INVESTIGATION INTO THE WAKES OF BLUNT TRAILING EDGE AEROFOILS AT LOW REYNOLDS NUMBERS

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ABSTRACT

The wakes of a plain and segmented blunt trailing edge aerofoil were investigated at low Reynolds numbers. A laminar discontinuity in the Strouhal-Reynolds number curve, similar to that in the case of the circular cylinder, was also present in the case of the blunt trailing edge aerofoils. Evidence was found to support the idea that partial conversion of nominally two-dimensional spanwise vorticity into streamwise vorticity is the main mechanism for drag reduction of segmented blunt trailing edge aerofoils.

1 INTRODUCTION

Various authors in the past have shown that there are considerable gains to be made from aerofoils with blunt trailing edges at both supersonic (Chapman 1952) and transonic speeds (Holder 1964). These aerofoils however, exhibit a high base drag, which becomes the dominant contribution to drag in the subsonic, transonic and even low supersonic regimes.

It has been shown that the main reason for this high base drag, or low base pressure, is the predominantly two-dimensional vortex shedding (Roshko 1955). As a result, any method employed to inhibit this two-dimensional shedding would also modify the base pressure. The use of splitter plates and base bleed to increase base pressure and modify two-dimensional vortex formation have been investigated (Bearman 1965, Wood 1964); however, other means of obtaining favourable base pressure recovery, such as geometrically altering the trailing edge have not yet been fully investigated

One successful method of altering the geometry of the trailing edge is that of forcing a discontinuous separation line. Examples of this have been segmented trip wires near the separation point on a cylinder (Naumann *et al* 1966) and castellations on a blunt trailing edge aerofoil (Gai & Sharma 1986, Pollock 1972, Tanner 1972). In the latter example it has been shown that up to 60% base pressure recovery is obtainable through what is attributed to be the inhibition of the spanwise vortex shedding. Studies by Gai & Sharma (1986) into the wakes of segmented trailing edges through the use of hot wire anemometry and base pressure measurement have found that the two-dimensional vortices were weakened by the presence of the castellations but not totally destroyed. It is believed that the castellations turn some of the spanwise vorticity into streamwise vorticity, and thus reducing the base drag.

This paper presents shedding frequency data and aims to clarify the mechanism of base drag reduction through the use of hot film anemometry and flow visualization experiments.

2 EXPERIMENTAL ARRANGEMENT

The experiments were performed in the 160 x 80 mm gravity driven water tunnel in the Mechanical Engineering Department at the Australian Defence Force Academy. The freestream turbulence level was of the order of 0.3% in the velocity range 0.7 to 27 cms^{-1}. The Reynolds number range, based on aerofoil base height, h was 150 to 2300.

The models were two-dimensional 10% thick blunt trailing edge aerofoils, as shown in Fig. 1. The semi-elliptic leading edge section was common to both models with the trailing edge section being inter-changeable. Two trailing edges were used, namely: (i) A plain trailing edge, and (ii) a segmented trailing edge with $a/h = 2$, $b/h = 3$, with $h = 6$ mm, dimensions being defined in Fig. 1. Both trailing edges had dye injector holes located in the base shown in Fig. 1. The model spanned the test section giving an aspect ratio based on base height of 27 and a solid blockage of 7.5%.

Hydrogen bubble and dye line flow visualization experiments were conducted in most of the above velocity range mentioned. The hydrogen bubble wire spanned the model at a position of three base heights upstream of the trailing edge, and at approximately 1/3 the base height above the top surface of the model (see Fig. 1). Illumination of the hydrogen bubbles was provided by a laser light sheet orientated in the xz plane. Spherical objects such as bubble are best viewed at 135° to the incident illumination, and as a results of this, some skew is evident in the hydrogen bubble photographs. For the dye line experiments the dye was injected into the flow from an upstream probe (moveable in the y and z directions) and at three locations in the base. To avoid inducing base bleed the dye flow was shut off and the dye was then observed as it migrated out of the base region.

The velocity fluctuations in the wake were measured by a TSI conical hot film sensor with a TSI constant temperature hot film anemometer. The sensor was located four base heights downstream of the trailing edge, and just above the height of the trailing edge. The signal from the anemometer was then processed on an Analogic DATA 6000 wave-form analyzer.

