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UNSTEADY MOTION OF VORTEX-BREAKDOWN POSITIONS ON DELTA WINGS

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Abstract

The oscillatory, relative motion of the vortex-breakdown positions on the two sides of delta wings, which occurs at high incidence, just before the vortex system degenerates into a disorganised, bluff-body wake, was studied in a water tunnel, using flow visualisation. This phenomenon may play a part in initiating wing rock.

Two kinds of oscillation were normally seen - firstly a fore-and-aft type and then, at a higher incidence, a side-to-side type. However, two wings having the smallest sweepback tested (sixty degrees) exhibited the first kind only very briefly.

The parameters varied were wing size, sweepback, incidence and flow speed. An attempt is made to correlate the results using dimensional analysis and a tentative explanation of the phenomenon is proposed.

Nomenclature

c = wing mean chord
n = frequency of oscillations
Re = Reynolds number based on c
Sr = Strouhal number, nc/v
v = free-stream velocity
α = wing incidence
Λ = wing leading-edge sweepback

Introduction

The phenomenon of leading-edge vortex breakdown, with its important effects on the properties of thin, highly-swept wings, has been studied for over thirty years and, although it is still not completely understood, its qualitative nature is well known and some empirical, quantitative data on breakdown behaviour is well established. For more complete information the reader is referred to the survey papers by Hall(1) and Leibovich(2).

The current interest in rapid, high-incidence maneuvers of aircraft and missiles has led to an upsurge of interest in dynamic aspects of vortex-breakdown behaviour (see, for example, references 3 and 4), although an earlier paper touched on the subject(5). Time-dependent changes within the vortex-breakdown flows themselves have been investigated by Chanaud(6) and Garg(7).

However, whereas references 3 to 5 deal with vortex-breakdown movements in response to those of the wing, the present paper deals with oscillatory movements of the breakdown positions on a delta wing fixed in a steady free stream. Such oscillations are seen when the incidence is high enough to bring the breakdowns to within a few percent of the root chord from the apex and they occur only over an incidence range of a few degrees, prior to the complete disappearance of any kind of organised vortex structure on the wing upper surface and the appearance of a disorganised, bluff-body type of wake in its place.

The observations on fixed wings reported here may have some relevance to certain forms of the wing-rock phenomenon, which has been fairly extensively studied in recent years.(8-12) However, although the present phenomenon may initiate wing-rock at high incidences, the actual mechanism maintaining the process seems to depend on the dynamic interaction of the wing and vortex motions, so that the present results may only have a very indirect connection with it.

Apparatus and Method

The experiments were carried out in the RAFAEL Water Tunnel, which is a vertical-flow, gravity-operated tunnel, with continuous-flow capability up to a working-section velocity of about 60 cm/s, the water being returned to the upper tank by a centrifugal pump. Velocities up to 170 cm/s can be reached in the "fall-down" mode at flow rates beyond the maximum supply capacity of the pump. The working section has a cross-section 45 cm. square and 180 cm. high. Water speeds from about 10 cm/s to 60 cm/s were used in the experiments.

The design of the tunnel permits operation for extended periods without the high quality of the flow deteriorating or the water speed in the working section changing significantly - an essential requirement for the present investigation which involved observation of the flow for fairly long time intervals. In addition, the tunnel circuit contains a large volume of water, so that the build-up of background colour in the flow is very slow with the small amounts of dye used in these experiments.

Six delta wings, with sharp edges, produced by symmetrical bevelling on upper and lower surfaces, were used and their properties are given in Table 1.

MODEL	L.E. SWEEP-BACK ANGLE (deg.)	ROOT CHORD (mm.)	THICKNESS (mm.)	INCLUDED EDGE ANGLE (deg.)
1	60	68.4	0.8	15
2	60	136.8	1.6	15
3	65	84.7	0.8	15
4	70	108.5	0.8	15
5	75	150.0	3.175	20
6	75	300.0	6.35	20

TABLE 1

Two fine dye tubes were fixed along the center line of the under surface of each wing, terminating slightly behind the apex, with exits cut back parallel to the leading edge, so that the dye was ejected sideways into the stream where it was swept backwards over the leading edges into the core region, so that the core and the vortex burst were made visible. The supply ends of the tubes left the tunnel via the support strut and were connected to a dye-supply apparatus which utilised compressed air to overcome the hydrostatic pressure in the working section. The models were supported by a strut fixed perpendicularly to the under surface, except for the large 75 deg. sweepback delta (model number 6), which was mounted on a sting.

At the desired water speed, the incidence was increased until oscillations appeared and these were timed at regularly increasing incidences until the organised vortex structure completely vanished, leaving only a disorganised, bluff-body type of wake.

