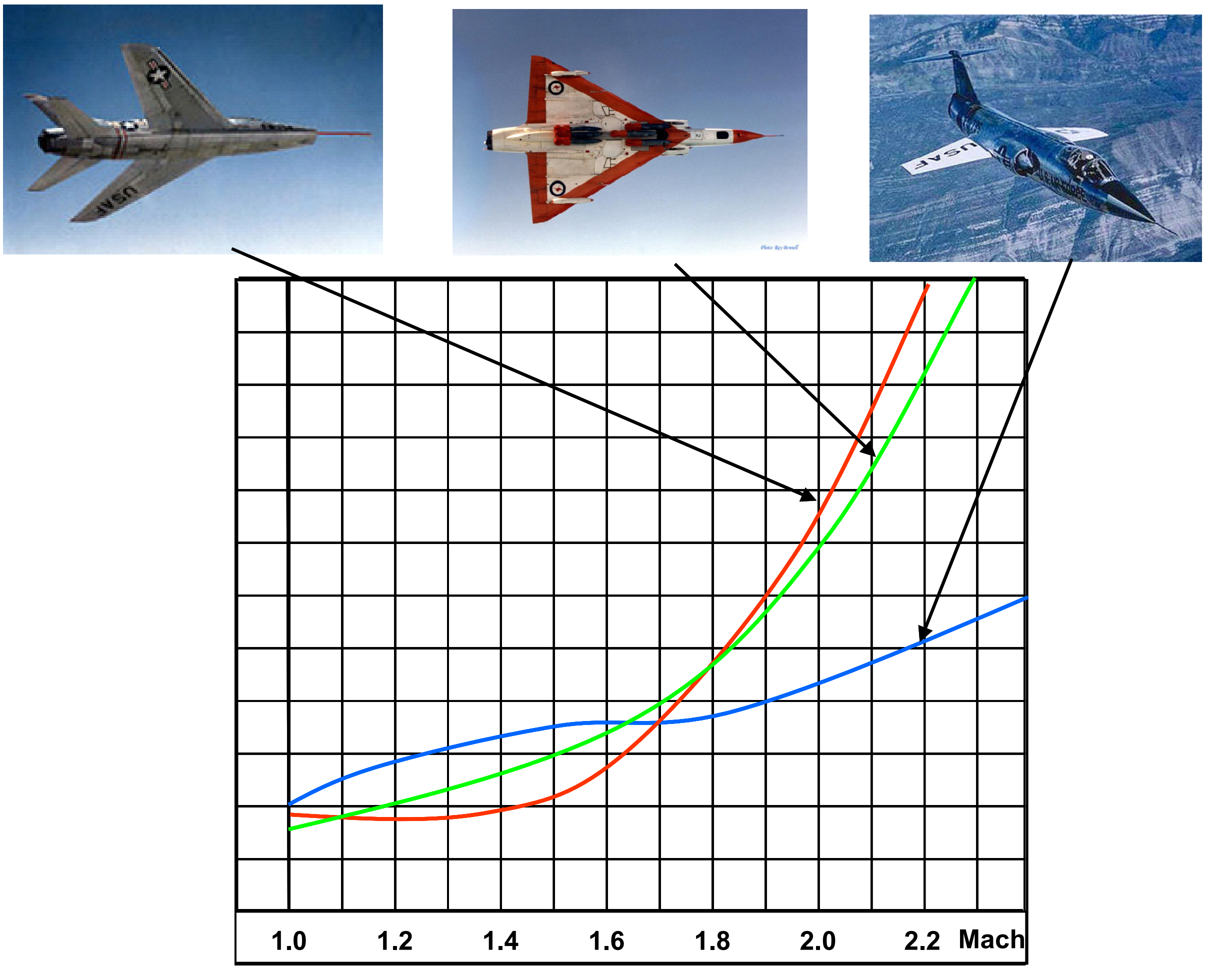


Figure 3-11 Plan form V_S Drag

The straight wing gives less drag at the higher Mach numbers than the delta or swept.
It appears that below Mach 2 the advantage lies with the **highly swept.**
The drag can be reduced still further by sweeping the wings even more provided that the low speed problems can be overcome.
This certainly was achieved by some notable aircraft such as the SR71 Blackbird and the Concorde. Synthetic stability played a large part in this as well as clever design and increasing knowledge of supersonic flight.

