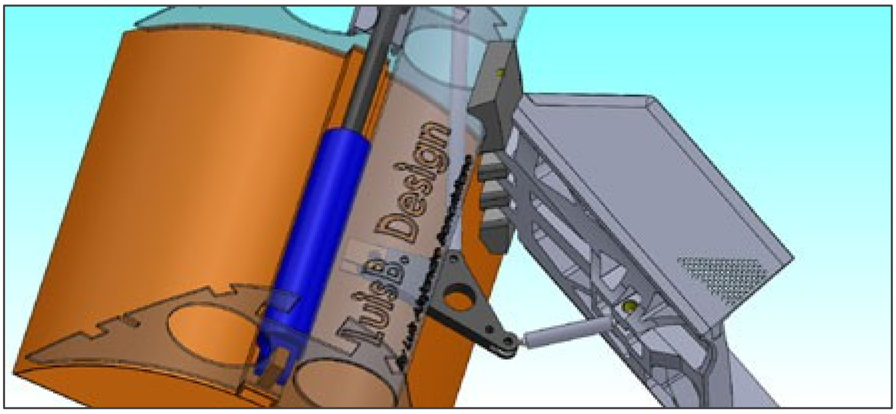
Aussie Invader Airbrake Design by Paul Martin

When I design anything, my first step is to create a succinct reference. At the most elementary level, it is the answer to the question, *"What is the goal?"* So, in relation to the Aussie Invader airbrakes, I asked the question, "What do the airbrakes have to do?" The answer is of course, *"To provide a means to decelerate the vehicle from 1000 mph rapidly in a controlled manner."*



Current Aussie Invader Airbrake - Engineered by Paul Martin, 3D Drawing by Luis Boncristiano

This retardation can best be achieved by creating a drag force that resists the direction of forward movement of the car. Aerodynamic drag is due firstly to the creation of a high-pressure region on the oncoming face of the airbrake. This is the side one would see if you stood next to the nose and looked rearward. Secondly, drag is enhanced by creating a low-pressure region on the trailing face of the airbrake. Thirdly, significant wave drag is accrued when the airbrakes are deployed supersonically.

Good engineering may be best described as "the ability to optimise compromises". The airbrakes on the Aussie Invader are a good example of this maxim. For example, for packaging reasons, the Invader's airbrakes are limited to having a 650mm long chord with a 440mm wide span. The result is an aspect ratio (span to chord ratio) of 0.68 which is very low. *[Aspect ratio is defined for a rectangular planform as the ratio of span to chord. It is a measure of how efficient or 2-Dimensional the flow is over the wing (or plate)].* Unfortunately, stubby plates or wings are not as efficient at creating the desired forces as their higher aspect ratio counterparts. Thus, it is a significant challenge to generate large amounts of drag from relatively small plates or wings.

The airbrakes resemble flat plates and therefore wing section theory does not strictly transfer to this situation. Most wing aerodynamics focuses upon the flight envelope or angles of attack up to the point of stall. Aerodynamic stall is when the air on the lower pressure side of the airfoil (usually the upper surface) separates causing loss of lift and large drag forces. Stall is something to avoid when flying an aircraft. However, high angles of attack as found on the Invader's airbrakes at large angles of opening generate much needed aerodynamic drag to slow the rocket vehicle. Because of this large angle of attack and the proximity of the airbrake to the vehicle's main chassis tube, the airbrake design work was principally focused upon the pressure side of the plate and the optimisation of the resultant drag force (Figure 1 & Figure 2).

The Aussie Invader's airbrakes also have to operate at transonic speeds, hence, it is fair to say that the technology is being pushed to the limit, and as such, the supersonic and subsonic aerodynamic characteristics of a short span have to be investigated and predicted. With these factors in mind, the key focus of the body of engineering work was to find a solution that would enhance the performance of the basic shape to achieve the desired retardation.

Why did the design end up with endplates?

To make the airbrakes work well, the aim is to maximise the energy and subsequent work that may be extracted from the air. That means that when the airbrakes are deployed, they must capture as much air mass as possible and "encourage" that mass of air to travel the full length of the end plate without spilling over the sides. At subsonic speeds, the air flow around a very low aspect ratio wing or plate (without end-plates) is very much 3 dimensional. Specifically, the air flow wants to spill over the sides and in the case where the chord is significantly longer than the span, the air spillage becomes so great that little of the rear of the wing or plate contributes to lift. Though the airflow is virtually longitudinal (2-Dimensional) along the centre line of the wing, the adverse pressure gradient at the outboard tips of the wings, encourages a significant span-wise flow on the underneath or pressure surface side of the wings. This air tends to flow longitudinally to the wing tips rather than from the leading edge to the trailing edge of the wing. The interaction of top and bottom of span wise airflows results in a strong wing tip or plate edge vortex. Unfortunately, such tip vortices reduce the effective wing span and the subsequent working area of the plate (Figure 3).

At supersonic speeds, the usual aerodynamic benefits are again reduced due to the very low aspect ratio because the leading edge tips of the airbrake create a shockwave. As the air-flow slows down past the shockwave and changes direction as it meets a surface, there is a reduction in velocity from sonic to subsonic speed. The change in air velocity forms a cone-like shape known as a Mach cone Figure 4. Outside the Mach cone, the airflow is almost 2-Dimensional, and it almost behaves as if the airbrake was of infinite length. However, within the Mach cone, the flow is very much 3-Dimensional. The flow is subsonic because there is plenty of forewarning*. Fluids flow from a high-pressure region to a lower one if they are free to do so. So the air flows from the bottom surface to the top surface because an inclined plane creates such a pressure gradient (Figure 5), and the result is a vortex which reduces the normal force value.

**The reason for the difference inside and outside the Mach cone is due to the way energy is propagated. When the air is travelling faster than the speed of sound, the neighbouring and upstream particles of air get no notice of what is to happen downstream. This is because most of the energy in a moving fluid is transmitted via sound waves, so the limiting speed becomes the local speed of sound. If the local velocity is greater than the speed of sound (>Mach 1.0), the "notice" lags and the air particle does not have time to do much before its hit whatever it was in the way. It is analogous to seeing lightning and the lag in hearing the thunder. Air that travels faster than sound simply doesn't get any prior warning of what is to happen so the air tends to flow longitudinally (2-D).*

One way to recover the losses associated with 3-Dimensional flow is to seek ways to make the flow more 2-Dimensional in its behaviour. This can be done by creating a physical barrier such as the addition of end-plates to aerofoils. The region of influence of the end-plate is restricted to that within the Mach cone (Figure 4). There is a small range of aspect ratios where endplates have significant benefits. Fortunately, the Invader's end-plates fall into that bandwidth. Outside that range, the benefits are marginal, and the operating envelope and cruise drag requirements do not justify the fitment of end plates. However, there are still many supersonic aircraft that employ devices to restrict the span-wise flow (Figure 6) but not to the extent of end-plates. What is useful to a project such as this is that there is a considerable amount of high-quality test data available from pioneering work done by NACA in the 1950's on supersonic aircraft. Such historical data was used to verify the Invader's drag performance (Figure 7). Figure 8 shows the lift curve slope of the delta wing model shown in Figure 7 both with and without end-plates. Note the difference in lift curve performance with and without end plates.

On short wings and plates in supersonic flow, the tip of the Mach cones overlap each other, whereas, in a 2-Dimensional case, the lift would be uniform over the entire span Figure 9. I stated earlier about much of the trailing region of the chord being ineffective. The Busemann model shows the extent of how little it would contribute without end-plates. Almost the Invader's entire airbrake surface is affected by 3-Dimensional flow. In terms of *"bang for one's buck"*, adding end plates to the Invader's airbrakes would make a significant performance improvement. The current air brake end plate design confers an approximately 4**0% increase in aero drag over non end plate designs**.

The end plates are bolted on, so that efficiencies greater than 50%, up to approximately 80% can be accrued by bolting on end plates with greater area. The current end plate height was selected to ensure that most of the end plate is contained within the boundary layer of the vehicle, thus a minimal amount of drag is present when the air brake is stowed.

