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BASE PRESSURE RECOVERY FOR SEGMENTED TRAILING EDGE AEROFOILS

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ABSTRACT

The wakes of plain and segmented blunt trailing edge aerofoils were investigated at subsonic speeds for a range of Reynolds numbers and separating boundary layer states. The trailing edge employed the most fundamental type of segment, namely the regular rectangular segment. It was found that the base pressure was a function of both the state of the separating boundary layer and the segment width. Based on these findings, and through the use of previous flow visualization experiments, the process for replenishing the fluid drawn out of the base region by the free shear layers is postulated and has been argued to be dependent on the segment width and separating boundary layer state.

1. INTRODUCTION

The blunt trailing edge aerofoil can be shown to have considerable gains in the supersonic and transonic flight regimes. However, these aerofoils exhibit a high base drag (low base pressure), which becomes a dominant contribution to the total drag in subsonic, transonic and low supersonic flight regimes.

It has been shown that this low base pressure is caused by the nominally two-dimensional vortex shedding process. Thus, any method employed to inhibit this two-dimensional shedding would also modify the base pressure. The splitter plate and base bleed techniques, used to modify the vortex formation and increase the base pressure (Bearman, 1967 for example) are well understood. However, other means of obtaining favourable base pressure recovery, such as the use of segmented trailing edges, have not been fully investigated.

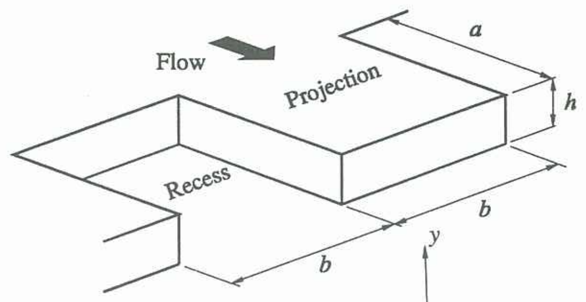
The segmented blunt trailing edge (see figure 1) has been investigated in the two decades (Pollock, 1972, Tanner, 1972, Gai & Sharma, 1986 and Petrusma & Gai, 1989) and a base pressure recovery of up to 60% has been achieved. At low Reynolds numbers the increase in base pressure has been associated with the three-dimensional vortex shedding (Petrusma & Gai, 1989) and it can be inferred from the shedding frequency results presented by the above authors that, at least at low Reynolds numbers, the increase in base pressure is caused by the partial conversion of spanwise vorticity to crosswise and streamwise vorticity. The latter component of vorticity can be shown to have no drag associated with it.

This paper presents base pressure data and aims to clarify the mechanics of the formation region of the segmented blunt trailing edge aerofoil.

2. EXPERIMENTAL ARRANGEMENT

The experiments were performed in the 460 x 460 mm open circuit, closed test section wind tunnel at the Australian Defence Force Academy. The freestream turbulence level was less than 0.25% at the test speed of 31.5 ms^{-1}, which corresponded to a Reynolds number, based on aerofoil chord, of approximately 3×10^5. The boundary layer was either natural or was tripped at the 30% chord position and the profile measured at one third of a base height (5 mm) from the trailing edge.

The models consisted of a two-dimensional semi-elliptic forebody followed by parallel sides to the trailing edge which was either straight or segmented. The aerofoil chord was 155 mm and the thickness ratio was 10%. The salient characteristics and the definition of geometry is given in figure 1.



h = base height of the trailing edge
a = depth of recess
b = width of segment
Æ = b/a = Aspect Ratio of the segment

	Model					
	1	2	3	4	5	6
a/h	0.0	2	2	2	2	2
b/h	-	8	4	3	2	1
Æ	∞	4.0	2.0	1.5	1.0	0.5

Figure 1. Segmented trailing edge geometry

The base pressures and tunnel reference pressures were measured with a Furness Controls FC012 micromanometer via a scanivalve. The boundary layer profiles were measured with a TSI 5μ hot wire probe coupled to a TSI constant temperature anemometer and processed using a modified version of the TSI hot wire software.