The SR-71 Blackbird is one of history's great aircraft. It was built during the Cold War in the early 1960s by Lockheed at its secret Skunk Works facility and flew from 1966 to 1998. With black paint covering its titanium fuselage, it was designed as a reconnaissance platform capable of flying 2,900 nautical miles (5,400 km) at sustained supersonic speeds at an altitude of 80,000 ft (24,000 m). The Blackbird could fly so fast and so high that it could literally outrun enemy missiles, and routinely did.

BAC Concorde is a turbojet-powered supersonic passenger airliner that was in service from 1976 to 2003. It is one of only two supersonic transports to have entered commercial service; the other was the Tupolev Tu-144. Concorde was jointly developed and produced by Aérospatiale and the British Aircraft Corporation (BAC) under an Anglo-French treaty. It featured a maximum speed of Mach 2.04 with seating for 92 to 128 passengers. First flown in 1969, Concorde entered service in 1976 and continued commercial flights for 27 years.

BUFFET BOUNDARIES

Any altitude increase reduces available turbine engine thrust while increasing compressibility and density correction; in turn increasing the minimum EAS and TAS for sustainable level flight. The altitude increase means that sonic speed (TAS) reduces with the lower temperatures, reducing the M_{crit} TAS. Higher density correction means that M_{crit} (already occurring at a lower TAS), occurs at a much lower EAS / CAS / IAS. Refer to Figures 3-12 and 3-13.

Operating at a higher flight level would reduce the mass for no safe speed envelope availability, hence the term, **"Coffin Corner".**

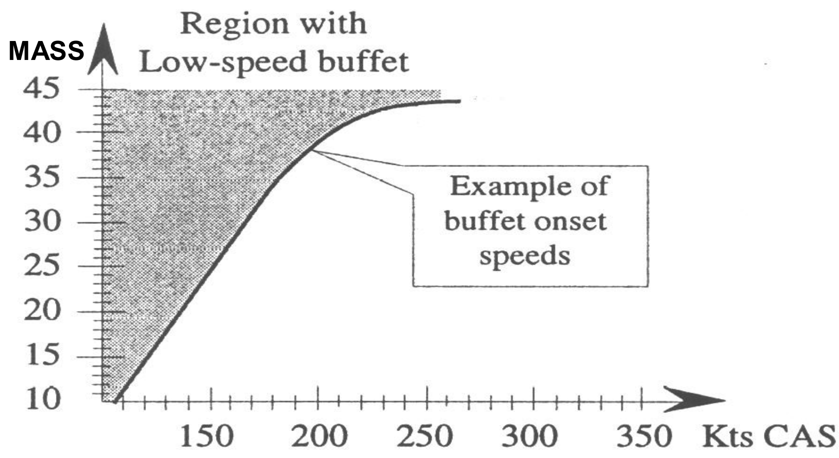


Figure 3-12 Low speed buffet

Stall speed EAS is proportional to the square root of the wing loading (weight / wing area). A mass increase will increase the stalling CAS/IAS to an even higher value.

Stall speed EAS is also proportional to the square root of the load factor N (lift / weight), but the diagram deals only with wings level (and N=1) flight.