In addition to generating a decelerating force through aerodynamic means, the design needs to consider structural issues such as stiffness and strength. The air brake assembly's stiffness is of particular interest, especially when it is linked with the mass of the structure, as the stiffness of the air brake dictates its frequency of vibration. Natural frequencies are the frequencies that any object prefers to vibrate at, given a chance. An analogy can be made when pushing a swing. If the "push" cadence is in time with the swing's travel, the structure resonates. That is, the swing/wing is excited and caused to swing to a higher amplitude. Conversely, when the "push" is out of synch with the motion of the swing, the swing slows down or stops. If the natural frequency of one element of the structure excites another structure on the vehicle, failure may ensue. Aero Engineers call this "flutter" or "divergence" and hence, they take great pains to avoid it. The engineering challenge is to minimise antagonistic frequencies within a system. The minimisation or randomisation of air shedding vortices from wing tips is a good example of this.

In addition to not having dangerous resonant frequencies, the air brake structure needs to be strong. The airbrakes have an operating range of 0 to 60 degrees - the magnitude of their deflection of course depends upon the desired vehicle deceleration. This is a tough operating load range, especially given that the aero loads generally increase as a square function of vehicle speed.

Because suitable record run venues are limited as peak velocities increase, vehicle acceleration and deceleration rates have becomes far more critical than they were in the past. Ultimately, the track length will be the limiting variable for future LSR attempts. The engineering challenge is to optimise the overall vehicle acceleration and top speed and brake the vehicle smoothly. This demands the timely and smooth deployment of airbrakes, parachutes and wheel brakes. The maximum designed retardation force of the total airbrake system was calculated to be 132.6kN - that's **13.5 tonnes force**!. This retarding force equates to a potential deceleration of around **2.5 g**. See the magnitude of the forces involved as the airbrakes are deployed in Figure 10.

Like most complex structures, the design case is an iterative process and as future elements of the car are completed, it may be necessary to revisit previously completed structures and retune them to optimise vehicle performance. As a starting point, the natural frequency of the endplates were designed to be above 150Hz. This put excitation frequencies far outside the range of calculated natural frequencies for the Invader's tailplane and tailfin.

In terms of deflection, if the air brake end plate vibrated at a natural frequency of 150Hz, this translates into an approximately 13mm deflection at the plate ends. Further, because of the regular sectional shape and the fact that the material being used is isotropic, this maximum bending also corresponded to a minimum sectional torsional stiffness. The minimum torsional stiffness set the lowest expected divergence velocity at 514m/s which is 1.15 x maximum vehicle velocity. Ultimately, the final solution was around 6 to 7mm at the maximum displacement point near the rear tip region (Figure 11 & Figure 12). The intended material for the end plates is 7075 –T6. For the record, when all of the variables including material, section and hole spacing is considered, the overall end plate structures is designed to have a working factor of safety of 2. (Figure 13).

The detailed end-plate shape, see Figure 14 & Figure 15.

The form of the end plate is a cropped delta when viewed from the side. It is known that any abrupt change in shape is likely to cause a shockwave as air passes over it. Hence, it was most important to ensure that any generated shock waves were firstly weak and secondly, the part of the car which caused the shock wave must have minimal drag when the air brake was stowed, but maximum drag when deployed. To this end, the leading edge of the air brake is angled so that at Mach 1.3, the leading edge of the end plate would still be behind the shock cone created by the physical existence of the end-plates as they protrude into the free stream air (Figure 16).

The goal is to have the end-plate leading edge subsonic so that the drag in the stowed position is kept to a minimum. When the airbrake is initially deployed to 15 degrees, the leading edge should pass through this shockwave which guarantees that the end plate is operating in clean supersonic air which causes a steep rise in drag.

Shockwave prediction is mathematically complex, especially when the shock wave becomes detached from the vehicle’s surface. Preliminary calculations show that the shock wave should remain attached at up to at least 6 degrees of airbrake deflection, but will move forward when detached. By allowing a 5-degree margin between the angle of the leading edge and the shockwave, this gives the driver leeway if the vehicle yaws excessively. This in theory negates the possibility of the driver having to contend with asymmetrical drag due to one of the airbrake's leading edge being supersonic and the other subsonic.

More discussion on the end plates is warranted. The chamfer on the leading edge and the sides of the plates are asymmetric and have two purposes. Firstly, the chamfers recover energy making the flat endplates behave more like winglets but without the restriction they impose by not being adjustable. This is further explained when the Gurney Flap is discussed. The second reason for the chamfer is to encourage a strong and stable vortex when the airbrakes are deployed.

Delta wings have a unique characteristic in that their shape encourages stable and predictable tip vortices and that vortices enhance lift as the angle of attack is increased (Figure 17 & Figure 18). Unless the end-plates were infinitely high, there would always be a degree of leakage around the tips. Hence, the “trick” is to use the energy in the movement of air to yield an advantage. The sharp trailing edge of the end plate recovers energy as it takes the air flowing over the edge and abruptly trips it and turns it into a vortex. This causes a drop in pressure on the reverse side of the end plate and increases the effectiveness of the air brake.

The Gurney flap

The purpose is to maintain air stream attachment of the low-pressure side of an inclined plate or airfoil at high angle of attack (Figure 19 & Figure 20). It's known as the Kutta condition. In the Invader's case, the initial configuration is below the thickness of the boundary layer, so this minimises the drag of the endplates when they are in the stowed position. More importantly, the Gurney Flap also acts to put a reflex in the plate camber-line akin to making the plate curved which increases the lift, this aligns the end-plate closer to the flow of the air over the end plate (especially at subsonic speeds) and extracts more energy from the air. It is akin to having a scoop at the front of the plate which in turn increases the capture area.

Along with the leading edge chamfers, the Gurney flap makes the flat end plate section behave in a similar manner to a curved airfoil shaped winglets (Figure 21). The flap is a tuneable structure via bolting on varying heights of flap. The chamfer forward of the Gurney flap (identified as the divergent section, see Figure 14) is designed to avoid separation and "hide" the Gurney from oncoming air when stowed. Though a negative pressure gradient occurs as a result of the vent holes, it encourages a proportion of the air flowing over the surface to go through the holes.

Vent holes and vortex generators

Large flat surfaces at high degrees of deflection are prone to shedding large regular (Von Karman) vortices at low frequencies, which manifest as severe buffeting. If the natural frequency of the vortices happens to coincide with the natural frequencies of other parts of the structure such as the tailfin, this may induce undesirable flutter into the system. Furthermore, large vortices have a detrimental effect on parachute deployment, so smaller vortices of different frequencies are preferred to make things feel smoother. By drilling vent holes in the end plates, this reduces the intensity of the flow leaving the training edge by essentially allowing a proportion of the air to leave earlier, helping meet the *"controlled manner"* requirement. It seems a little counter-intuitive, but if the position and sizes of the holes in the end plates are right, then the losses in performance is less than the solid area lost. Additionally, if the holes are placed in the optimum position, the structure can be affectively damped. (Figure 22).

It is a well proven technique and over the years there have been a number of aircraft that have employed perforated surfaces on their wing flaps. It was found when fully deployed, the vortices shed by these aircraft's flaps were either exciting or shielding the tail plane and in doing so, severely reducing the stability of the aeroplane at this critical phase of flight. (Figure 23)

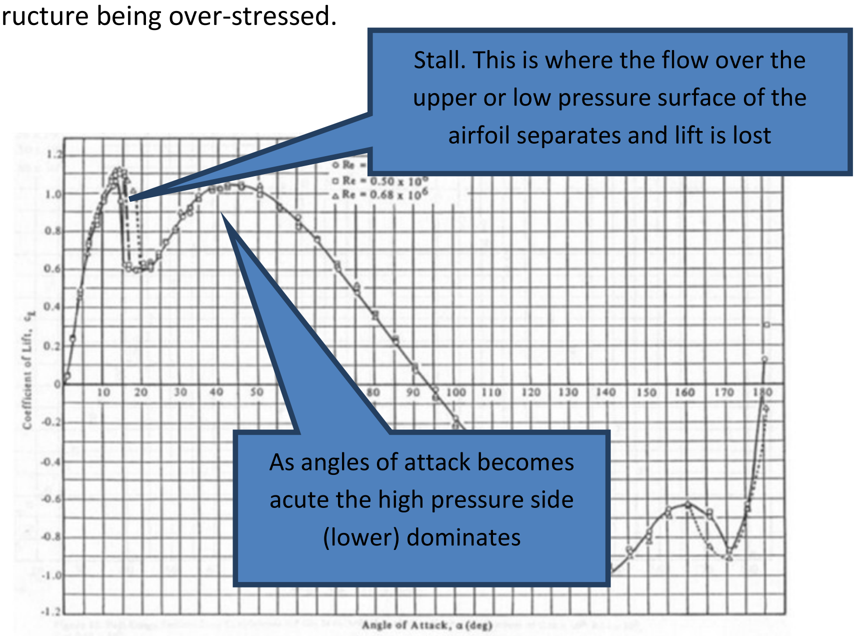
More on perforated end plates. Numerous hole sizes and spacing were tried on the Invader's end plates, and finally three holes sizes were selected to give a safe range of frequencies. This was also found to have a positive effect structurally, because by arranging the holes in a particular manner, the stress concentration factors were reduced. Unfortunately, the down-side of vent holes is that due to air leakage, they can reduce the performance of the end-plates so they have to be positioned near the rear as this is the region of least negative effect. The rearward location of holes reduced wave drag.