3. Results and Discussion

3.1 Base Pressure Distributions

In this investigation the base pressure coefficient, C_{pb}, has been defined as

$$C_{pb} = \frac{p_b - p_s}{1/2\rho u_\infty^2} \qquad (1)$$

Where p_b is the base pressure, p_s is the freestream static pressure, and $1/2\rho u_\infty^2$ is the freestream dynamic pressure.

The variation of base pressure along the span of the plain trailing edge was consistent with previous investigators. Figure 2 shows the variation of base pressure as a function of the separating boundary layer momentum thickness, θ (normalised with respect to the base height).

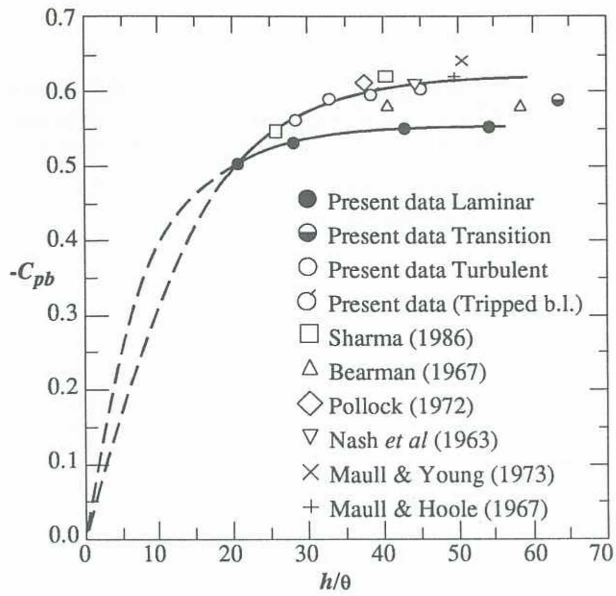
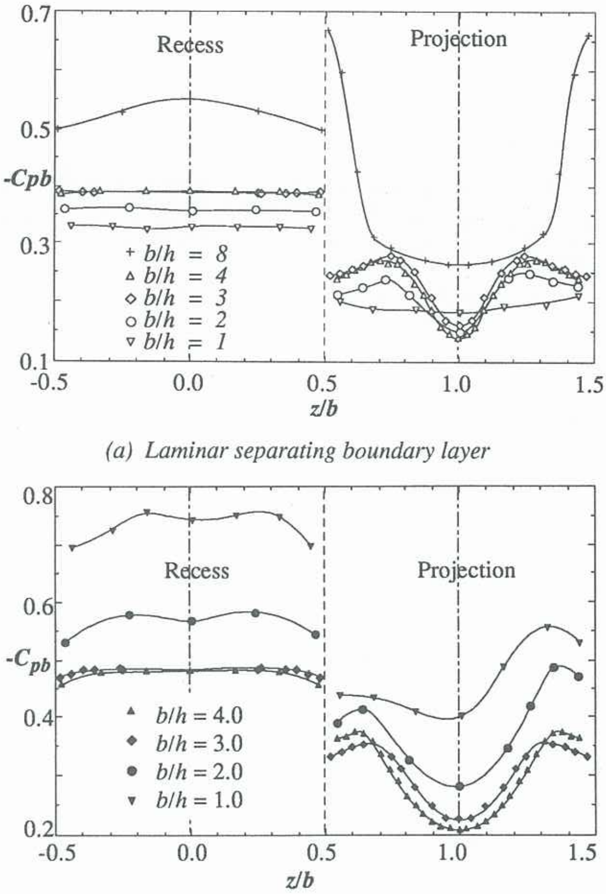


Figure 2 *Base pressure for the two-dimensional trailing edge as a function of separating boundary layer momentum thickness*

It can be seen that there are two distinct curves for the laminar and turbulent separating boundary layer (referred to simply as the boundary layer). Included in this figure are the results of previous investigators. In some of the references, the values of h/θ were not given and in these cases h/θ was taken from Sharma (1986) who calculated the values based on the given experimental conditions. The trend for both the laminar boundary layer (denoted by the filled circles ●) and the turbulent boundary layer (denoted by the open circles ○) is seen to be very similar with the transition results given with the symbol ◒.