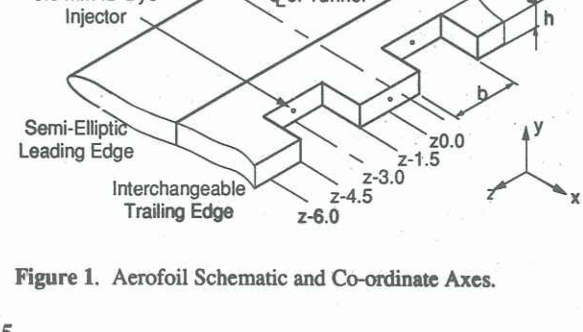


Figure 1. Aerofoil Schematic and Co-ordinate Axes.

3 RESULTS AND DISCUSSION

3.1 Shedding Frequency

From the data obtained from the hot film probe graphs of Strouhal number, *S* vs *Re* (Fig. 2) and non dimensional shedding frequency, *F* vs *Re* (Fig. 3) were plotted. *S* is defined as fh/u where f is the shedding frequency, h is the base height, u is the freestream velocity, and F is defined as fh^2/ν where ν is the kinematic viscosity. In these figures the data presented is the mean of approximately 3 to 10 data points taken consecutively while the experimental conditions were held constant. The data presented for the segmented trailing edge has been taken from the spanwise locations $z/h = 0, \pm1.5, \ldots, \pm6.0$.

Figs. 2 and 3 show that the onset of shedding occurred at $Re = 154$ for the plain trailing edge and at $Re = 274$ for the segmented trailing edge. These figures also show a laminar discontinuity in the *S-Re* relationship accompanied by a change of slope in the *F-Re* relationship at $Re \approx 215$ for the plain trailing edge and at $Re \approx 650$ for the segmented trailing edge. Transition to turbulence in the wake occurs at $Re \approx 570$ and $Re \approx 1765$ respectively.

Similar discontinuities in the *S vs Re* curve and changes in slope in the *F vs Re* curve have been seen for circular cylinders, however these discontinuities occur at a lower Reynolds numbers and the slopes of the lines between the discontinuities are less. Many reasons for this discontinuity have been suggested and include both non-fluid mechanical and real fluid mechanical properties. The elimination of the discontinuity in the *S vs Re* curve has been suggested in a number of ways which include the absence, or removal of: (i) freestream turbulence , (ii) model vibrations, and (iii) end effects. The validity of the existance of the discontinuity has also been argued on the basis of fluid mechanical properties.

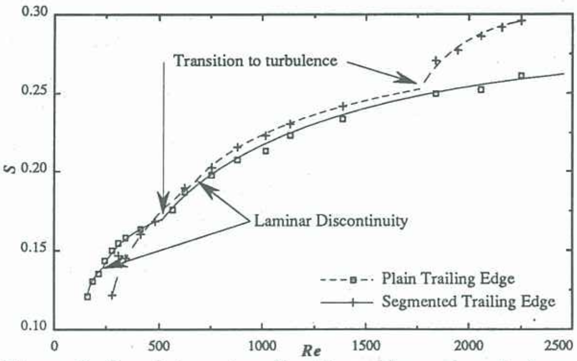


Figure 2. Strouhal number, *S vs* Reynolds number, *Re* for a plain and segmented blunt trailing edge aerofoil.

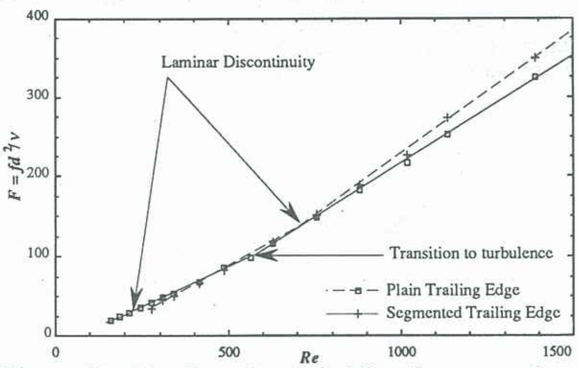


Figure 3. Non-dimensional shedding frequency, *F vs* Reynolds number, *Re* for a plain and segmented blunt trailing edge aerofoil.

The tendency for the Strouhal-Reynolds number curve to asymptote, as is the case for the circular cylinder, is not clearly evident for the plain and segmented blunt trailing edge aerofoils within the Reynolds number range investigated. However, the curve for the plain trailing edge could be extrapolated to $S = 0.26$, which is consistent with results obtained at slightly higher Reynolds numbers. What is clear is that in the Reynolds number range investigated the Strouhal number increases with Reynolds number for both models and that the final value of Strouhal number for the segmented trailing edge is higher than the plain trailing edge indicating that the base pressure for the former is higher. This is in agreement with other investigators who found a higher base pressure for a discontinuous separation line. (Tanner, 1972; Gai & Sharma, 1986).