The size and position of the holes were a consideration for reducing wave drag incurred by an increase in cross-sectional area seen by the airflow. This is as a result of the existence of the end plates even when in the stowed position. Historically, many early supersonic fighter aircraft fell short of their intended performance targets because of a lack of understanding of what was to become known as *"the area rule"* and the effect it has on wave drag (Figure 24 & Figure 25). Wave drag occurs at transonic speeds of around Mach 0.9 to 1.1 and is by far the biggest increment of drag. It requires the cross-sectional area of the aircraft or vehicle to increase and decrease smoothly. Two vehicles with the same cross sectional area but one that doesn't employ the area rule could easily have twice the drag twice of one that does.

On the main face of the airbrakes, there are also vortex generators. Their purpose is to encourage the air leaving the trailing edge to separate into smaller, but higher frequency vortices. By adjusting the orientation and size of the wedge shape vortex generators, it allows the shedding vortex to come off clockwise or counter clockwise which is handy when it comes to tuning the airflow over the car. The Vortex Generators (VGs) are designed so that when stowed, they are hidden below the boundary layer displacement thickness of the vehicle – thus they have minimal drag when not in use. Any protuberance has an effect, no matter how small the surface feature is and the air-flow will see the VGs as an increase in cross-sectional area. Therefore, to avoid an aerial "spike", the end plate vent holes remove area from the end-plates to balance the air pressure.

Wave drag of the airbrakes

The third requirement of the airbrakes was to maximise the wave drag when deployed supersonically. This means that the air brake design does not have to rely solely on the brute force approach to meet its performance goals, but takes into account an aerodynamic phenomenon to improve the design's efficiency. Figure 24 shows the area-rule and the improvement made to the F102 prototype in the 1950's and how smoothing the area enabled the aircraft to meet its in-service performance requirements. By applying the rule in reverse, the Invader's requirements can be met. LSR vehicles are different as, inevitably, the cross-sectional area peaks at the back of the vehicle. This is due to structures such as the cockpit, tailfin, tailplane and the wheels all being positioned towards the rear of the vehicle. Fortunately, the packaging demands of the airbrakes dictated their placement at the rear of the vehicle as well. Such a placement is optimal in terms of the area rule. The cross-sectional area of the Invader at the rear of the cockpit is around $1.7m^2$ and with $0.74m^2$ of air brake deployed, we have a 43% increase in wave drag area. This is a significant increase in area. The advantage of using wave drag this way is due to the fact that the retardation forces that wave drag creates are spread over a large area of the vehicle and not simply over the airbrake surface. Significantly, the airbrakes become more effective without he air brake structure being over-stressed.



