TENTH AUSTRALASIAN FLUID MECHANICS
CONFERENCE - UNIVERSITY OF MELBOURNE
11-15 DECEMBER 1989

11B-3

# BASE FLOW BEHIND A CASTELLATED BLUNT TRAILING EDGE AEROFOIL IN SUPERSONIC FLOW

Eric C. MAGI and Sudhir L. GAI

Department of Mechanical Engineering
University College, University of New South Wales
Australian Defence Force Academy, Canberra ACT
AUSTRALIA

## ABSTRACT

A study of the near wake flow of castellated blunt trailing edge aerofoils at Mach 2 was undertaken to increase the available data base and to understand the mechanism of base pressure recovery. This paper presents some of the results obtained during the course of this study .

Flow visualisation studies included oil flow, shadowgraphs, schlieren photography and Holographic interferometry looking at the near wake flow onto and along the span of the aerofoils. These showed that the base flow is three dimensional in nature, and have large spanwise pressure gradients. Base pressure measurements confirm the existence of these gradients.

## INTRODUCTION

Chapman (1950) identified two advantages of blunt trailing edge aerofoils over sharp trailing edged aerofoils. Firstly, a blunt trailing edge aerofoil can be made lighter and torsionally stiffer for a given wing thickness. Secondly, they have a lower drag at supersonic and hypersonic velocities. Whilst there is a component of drag due to low base pressure, the total drag is decreased due to the reduction of wave drag .

However the base drag created by a blunt trailing edge is significant at subsonic speeds and it is desireable to reduce this drag.

The origin of the base drag is due to vortex shedding. This occurs because the fluid being entrained is convected away from the base by vortices. Many methods exist to inhibit or reduce the strength of these vortices. One of these methods, which has been employed by Tanner (1971) and (1972), is to alter the geometry of the trailing edge from a straight edge to a castellated edge. Experiments by Gai etal (1986) indicate that this breaks up the periodicity of the two dimensional vortex shedding and perturbs it to give some streamwise vorticity.

At supersonic speeds the base flow for the plain blunt trailing edge is generally steady. Vortices are only observed behind the wake neck. The only known data to the authors' knowledge reporting the performance of castellated trailing edges in supersonic flow is by Tanner (1971), Hosking etal (1974), and Steen (1975). Hosking etal (1974), and Steen(1975) indicate that the castellated trailing edge still gives some pressure recovery . The mechanism for this pressure recovery, however, is not yet fully understood.

## EXPERIMENTAL ARRANGEMENT

Experiments were carried out in a small blow down supersonic wind tunnel at a Mach number of $M_\infty = 1.99$ and a Reynolds number based on chord length in the range of $2 \times 10^6$ to $9 \times 10^6$. The test section crossection is 155mm x 90mm.

Models were constructed having a wedge shaped leading edge, flat plate body and a blunt trailing edge. The base height, h, for all models was 6mm. Horizontally mounted models (see figure 1) have a wedge angle of $7.6^0$, span of 90mm and a chord length of 130mm. Vertically mounted models have a wedge angle of $9.7^0$, span of 155mm and a chord length of 75mm.

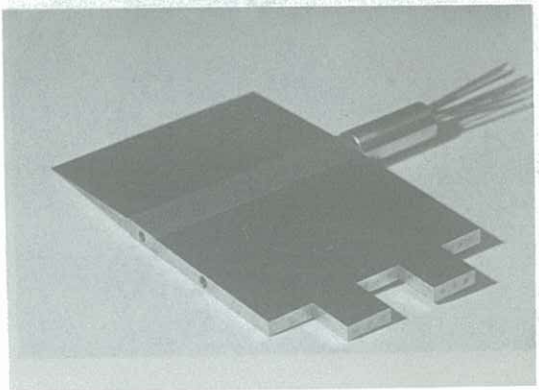

**Figure 1.** - Horizontally mounted castellated blunt trailing edge aerofoil with castellations dimensions, b/h = 3, AR = b/a= 1.

Rectangular projections from the trailing edge were spaced to form a recess region having the same spanwise width, b, as the projection. The length of the projections is denoted by, a, (see figure 5). Castellations on the horizontally mounted models have dimensions, b x a , equalling 18mm x 6mm, 18mm x 12mm, 18mm x 18mm, 12mm x 6mm and 12mm x 12mm. Castellations on the vertically mounted models have dimensions, b x a , equalling 18mm x 6mm, 18mm x 12mm, 18mm x 18mm, 12mm x 6mm, 12mm x 12mm and 12mm x 18mm.