3.2 Flow Visualization

(i) Plain trailing edge experiments. These experiments indicated that the wake of the plain trailing edge exhibited similar flow patterns to those behind a circular cylinder, although the different characteristics in the wake, as discussed below, were at higher Reynolds numbers for the plain trailing edge.

Immediately after the onset of shedding and for Reynolds numbers slightly greater than $Re = 154$ hydrogen bubble photographs indicated that the wake was stable and the vortex shedding was parallel to the trailing edge (similar to that seen in Fig. 4). For Reynolds numbers up to 209 the vortex lines exhibited strong bending, and again the wake appeared stable (similar to that seen in Fig. 5). In the Reynolds number range 209-635 periodic changes were seen in the wake. Assuming first that the vortex lines were parallel to the trailing edge (Fig. 4), they then began to bow downstream (Fig. 5). A short time later the vortices shed in the central portion of the wake could no longer retain their stretched shape and strong streamwise vorticity was seen as the central vortex lines attempt to terminate themselves at these points (Fig. 6). It should be noted that Figs. 4-6 are at the same Reynolds number, but are different events in time. At Reynolds numbers higher than 635 the vortex lines were essentially straight, although they were slanted at an angle to the trailing edge. The angle at which the vortices were shed varied in a periodic manner from the position shown in Fig. 7 to that of the dashed line also shown in Fig. 7. In all cases when the flow exhibited a periodic nature the period was of the order of seven to thirty times that of the shedding frequency. An exact value for this period is not given as the susceptibility of the wake to even minute changes in the freestream conditions made this difficult.

(ii) Segmented trailing edge experiments. Hydrogen bubble experiments showed that the wake exhibited similar modes of shedding to those seen above, but that it also contained added three-dimensionality due to the presence of castellations.

Below $Re = 650$ the shed vortices were stable and from the hydrogen bubble experiments it can be seen that the presence of castellations caused strong streamwise vorticity at $Re = 274$ in the form of vortex stretching (Fig. 8). Vortex stretching is not unique and has been observed in free shear layers by Breidenthal (1981) and also predicted in free shear layers by Pierrehumbert & Widnall (1982). With an increase to $Re = 417$, and with the aid of dye line experiments the stretched vortex filaments can be seen to undergo a change to being interlaced horseshoe shaped (Fig. 9). Once again these types of vortex patterns are not unique and have been seen in neutrally buoyant wakes. (Breidenthal, 1980; Perry, 1986).

Dye line experiments were also used to view the shed vortices from the side and it was noted that there were differences in the shape of the wake above, below and at $Re = 650$. Below $Re = 650$ the vortex pattern was very much like the typical von Kármán vortex street as seen in Fig. 10a. At $Re = 650$ the wake is distinctly chaotic in its behaviour (Fig. 10b), the suspected reason for which will be discussed in (iii) below. Above $Re = 650$ two photographs are presented for the side view of the wake. Fig. 10c shows the generally stable wake, while Fig. 10d shows the wake undergoing a periodic disturbance, the cause of which will be discussed below.

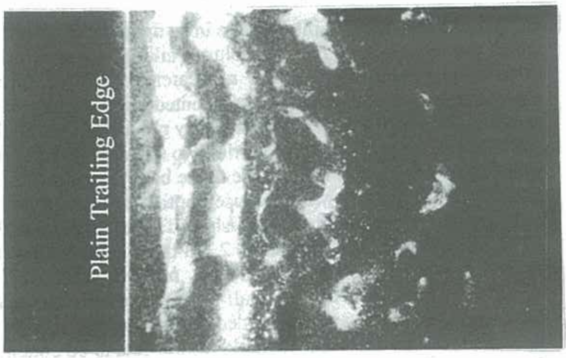


Figure 4 Plan view hydrogen bubble of the plain trailing edge. Illumination in the xz Plane. Re = 351. Flow from left to right.

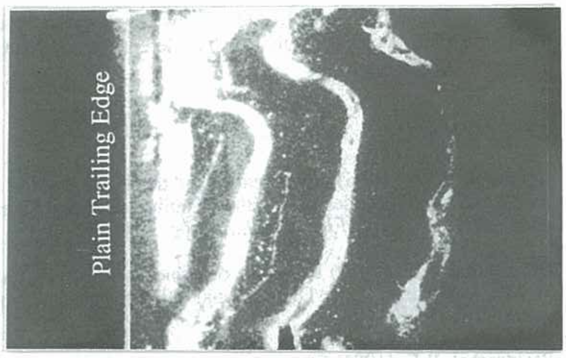


Figure 5 Plan view hydrogen bubble of the plain trailing edge. Illumination in the xz Plane. Re = 351. Flow from left to right.