Lift coefficient from 0 to 180 degrees

Figure 1

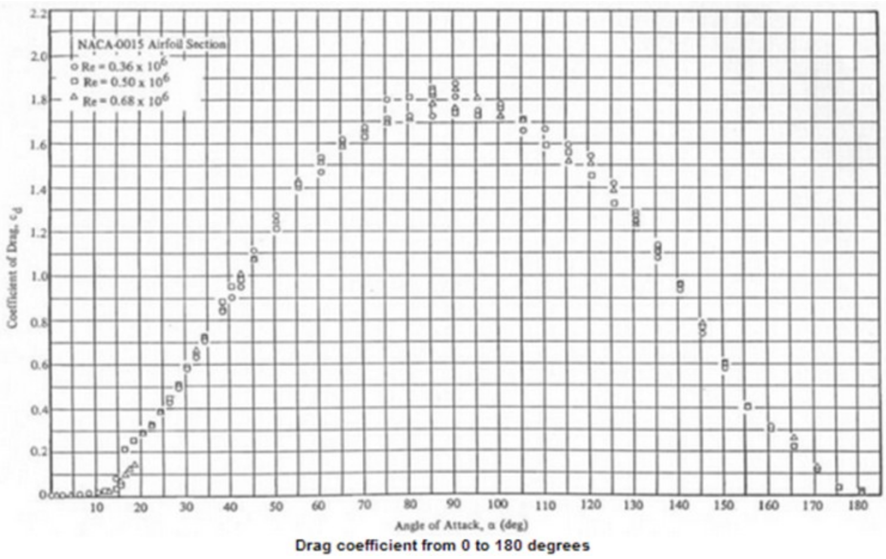


Figure 2

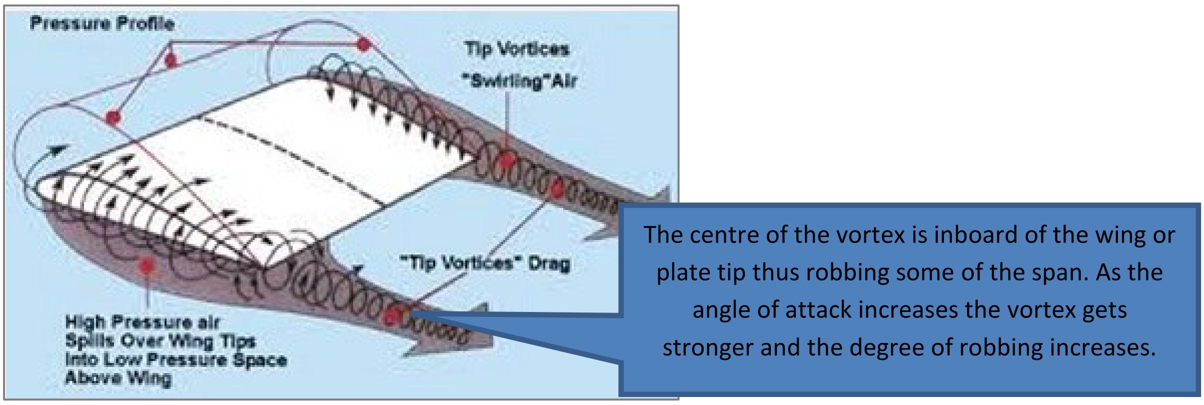


Figure 3

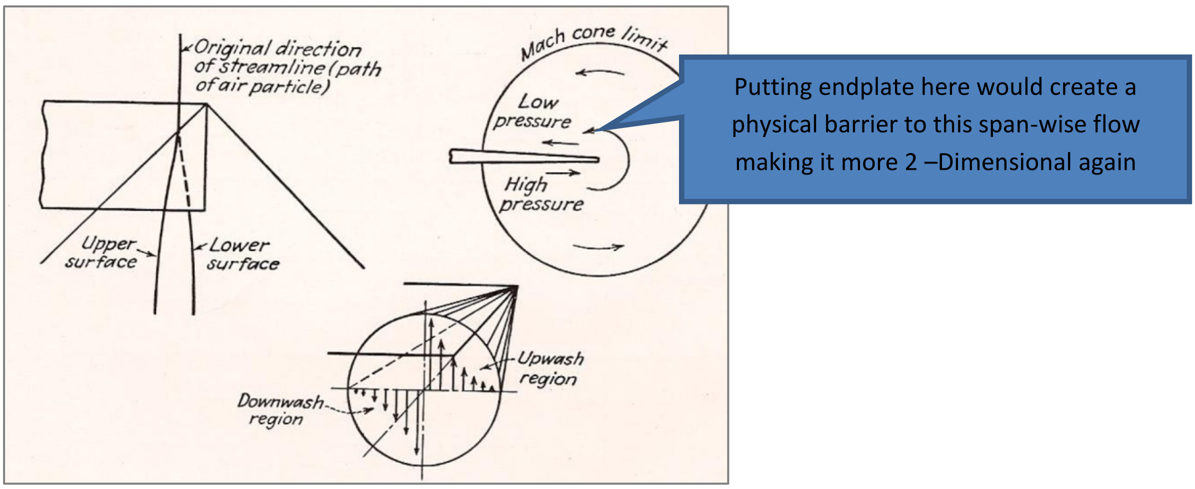


Figure 4

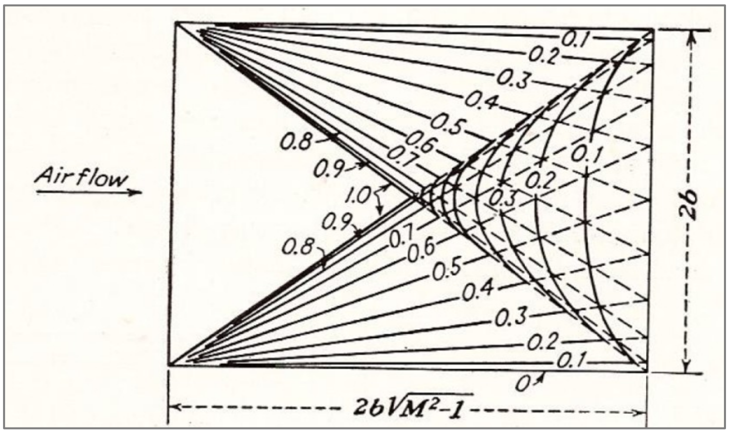


Figure 5

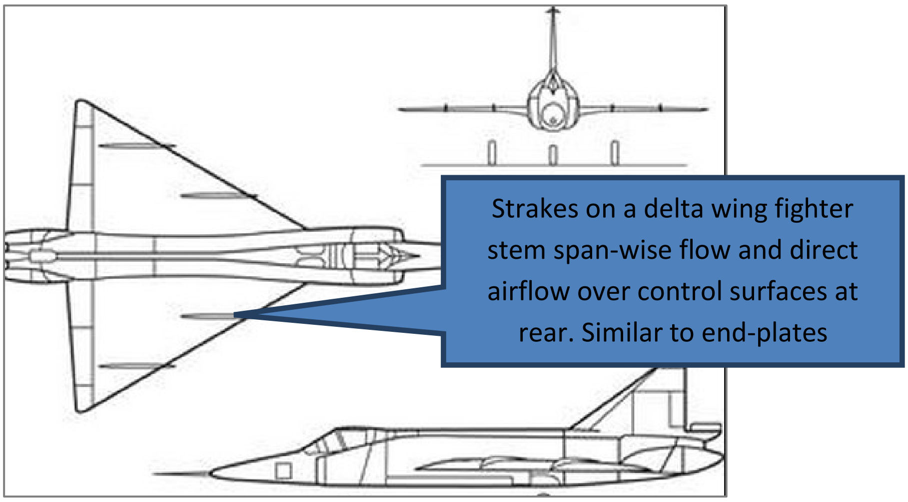
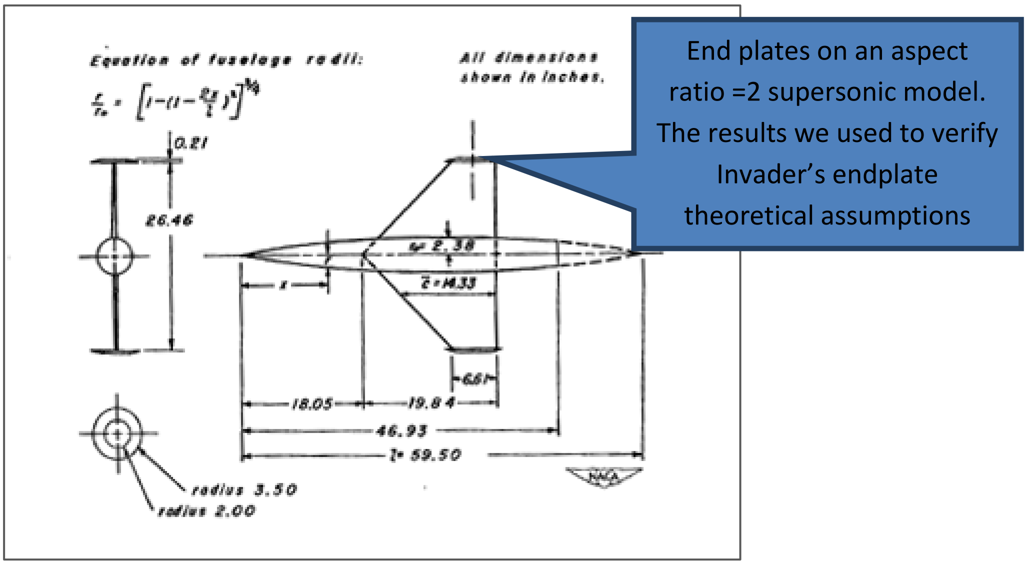


Figure 6



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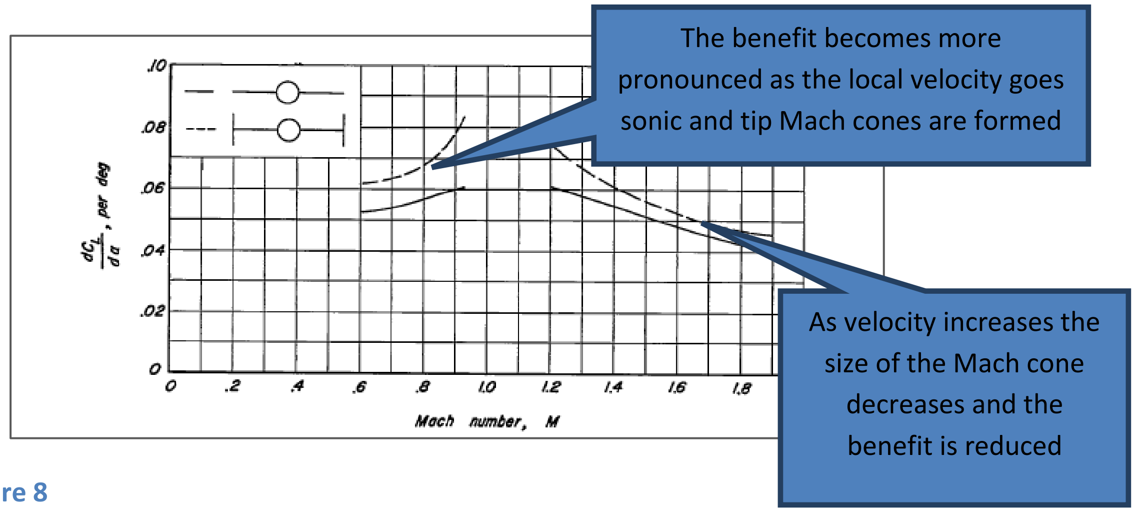