The turbulent boundary layer value of $C_{pb} = -0.6$ compares favourably with previous experiments. The asymptotic value for C_{pb} with a laminar separating boundary layer is approximately -0.55. The value of h/θ at which the base pressure is essentially invariant is denoted as h/θ^* and has the approximate value of $h/\theta^* \approx 30$ for the turbulent boundary layer and $h/\theta^* \approx 25$ for the laminar boundary layer.

Detailed measurements of base pressure on the segmented trailing edge (see figure 3) show that the pressure on the recess does not vary as much as on the projection. The reason for this is that the edges of the projection act like end-plates and therefore the base flow in the recess is more two-dimensional. The two-dimensional nature of the base region in the recess has been verified for $b/h = 3$ using low Reynolds number flow visualization (see Petrusma & Gai, 1989 and Rodriguez, 1991) and also at higher Reynolds numbers using surface flow visualization (Petrusma, 1990). The recess base pressures for smaller segment widths do show a greater variation across the span which can be attributed to a greater percentage of three-dimensional flow across the span of the segment. Most of the pressure distributions were similar, with the exception of the results for $b/h = 8$ which are discussed separately.



(a) Laminar separating boundary layer

(b) Turbulent separating boundary layer

Figure 3 Spanwise base pressure distribution for the segmented trailing edge.

For $b/h = 8.0$ the pressure distribution on the recess was more akin to that of a two-dimensional trailing edge spanning the tunnel width. In both cases the effect of higher static pressure near the side walls is observed with a lower base pressure at the centreline. In the case of a two-dimensional trailing edge the higher pressures were due to the presence of the tunnel sidewall boundary layer, and in the case of the segmented trailing edge ($b/h = 8.0$) the effect is due to the entrainment of fluid into the recess from the top sides of the projection. The base pressure distribution across the central region of the projection consisted of a broad, bucket shaped maxima (see figure 3a). The flatness of the base pressures is indicative of predominantly two-dimensional flow inside this portion of the vortex formation region, while end effects are clearly visible at the outer extremities. The value of base pressure in the central region does not assume that of the plain trailing edge which implies that the strength of the shedding spanwise vorticity is reduced.

For the other base geometries the base pressure distributions on the projection vary considerably more than that of the recess, and the flow visualization experiments referred to above indicate that this is due to a greater three-dimensionality in the base flow. The two minima in the distribution can be attributed to a pair of contra rotating vortices in the vortex formation region (see Petrusma & Gai, 1989). Evidence that these vortices exist in the higher Reynolds number, turbulent wake flow can be inferred from oil flow visualization experiments (Petrusma, 1990) which show an accumulation of oil on the outer extremities of the projection base. The surface flow patterns are consistent with the topology of these vortices. The importance of these vortices, and the flow induced by them, is fundamental to the reduction of base drag (as will be discussed below).

3.2 Effect of Reynolds Number

In this series of experiments the effect of Reynolds number on the base pressure was investigated using models with and without the turbulent boundary layer trip. The boundary layer velocity profile was measured with a hot-wire and from these traverses it was observed that the separating boundary layer was laminar until $Re_c \approx 3.8 \times 10^5$ and that a fully turbulent separating boundary layer was not observed until $Re_c \approx 4.8 \times 10^5$.

3.2.1 The plain blunt trailing edge

In the laminar regime, up to $Re_c \approx 3.8 \times 10^5$, the base pressure decreases monotonically with Reynolds number (see figure 4) and it is noted that the boundary layer thickness also decreases with Reynolds number in this range. The rate of increase in base pressure with Reynolds number is not great because the values of h/θ are close to h/θ^*. As the boundary layer undergoes transition h/θ decreases with Reynolds number until the fully turbulent boundary layer is attained. From this point on small increases in h/θ can be expected as the Reynolds number increases.

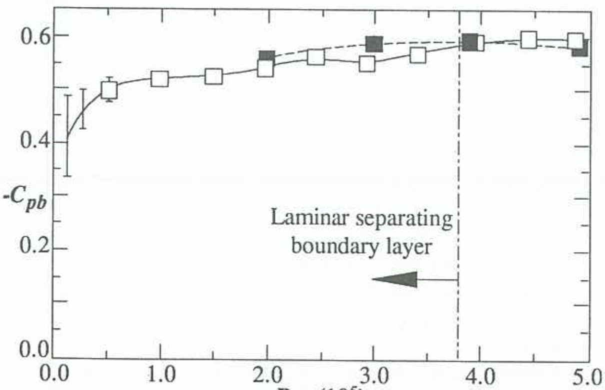


Figure 4 Base pressure coefficient vs Reynolds number for the plain trailing edge. Filled symbols and dashed lines represent the tripped boundary layer data.