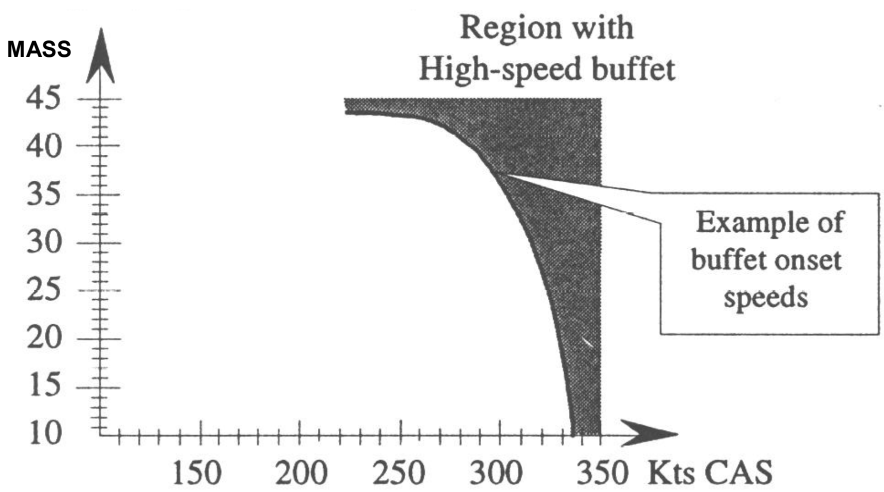


Figure 3-12 High speed buffet

An increase in aircraft mass or load factor means that at any given CAS or Mach number, a greater CL is required.

This means a higher mass or load factor (N) requires a greater angle of attack for any given CAS or Mach number.

The effect is that **HIGHER AIRCRAFT MASS OR LOAD FACTOR results in LOWER M_{crit}.**

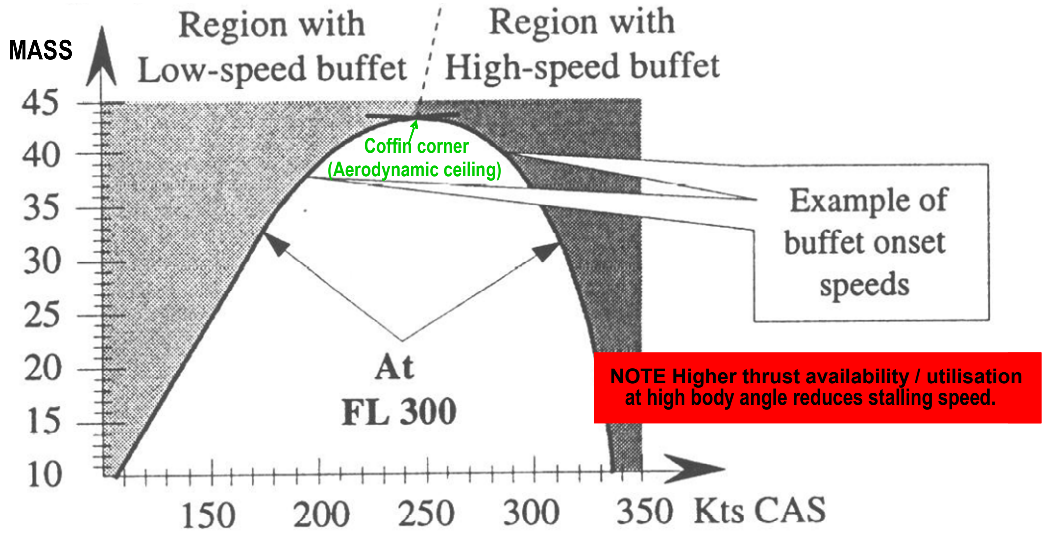


Figure 3-13 Coffin Corner

Figure 3-13 above, simplifies the issue by showing the speed envelope becoming narrower at a constant flight level (FL300) but with increasing aircraft mass. The safe speed envelope is reduced to zero at slightly less than 44 tonnes.