Figure 8

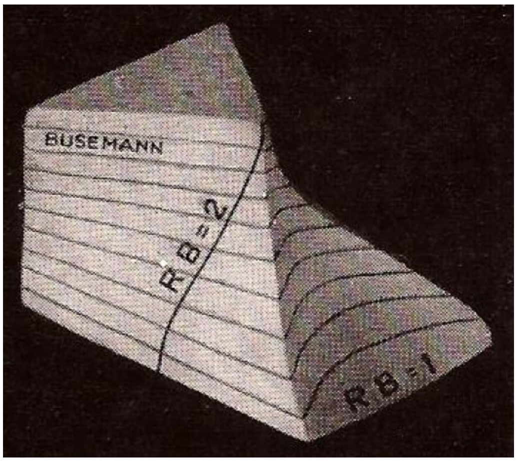


Figure 9

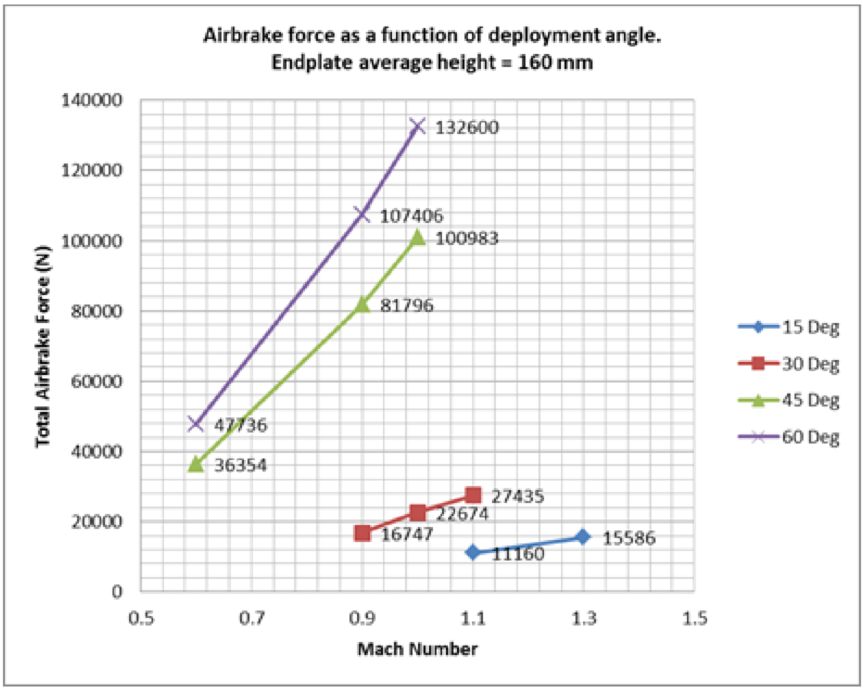


Figure 10

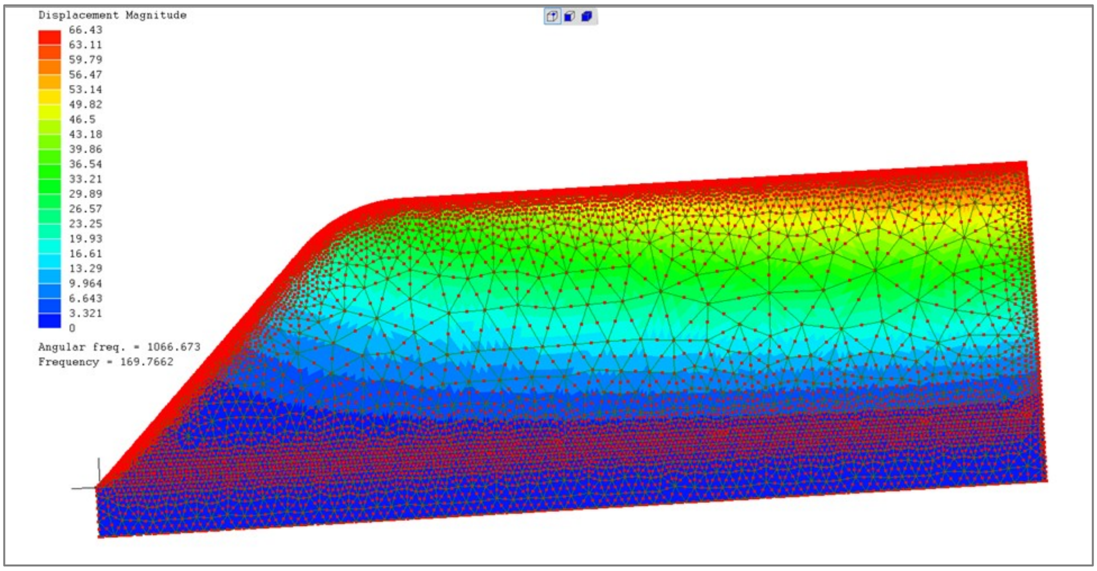
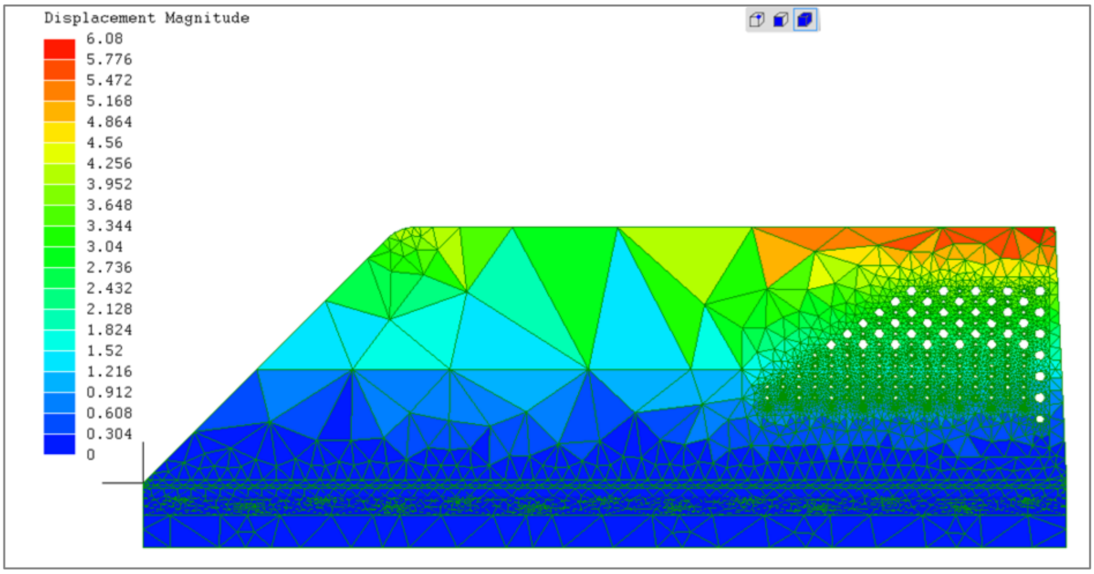


Figure 11



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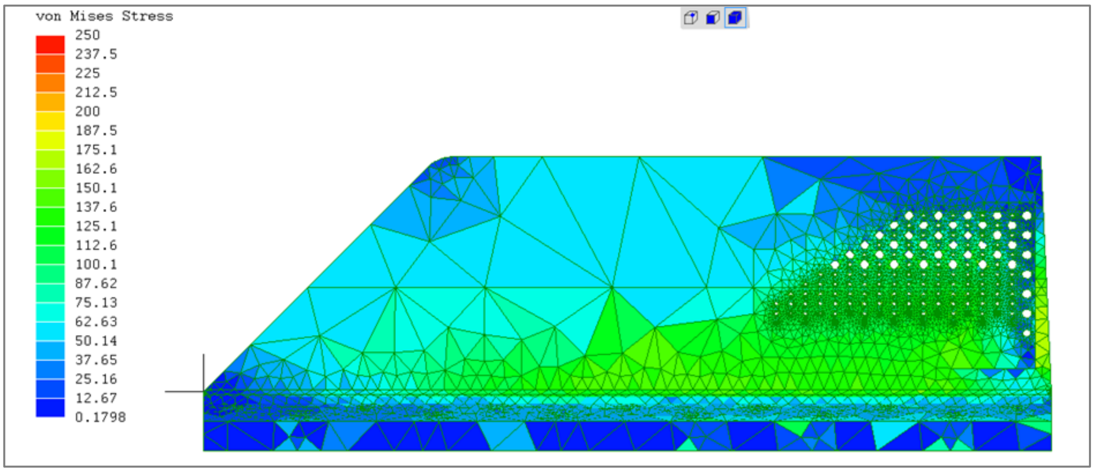