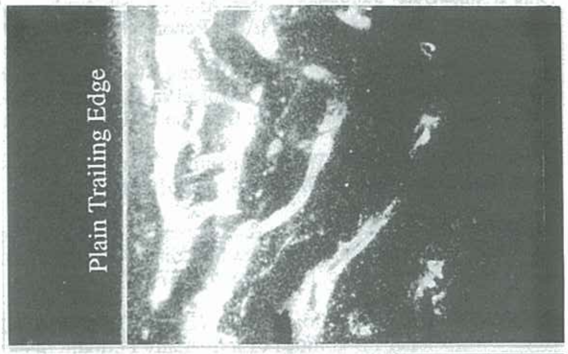


Figure 6 Plan view hydrogen bubble of the plain trailing edge. Illumination in the xz Plane. Re = 351. Flow from left to right.

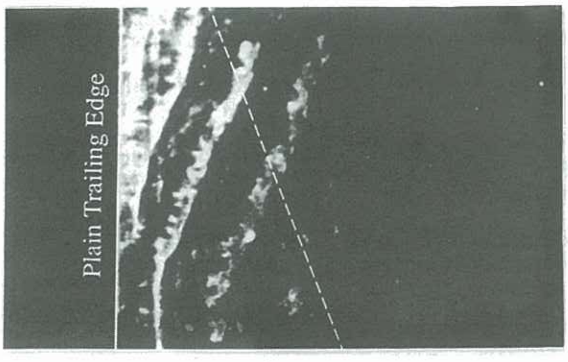


Figure 7 Plan view hydrogen bubble of the plain trailing edge. Illumination in the xz Plane. Re = 766. Flow from left to right.

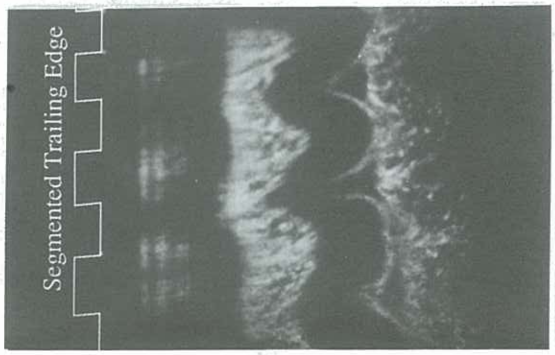


Figure 8 Plan view hydrogen bubble photographs of the segmented trailing edge at Re = 274. Flow from left to right.

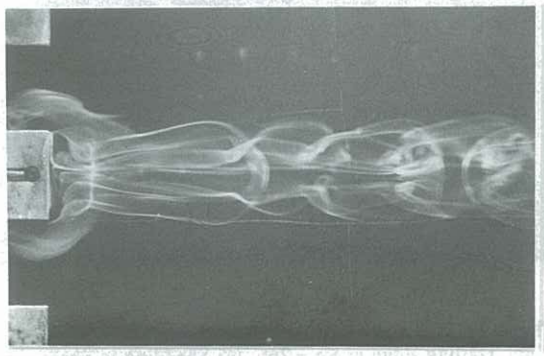


Figure 9 Plan view dyeline photographs of the segmented trailing edge at Re = 417. Flow from left to right.