## GROSS FEATURES OF THE FLOW

The base flow of a two-dimensional blunt base can be conveniently divided into various flow regions. The separating flow undergoes an expansion around the corner, forming a recirculation region behind the base. A free shear layer separates the recirculation region from the expansion fan. The flow recompresses approximately one to three base heights downstream of the base forming a wake neck and a wake shock which then turns the flow back to the freestream direction. The expansion fan is sometimes terminated by a lipshock as can be seen in Figure 2a) . The lipshock recompresses the flow to the base pressure. Hama (1968) has shown that the location and strength of the lipshock depends on the Reynolds number, Mach number and geometry of the base.

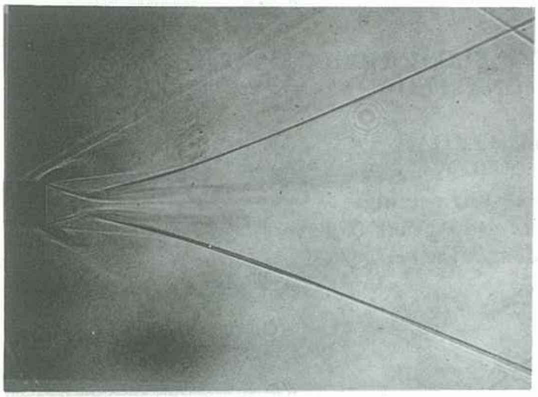

**Figure 2 a). - Shadowgraph of horizontally mounted plain base, blunt trailing edge aerofoil. $M_\infty = 1.99$, Re( chord) = $(8.3 \pm 0.3) \times 10^6$**

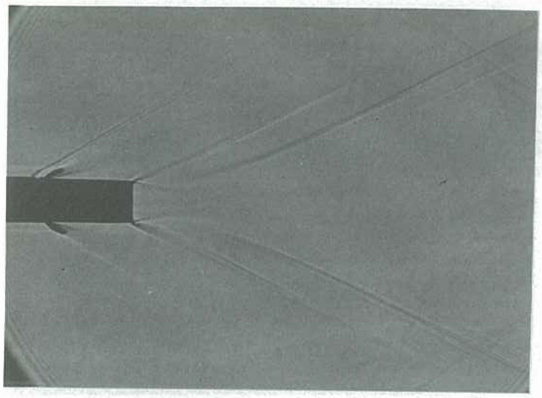

**Figure 2 b).** - Shadowgraph of horizontally mounted castellated blunt trailing edge aerofoil.
b/h = 2, AR= b/a = 1
$M_\infty = 1.99$, Re( chord) = $(8.6 \pm 0.2) \times 10^6$

The base flow due to a castellated edge is similar to the plain two-dimensional base, in that the separating flow undergoes an expansion. However , due to the discontinuous nature of the trailing edge, a spanwise pressure gradient is set up between the base region of the recess and the top surface of the projection. Some of the flow over the top of the projection is then entrained into the recess as a result of this pressure gradient. The separated flow in the recess is consequently recompressed and a weaker compression shock emanates in the neck region.

The base pressure of the projection is also characterised by a large transverse gradient with the lowest pressures at the edges. This gradient is a result of the mass entrained from the top surface of the projection into the recess, as mentioned above. The wake shock behind the projection is formed further downstream than behind the recess.

A pressure mismatch, therefore occurs between the out flow from the recess and the corner of the projection . The flow from the recess expands around the projection edge and the wake is characterized by a series of compression and expansion waves. Figures 3 a) and 3 b) are Schlieren photographs viewing onto the span of the aerofoil. They show that the flow forms a pattern similar to a series of under and over expanded jets. The spanwise gradients persist several base heights downstream of the base and are located in cells formed by the expansion and compression waves.