As transition to turbulence occurs several important characteristics of the separating boundary layer change. Of these characteristics only two will be discussed here: firstly, the thickness increases, and secondly, the rate of momentum transfer increases. The effect of the former is to increase the base pressure, as can be seen in the relationship of h/θ *vs* C_{pb}. The extent to which base pressure will increase is strongly dependent on the value of h/θ, for values of $h/\theta < h/\theta^*$. If $h/\theta > h/\theta^*$ then C_{pb} effectively remains constant.

The effect of increased rates of momentum transfer is to increase the rate at which fluid is entrained out of the base region, and hence the base pressure will decrease. For values of h/θ greater than h/θ^* any decrease in h/θ through transition will result in only small increases in base pressure. Given this, it is likely that the decrease in base pressure, due to higher rates of entrainment of fluid out of the base region, will be greater than the increase in base pressure caused by a thickening of the boundary layer and a net decrease in base pressure will occur as seen in figure 4.

3.2.2 The segmented blunt trailing edges

The results presented in figure 5 shows that the rate at which C_{pb} decreases with Reynolds number in the laminar regime is approximately the same for all of the models tested, including the plain blunt trailing edge. It is not until transition in the boundary layer that the greatest divergence in the results of the various trailing edges is observed.

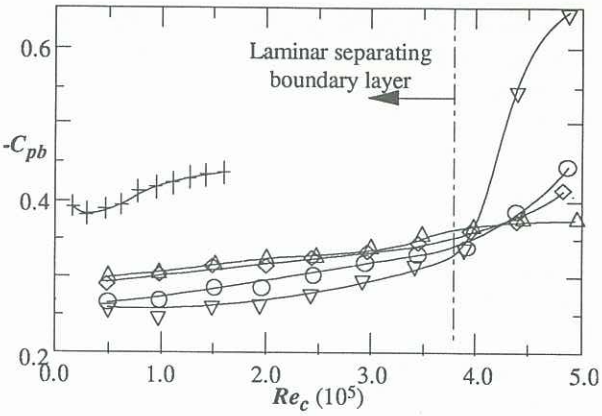


Figure 5 Base pressure coefficient vs Reynolds number for segmented trailing edge geometries. +, $b/h = 8$; △, $b/h = 4$; ◇, $b/h = 3$; ○, $b/h = 2$; ▽, $b/h = 1$.

With a laminar boundary layer the base pressure on the recess was higher than those of the plain trailing edge (in the range of b/h investigated) and the base pressure was observed to decrease with increasing Reynolds number. That is, C_{pb} decreased with increasing h/θ, or decreasing boundary layer thickness. The base pressures on the projection were always higher than on the recess and followed a similar trend.

The most significant changes in base pressure with Reynolds number were observed when the separating boundary layer underwent transition to turbulence and particularly so for short segment widths. In this Reynolds number range a decrease in base pressure was observed for all values of b/h with the short segment widths exhibiting a much greater decrease in C_{pb}. The variation of base pressure with b/h and boundary layer state can be clearly seen in figure 6

It was noted above that the boundary layer thickness increases with the onset of transition and that, depending on the value of h/θ, a variation in base pressure can result from a variation in the boundary layer thickness. However, in this investigation, the value of h/θ was nearly always greater than h/θ^*, particularly for Reynolds numbers at which transition occurs. Thus, the change in boundary layer thickness through transition does not have a significant effect on the base pressure.