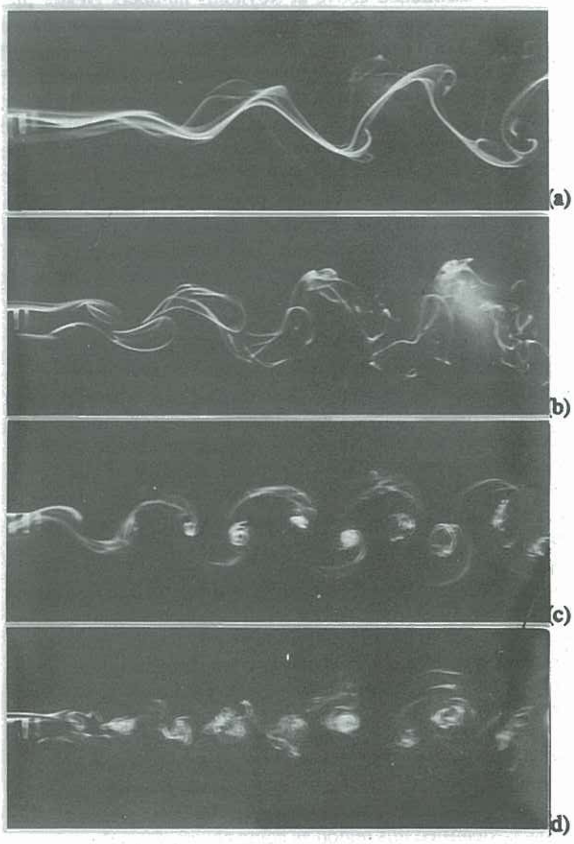
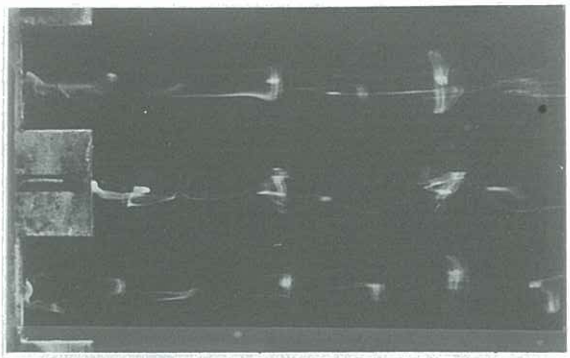


Figure 10 Side view dyeline photographs of the segmented trailing edge. (a) Re = 417, (b) Re = 650, (c) Re = 766 undisturbed, and (d) Re = 766 disturbed.



(a)

(b)

Figure 11 Plan View Dye Line Photographs of the Segmented Blunt Trailing Edge at Re = 766. (a) Shedding in phase, and (b) Shedding out of phase and disturbed.

As mentioned above at Reynolds numbers greater than 650 the wake was observed to undergo a periodic disturbance. From Fig. 11a it can be seen that when the vortices are shed off the recess and projection in phase the wake is undisturbed. A short time later, as noted in the case of the plain trailing edge, slantwise shedding begins, and the vortex filaments behind the recess and projection are out of phase. However, as of yet the wake is undisturbed. Finally as the phase angle between the vortices shed off the recess and projection approaches 180° a sudden disturbance is seen in which streamwise vorticity is seen (Fig. 11b). Unfortunately due to lighting arrangements the side and plan could not be photographed simultaneously, however the photographs of Fig. 10d and Fig. 11b are of similar events.

One possible reason for the sudden change to the disturbed, or excited state, is that a degree of tolerance exists to which the spatial separation between two sets of vortex cores does not effect local two-dimensional shedding (Naumann *et al*, 1966). Once this critical separation is achieved the shedding changes mode dramatically. The prominent lack of mixing between regions off the recess and projections has also been observed from hot wire data in the near wake (Gai & Sharma, 1986).

(iii) Comparison with the shedding frequency. It is readily apparent from flow visualization of the segmented trailing edge that there are distinctly different modes to the shedding at Reynolds numbers above and below the laminar discontinuity. Considering the wake of the segmented trailing edge at $Re = 650$ (Fig. 10b), which corresponds to the Reynolds number of the laminar discontinuity, it is seen that the wake is distinctly chaotic. The Reynolds number range immediately surrounding the laminar discontinuity in the *F vs Re* curve of a circular cylinder has been investigated by Sreenivasan (1985) who has identified this region as being chaotic from the velocity spectra obtained by hot wire. At Reynolds numbers above the laminar discontinuity the wake undergoes periodic slantwise shedding.

4 CONCLUSION

In the Reynolds number range investigated it is seen that whilst the wake behind the plain blunt trailing edge aerofoil is three-dimensional, there exists a greater amount of three-dimensionality in the wake of a segmented blunt trailing edge aerofoil. This added three-dimensionality manifests itself in the partial conversion of spanwise vorticity to streamwise vorticity, which in turn is seen as an increase in the base pressure. As regards to the geometry which causes optimum base pressure recovery, it has already been established (Tanner, 1972) that the depth of the recess, a/h, should be 2. In these experiments the spanwise geometry of the castellation, b/h was based on the work by Pierrehumbert & Widnall (1982), however the optimum configuration is yet to be decided on the basis of base pressure measurements and Reynolds stress data to be obtained from the wind tunnel testing of several different models.

ACKNOWLEDGEMENT

The first author would like to acknowledge the support of a research scientist cadetship given by the Aeronautical Research Laboratories, Melbourne.

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