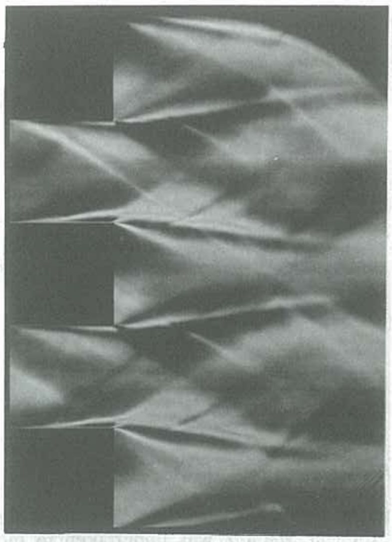

**Figure 3 a).- Schlieren photograph of vertically mounted castellated blunt trailing edge aerofoil .
b/h = 3, AR= b/a = 1
$M_\infty = 1.99$, Re( chord) = $(4.9 \pm 0.1) \times 10^6$**

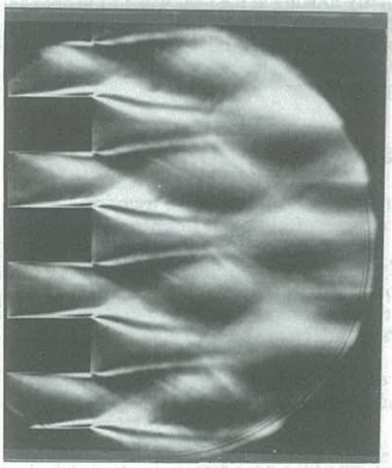

**Figure 3 b). - Schlieren photograph of vertically mounted castellated blunt trailing edge aerofoil.**
b/h = 2, AR= b/a = 2/3
$M_\infty = 1.99$, Re( chord) = $(5.1 \pm 0.1) \times 10^6$

Viewing along the span, as can be seen in figure 2 b), the wake shock with the castellated base forms further away from the axis. The wake neck is not as well defined as in the case of a plain base. The contraction is segmented in the spanwise direction.

Vortex like structures form downstream of the wake shock in the vicinity of the spanwise neck, behind the projection. These can be recognised in the holographic differential interferograms , figures 4 a), 4 b) looking on to the span.

Depending on the geometry of the castellations , shock waves can be seen, figures 2 b, 3 a), forming down stream of the wake shock.

The base pressure measurements, figure 5) , confirm the existence of the spanwise gradients indicated by the schlieren photographs, and the reduction of the base drag. The measurements, however indicate that the base pressure distribution is significantly different to those in subsonic flow (Tanner 1972) . In subsonic flow, the recess pressures are lower than those on the projection. Pressure measurements also indicate that the optimal geometry in subsonic flow is not necessarily the optimal at supersonic speeds.

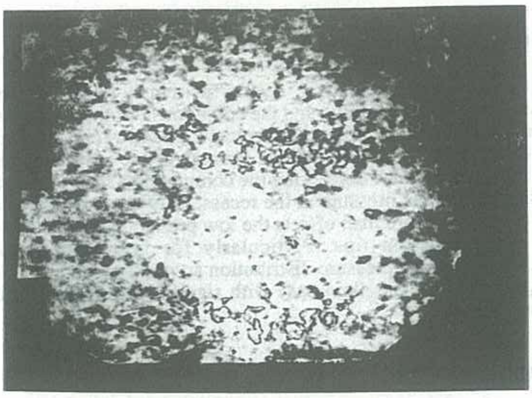

**Figure 4 a).** - **Holographic differential interferogram of vertically mounted castellated edge aerofoil.**
Pulse separation = 1μs, b/h = 3, AR= b/a = 3
**$M_\infty$ = 1.99, Re( chord) = (5.0 ± 0.1) x $10^6$**

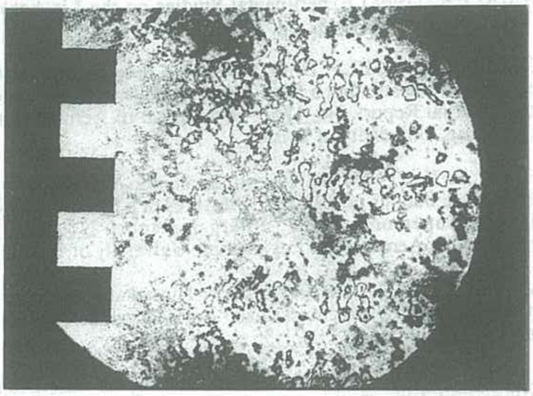

**Figure 4 b).** - Holographic differential interferogram of vertically mounted castellated edge aerofoil.
Pulse separation = 6μs, b/h = 2, AR= b/a = 1
$M_\infty$ = 1.99, Re( chord) = (5.0 ± 0.1) x $10^6$