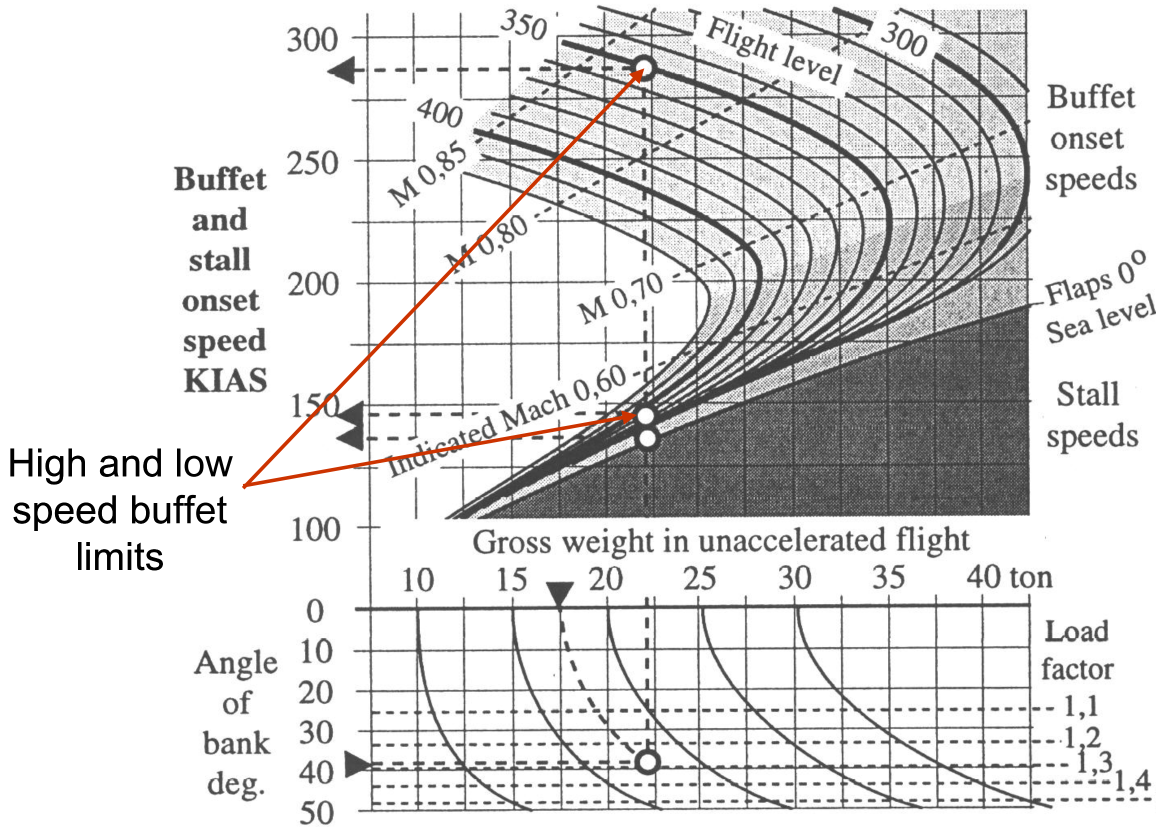


Figure 3-14 Onset of buffet and stall

In Figure 3-14, we can see that for this particular aircraft with a **mass of 17.5 tonnes and at FL 350 ,it** has a **High speed buffet limit of 283 kts IAS /Mach 0.83** and a **low speed buffet limit of 148 kts IAS** and a stall speed of 135 Kts IAS with no flap at sea level. It also shows that the maximum bank angle that can be used with a safety buffer of 1.3 load factor is 40 degrees. As mass or altitude increases, these will be closer together. So a high speed aircraft will be limited in its speed by high speed buffet.

THE FUTURE?

What does the future hold for Supersonic air travel? There are designs on the board for Mach 3 plus air travel. This will significantly shorten travel times over huge distances. We shall see what unfolds. I can't wait!

A Hypersonic airliner

Something completely different…

An interesting achievement was getting a car to go supersonic. This was achieved in October 1997 by Englishman Richard Noble's Thrust SSC. The close proximity of the ground and the complications arising from this in regards shock wave formation made this a difficult achievement.

Here is Thrust SSC doing about **Mach 1.05** or about **800 mph or 1286 kmh!** Note the normal shock wave forming at the front of the car and raising the dust from the desert floor. They are now trying to break the 1,000 miles per hour barrier!

Thrust SSC

The end...or is it?