Figure 13

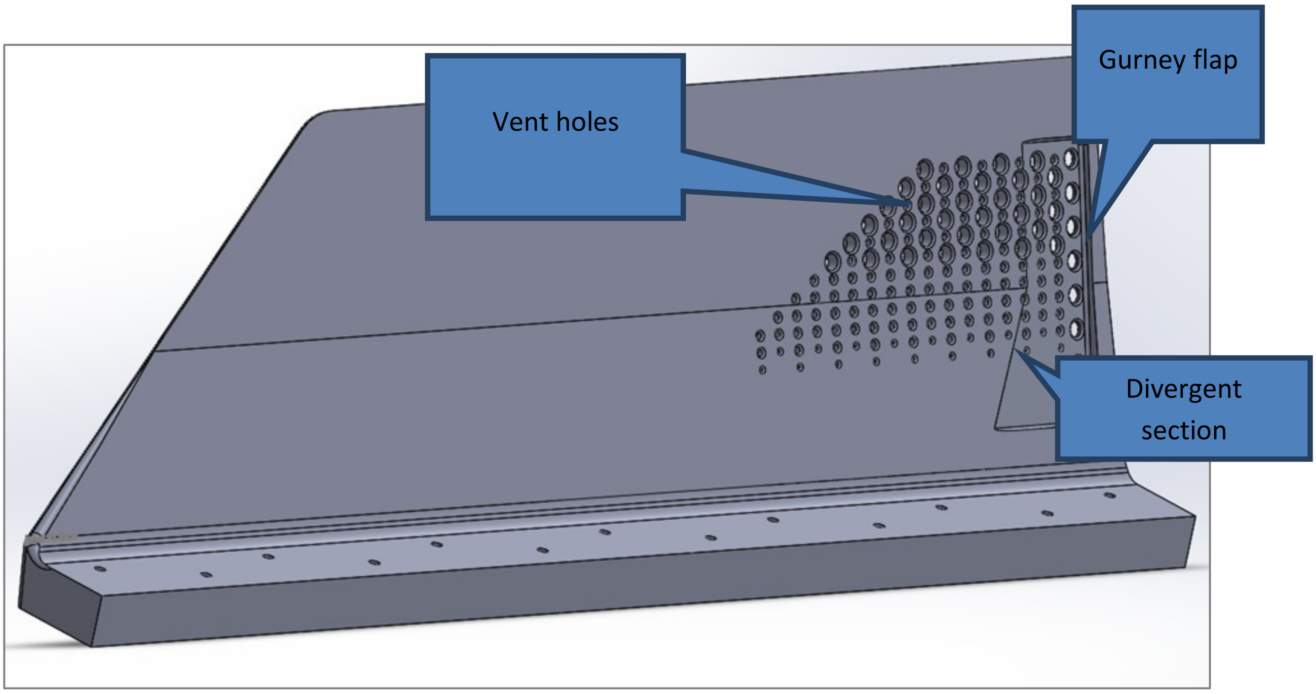


Figure 14

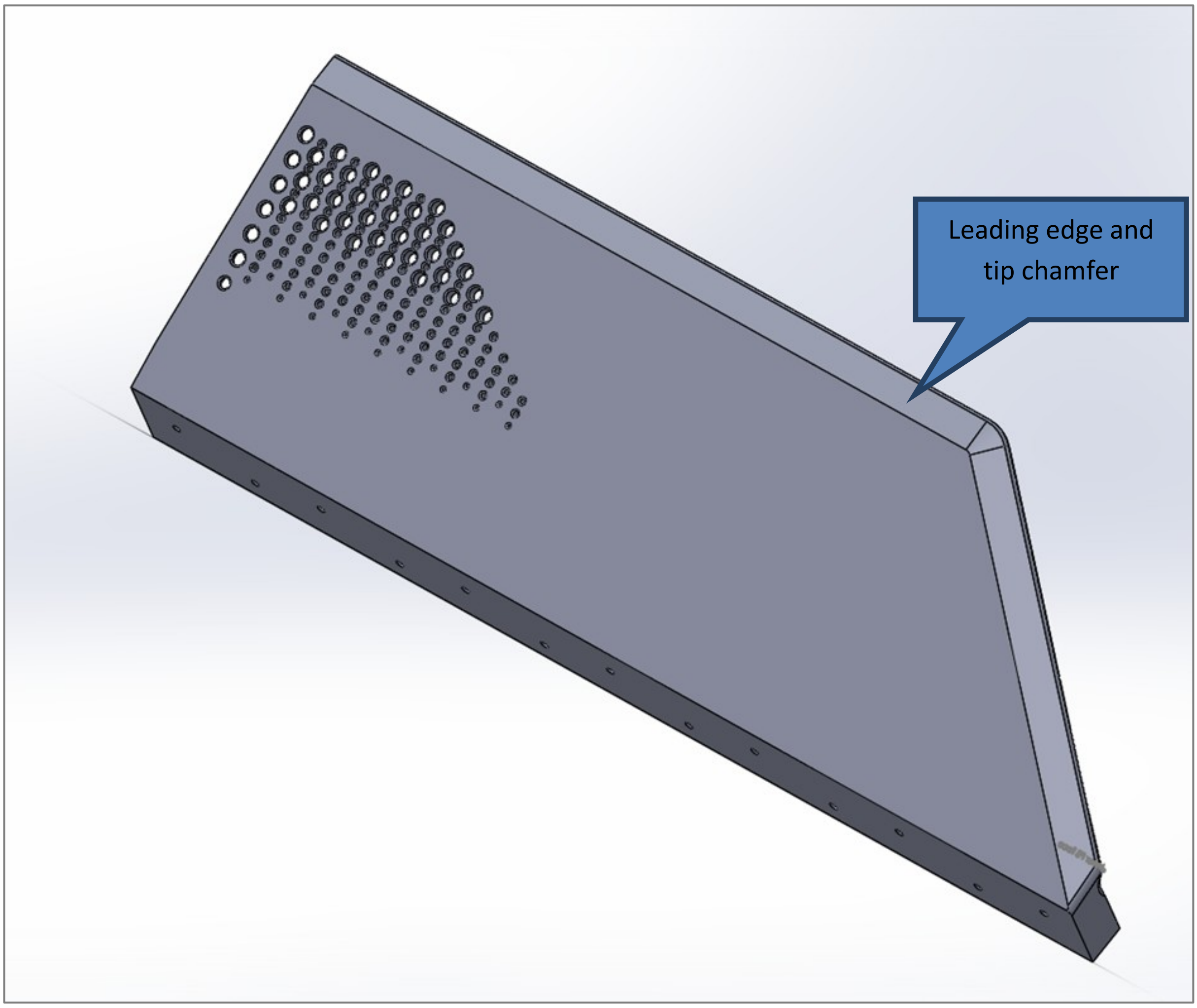


Figure 15

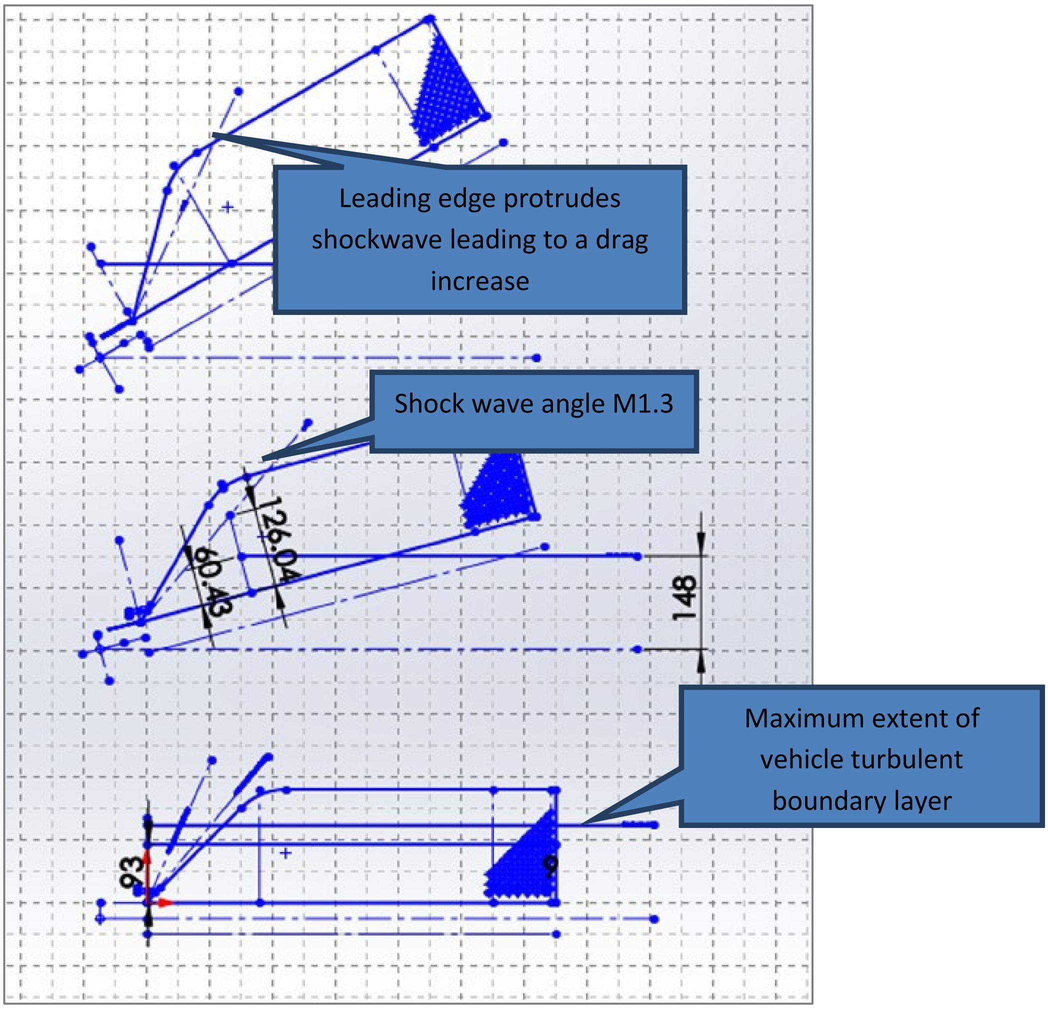


Figure 16