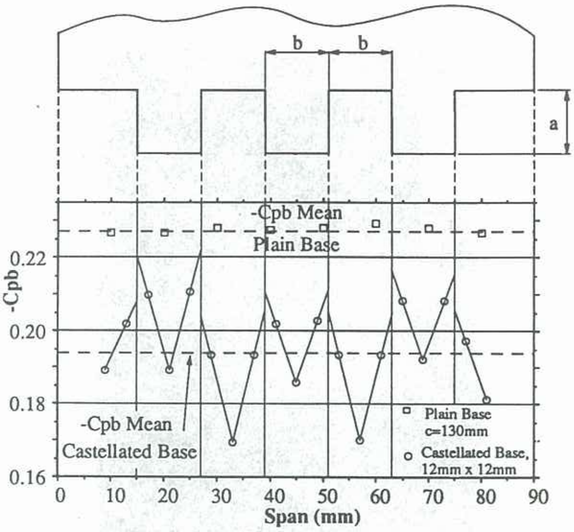

**Figure 5.** - Pressure distribution for horizontally mounted plain base and castellated blunt trailing edge aerofoils. Castellation dimensions are b/h = 2, AR= b/a = 1.

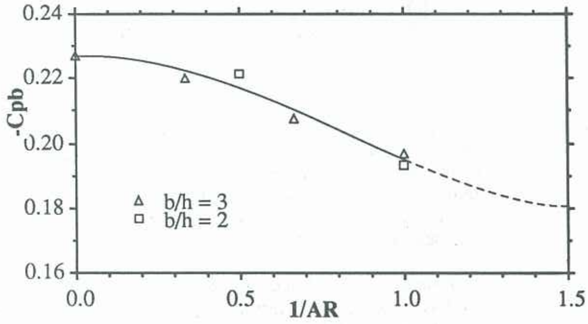

**Figure 6.** - Mean base pressure as a function of aspect ratio for horizontally mounted plain base and castellated blunt trailing edge aerofoils. Castellation widths are b/h = 2 and b/h = 3.

## MECHANISMS FOR DRAG REDUCTION

### Effect of vortex formation

As previously indicated, the drag reduction in subsonic flow is primarily due to the perturbation and breakup of two dimensional vortex shedding. The amount of fluid being entrained and convected away from the base by the vortices depends on the strength and orientation of the vorticity axis. The separating vortex filaments associated with the boundary layer are skewed in a streamwise direction at the trailing edge discontinuity.

At supersonic speeds the skewing of the vortex filaments must also occur. Features consistent with the formation of streamwise vortex cores have been observed in schlieren photographs sensitive to spanwise density gradients. These are evident for castellations with large aspect ratios. They can also be seen in flows with lower aspect ratio castellations, for example see figures 2a) and 2b). Their formation occurs typically 2.5 to 3 base heights downstream from the recess edge and a base height across in the span direction from the tip of the projection.

The action of these vortices would be to entrain fluid in a direction toward the cores. This means that these vortices may influence the spanwise pressure distribution on the tips of the projection. Since the vortices are located in a region downstream of the recess compression shock, they are unlikely to influence the base pressure on the recess. For castellation lengths, a/h, larger than two, there is a strong expansion wave, turning the flow from the recess in a spanwise direction to the region behind the projection. This suggests that the streamwise vortices in this case are not the dominant feature influencing the flow.

Similarly the vortex formation behind the projection occurs downstream of the wake neck and apparently they are unlikely to influence the base pressure since the formation region of these vortices is in supersonic flow.

### Effect of Castellation Aspect Ratio

The aspect ratio of the castellation, AR , is defined as the square of the projection width b, to the top surface area of the projection, so that AR = b/a ( see figure 5). The drag reduction of a castellated trailing edged aerofoil is a function of AR and the non-dimensional width b/h. The mean base pressure coefficient is plotted as a function of the castellation aspect ratio for two different widths of castellation. This is shown in figure 6).