Bearman (1967) has shown that for a two-dimensional blunt trailing edge there is a balance between the rate at which circulation is shed (and hence the rate at which fluid is entrained out of the base region by the shear layers), the vortex formation length and the base pressure. For a two-dimensional trailing edge the fluid entrained out of the base region must be replenished by the shear layer being drawn across the wake, whereas for the segmented, or three-dimensional, trailing edge the replenishment of fluid drawn out of the base region can also come from other sources (see flow visualization of Petrusma and Gai, 1989 and Rodriguez, 1991). One of these sources is the pair of contra rotating vortices (see §3.1) on the projection which draws fluid from the recess into the formation region of the projection. It has been shown (Petrusma, 1990) that this second replenishment process, denoted as $\dot{\vartheta}$, reduces the amount of fluid required from the shear layer crossing the wake and hence increases the formation length and base pressure.

It has already been noted that the two-dimensional trailing edge is little affected by the change in the state of the boundary layer. On the other hand the results of the segmented trailing edge imply that the change in the boundary layer state has a significant effect on $\dot{\vartheta}$. It can be argued that since the existence of $\dot{\vartheta}$ is a result of three-dimensionality in the trailing edge then a change in $\dot{\vartheta}$ will be observed to a greater extent in the trailing edges with more three-dimensionality per unit span, namely the shorter width segments. Hence, given that a change in the state of the boundary layer effects $\dot{\vartheta}$, this will be seen to a greater extent in the shorter width segments. The results presented in figure 5 show that the base pressure for the shorter width segments has a much greater dependence on the state of the separated boundary layer giving some validity to the arguments.

3.3 Effect of Segment width

The effectiveness of each geometry, in terms of base pressure recovery, was obtained by normalising the mean base pressure of the segmented trailing edge with respect to the base pressure of the plain trailing edge (denoted Λ). The base pressure recovery can then be defined as $(1-\Lambda)$. The base pressure recovery has been plotted as a function of the trailing edge geometry. In this case the segment span was chosen since the optimal depth of the recess was used. Figure 6 gives Λ as a function of h/b.

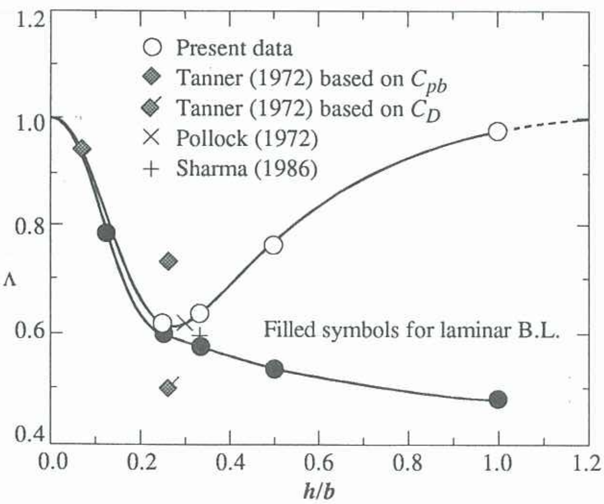


Figure 6 Effect of segment width on the base pressure recovery factor, Λ.

The trends in Λ for both laminar and turbulent separating boundary layers are initially very similar, however a divergence is seen at $b/h \approx 4.0$. This value of segment width is also close to the optimum value for the turbulent boundary layer for which the maximum base pressure recovery is 38%. The results for the turbulent boundary layer show an increase in Λ (or a decrease in the effectiveness of the segments) which continues past $h/b = 1.0$ and appears to be asymptotic to $\Lambda = 1.0$.

The laminar separating boundary layer, on the other hand, shows no decrease in base pressure and it is observed that a maximum base pressure recovery of $\Lambda = 52\%$ occurs for $b/h \approx 1.0$. It is reasonable to assume that if $h/b >> 1.0$ then eventually trend similar in nature to that seen when the separating boundary layer is turbulent may be expected to occur. Then one would expect that reducing b/h would have a detrimental effect on the base pressure recovery. In fact, when $h/b \to \infty$ (or $b/h \to 0$) or when there are an infinite number of segments, the geometry tends to that of the plain trailing edge and $\Lambda \to 1.0$.

4. Conclusions

Base pressure measurements and flow visualization were used to investigate the flow behind segmented blunt trailing edge aerofoils. The base pressure was found to be a function of the separating boundary layer and it has been shown that the state of the boundary layer has a strong influence on the replenishment process of the vortex formation region and hence the base drag.

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