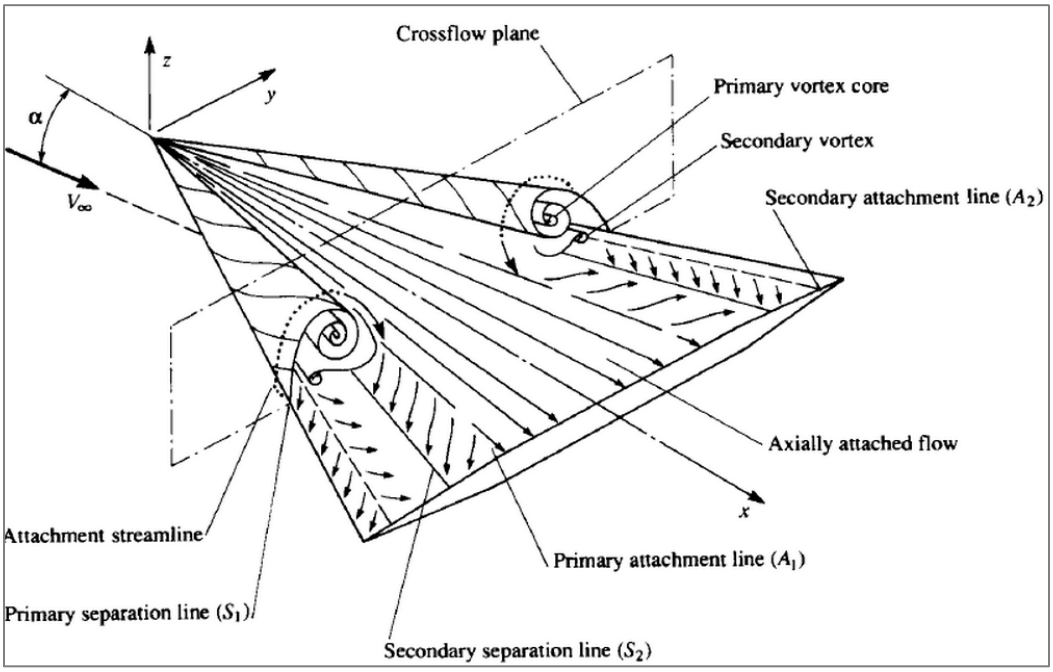
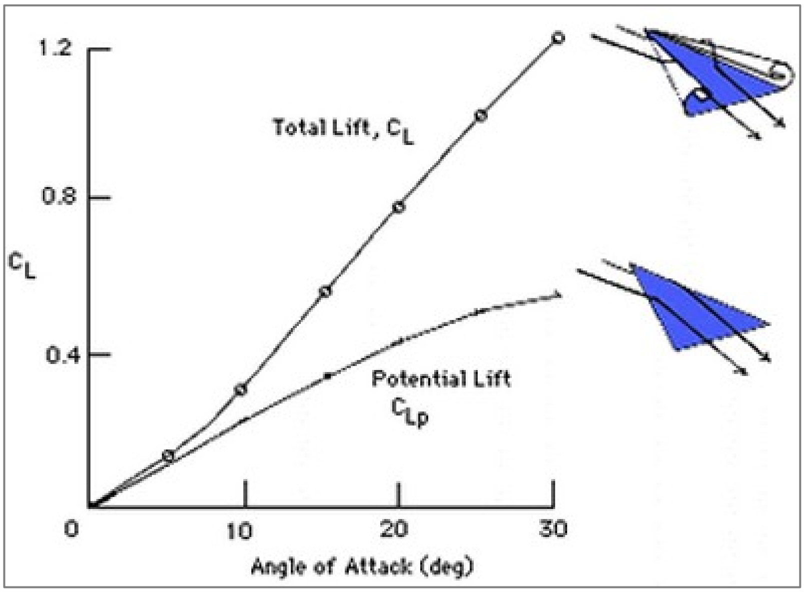


Figure 17



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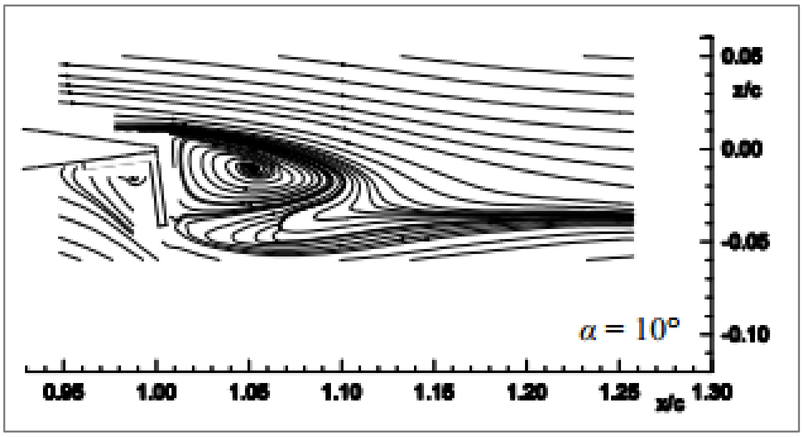