As the aspect ratio is decreased from infinity, (the plain

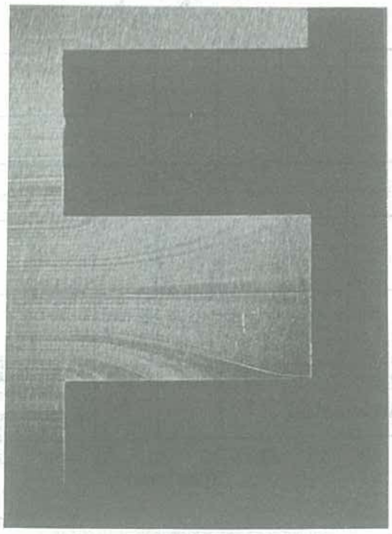

**Figure 7. -** Oil flow visualisation of a castellation of the vertically mounted castellated blunt trailing edge aerofoil .
b/h = 2, AR= b/a = 2/3
$M_\infty = 1.99$, Re( chord) = $(4.5 \pm 0.1) \times 10^6$

base case), the trailing edge discontinuity acts as a streamwise vortex generator. For aspect ratios larger than 2, the spanwise pressure distribution is changed whilst the mean base pressure is approximately the same. As the castellations length is increased the pressure distribution is effectively shifted to obtain a higher mean base pressure.

The recompression shock behind the recess emanates approximately two base heights downstream. This length is significant since it marks the position where further increases in castellation length start having a reduced effect on the recess base pressure. It should be noted that the separating boundary layer is turbulent and the position of the wake shock is relatively independent of the Reynolds number.

For castellation lengths much larger than two base heights, it is suggested that the recess flow up stream of the wake shock is isolated from the downstream influence so that the recess pressure becomes independent of castellation length.The increased pressure in the recess downstream of the wake shock, then provides an adverse pressure gradient to the flow separating from the projection tips. Oil flow visualisation (see figure 7) indicates that the flow near the top surface is turned back to the free stream direction for castellations with aspect ratios less than 2/3. For aspect ratios less than this value (2/3), it is conjectured that the projection's base pressure asymptotes to it's highest mean pressure.

## Entropy production

From a heuristic argument, the drag of a body can be associated with entropy production since energy is lost to the flow. It is worth noting that the wake of the castellated trailing edge contains a series of weak shocks recompressing the flow back to the freestream pressure. The entropy increase, due to recompressing the flow through a series of weak shocks rather than a single shock , is less. The wake shock also appears to form further away from the base axis.

The wake shock behind the recess of low aspect ratio castellation has a curved shock surface due to the inflow off the top surface of the projection. The shock length is approximately six to ten base heights in length (see figure 2b). This length is very much smaller than for the plain base wake shock.

## CONCLUSION

The drag reduction seems primarily due to, the segmentation of the flow, and the entrainment of the fluid from the top of the projection into the recess. The entrainment of air into the recess acts to lessen the strength of the expansion fan off the recess hence decreasing the compression shock strength and increase the pressure at the recess. This pressure increase in the recess more than offsets the low pressure region created at the projection tips. Particularly for low aspect ratio castellations, the pressure distribution across the entire span is higher than for the plain base with significantly higher mean base pressure.

## REFERENCES

CHAPMAN, D.R. (1950) Airfoil Profiles for Minimum Pressure Drag at Supersonic Velocities. General Analysis with Application to Linearized Supersonic Flow. N.A.C.A. Report 1063

GAI, S. L. SHARMA, S. D. (1986) Vortex Shedding from a Segmented Blunt Trailing Edge Aerofoil in Subsonic Flow. Proc. 9th Australasian Fluid Mech. Conf.

HAMA, F.R. (1968) Experimental Studies on the Lipshock. A.I.A.A. Journal, Vol. 6, pp. 212-219

HOSKING, P. R. SELF, D. Q. (1974) An Investigation into the Effect of Castellating a Blunt Trailing Edge in Supersonic Flow. Internal Report No. 175 , Department of Aeronautical Engineering, University of Bristol,

STEEN, P. H. (1975) An Investigation into the Effect of Certain Castellations on The Base Pressures of a Blunt Trailing Edge in Supersonic Flow. Internal Report No. 183 , Department of Aeronautical Engineering, University of Bristol

TANNER, M. (1971) Der Einfluss der Hinterkantenform auf den Widerstand eines Rechteckflugels im Machzahlbereich von Ma = 0,5 bis 2,2 . DLR-FB 71-85

TANNER, M. (1972) A Method for Reducing the Base Drag of Wings with Blunt Trailing Edge . Aeronaut. Quart. Vol. 23