Figure 19

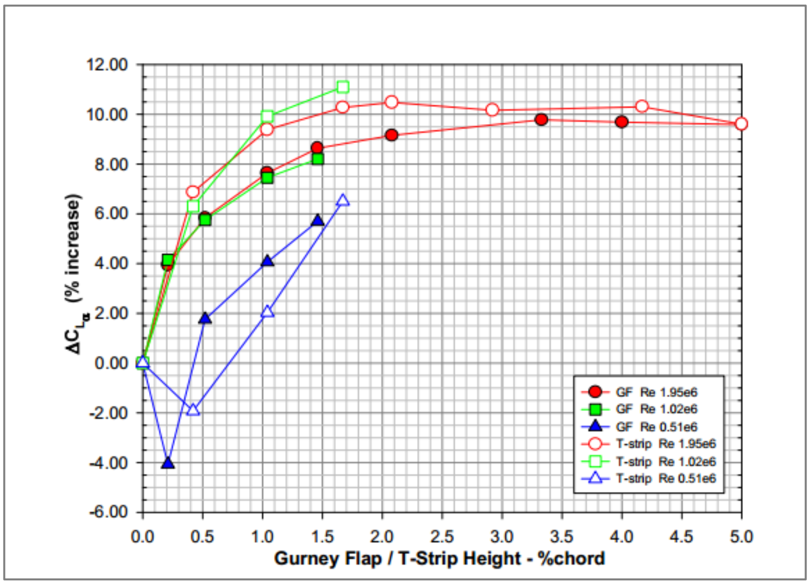


Figure 20

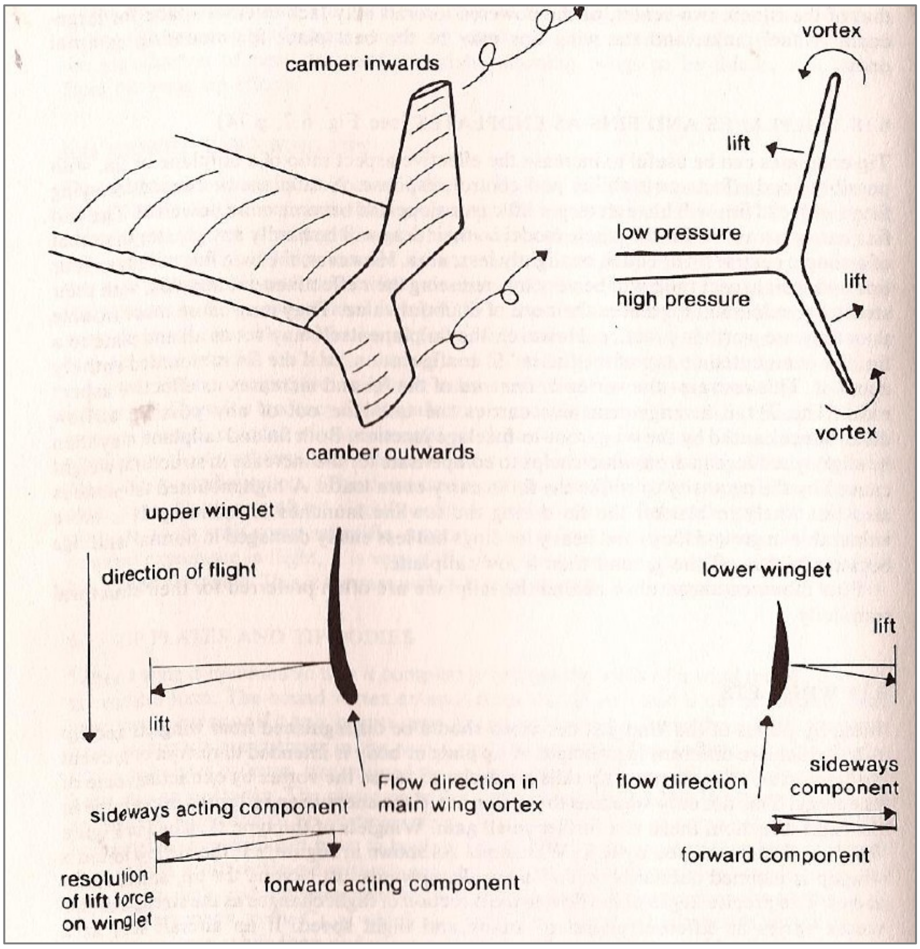


Figure 21

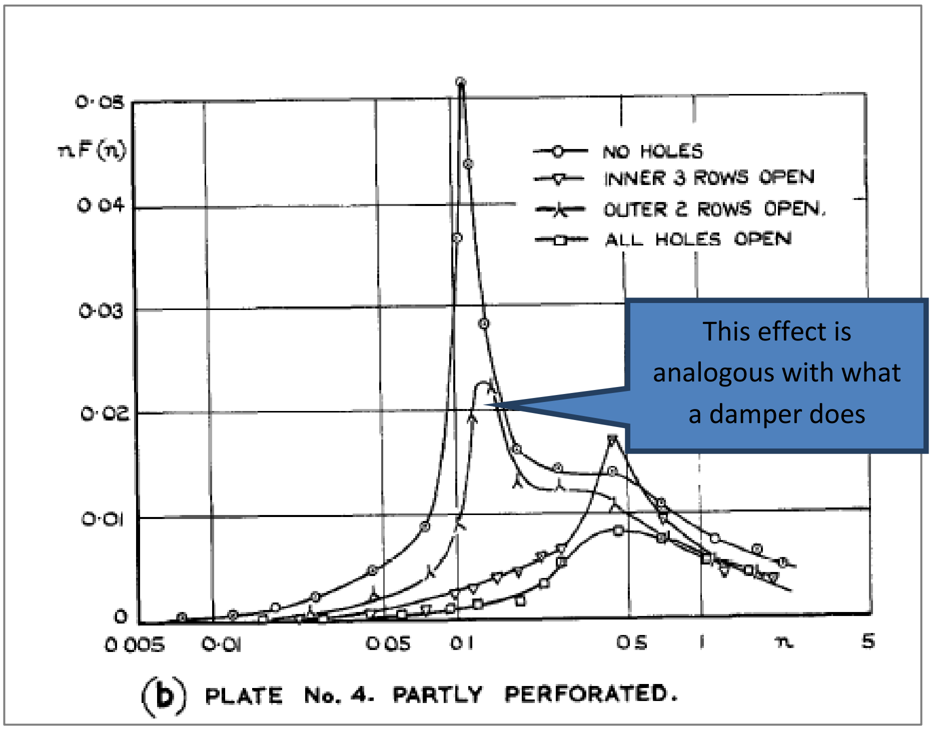
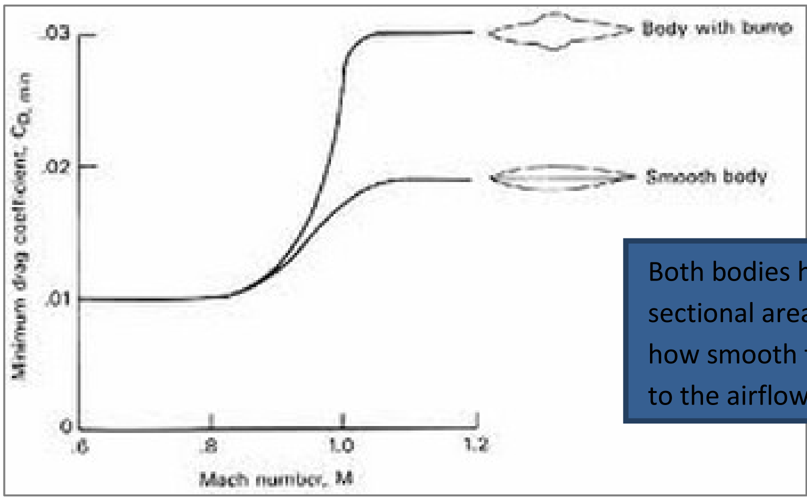


Figure 22

SBD Dauntless
A-24 Banshee

A U.S. Navy SBD releasing a bomb. Note the extended dive brakes on the trailing edges.

Figure 23



Both bodies have the same cross sectional area. The difference is how smooth that area is presented to the airflow.

Figure 24

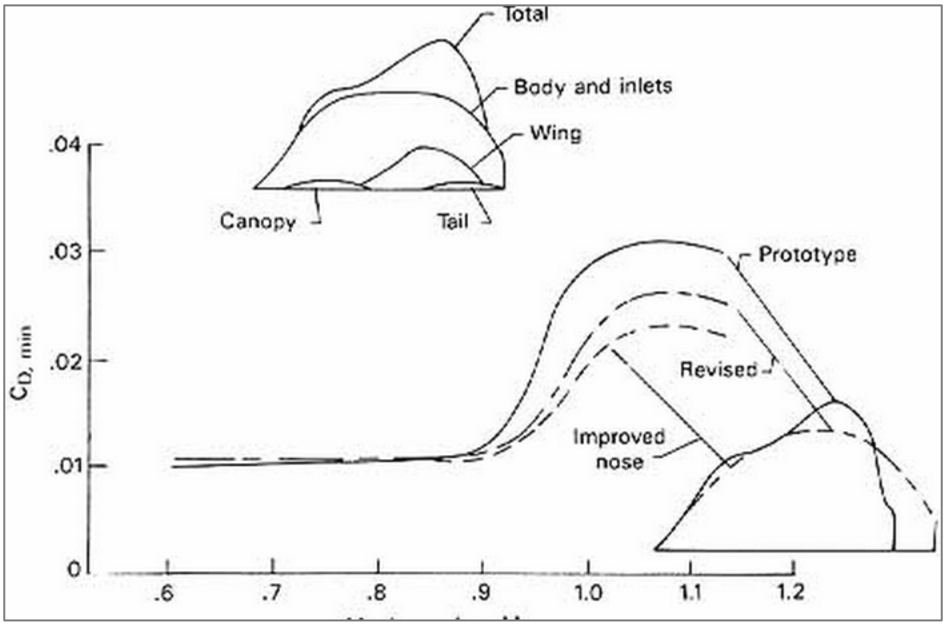


Figure 25

Author - Paul Martin

During his 30 year engineering career, Paul has worked in senior positions on numerous speed record vehicles including;

- Oldsmobile Aerotech Quad 4 record car 257 mph around Indianapolis race circuit
- McLaren F1 Supercar. The world's fastest production car 241 mph
- McLaren Maverick WSR car 1000mph target
- Bloodhound SSC LSR car 1050 mph target
- Quicksilver water WSR boat 500 mph target

- Born Kalgoorlie WA and up to the age of 15 lived mainly in Bayswater, Victoria
- Tertiary educated in the UK
- Graduate Engineer Rolls Royce Aero Engines in Derby
- Senior Project Engineer Advanced Composite Technology Ltd
- Chief Composite Engineer Leyton House Formula One
- General Manager COMTEC Ltd
- Head of Composite Structures Engineering on the McLaren F1 supercar project
- Engineering Director Composite Engineering Innovations Ltd
- Head of Group Manufacturing Lola Cars
- Engineering Director Ling Dynamic Systems
- Managing Director Technical Resin Bonders Ltd
- Engineering Director Quiet Revolution Wind turbines

Paul's proper job, when not involved with speed record ventures, is as a freelance engineer specialising in the design, development and manufacturing of advanced lightweight and high performance structures.