Results and Discussion

As the incidence was increased at constant water speed, several stages in the vortex-breakdown behaviour were observed. The first was the well-known appearance of the bursts far downstream and their movement forward, over the trailing edge and onwards, over the upper surface, towards the apex. During this stage the vortex-burst positions were steady, apart from small, rapid, fore-and-aft movements, caused, it seems, by the rotating, spiral, breakdown structure (c.f. reference 6) or by buffeting due to turbulence in the core after breakdown(7). These perturbations continued in the later stages, described below, superimposed on the main oscillations.

When the breakdowns had reached a position over the front part of the wing, exactly where depending on the sweepback angle, a stage of alternating fore-and-aft oscillations began on all the wings and the larger the sweepback the longer this continued. For Wings One and Two this stage was very brief. After a short transition phase, the oscillations changed to a new type in which a slight fore-and-aft movement was accompanied by a vigorous side-to-side one, in which one vortex was swept across the wing and under its opposite number, which lifted up to accommodate this, reappeared on its own side after a short interval and then, in its turn, swept the other vortex across and under. On further increasing the incidence, these movements became weaker and the vortex structure gave way to an eddying wake with weak side-to-side movements and finally to a disorganised, bluff-body wake.

The breakdowns were occasionally seen to stop in the middle or at the end of an oscillation, due, apparently, to interaction with one of the perturbations mentioned earlier (c.f. reference 6, p.121). The side-to-side oscillations were usually much less prone to this interference than the fore-and-aft ones, due, presumably, to their more positive nature, although, occasionally, the two vortices did remain locked together in their side position for some time before resuming the oscillation.

According to dimensional analysis, for perfectly affine delta wings, the following relationship should hold:

$$Sr = f(Re, \alpha, \Lambda) \qquad (1)$$

In addition, the angles of incidence for the beginning and end of oscillations and for changeover between the two types of oscillation should be functions of sweepback angle and Reynolds number only. The present set of wings is not truly affine: (a) because the edge angles are not correctly scaled and (b) because the thicknesses are not correctly scaled (see Table 1). However, Wings 1 and 2 are correctly scaled with respect to each other, as are Wings 5 and 6. Nevertheless, even for these wings, small details, such as the dye tubes, the mounting and the degree of sharpness of the wing apex prevent complete affinity being attained. However, it seems reasonable to assume that (1) and the other results hold to a good approximation for the set of wings. We will see, however, that this assumption is not completely justified.

Figures 1 and 2 show that the use of non-dimensional parameters, as suggested by (1), collapses the results for Wing 4 into a fairly narrow band; the results for Re = 22600 being a bit out of line for $\alpha < 45$ deg., which is the region for fore-and-aft oscillations. The results for the remaining wings are given, in dimensionless form only in Figures 3 to 5. The graphs for any one of the wings at different Reynolds numbers are seen to fall close to each other, once more lending credence to the use of water tunnels, with their inherently low Reynolds numbers, for investigating vortex flows. The variation of Sr with α at a given Re is seen to be small - if anything there seems to be a slight tendency for Sr to rise as α increases. As wing leading-edge sweepback increases from 60 degrees to 65 degrees, the average value of Sr rises from about 0.05 to about 0.07 remaining fairly constant for higher sweepbacks. With increasing Λ the range of α covered by the oscillation observations moves to higher values, except for the case of the 65 degree sweepback wing (number 3), whose range is the same as that for the 60 degree wings (numbers 1 and 2). This matter is discussed below.

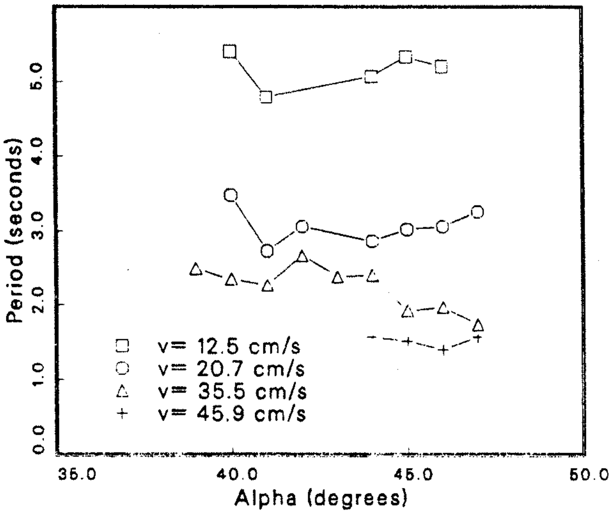

Figure 1. Periodic time vs. incidence for several water speeds - Wing number 4.

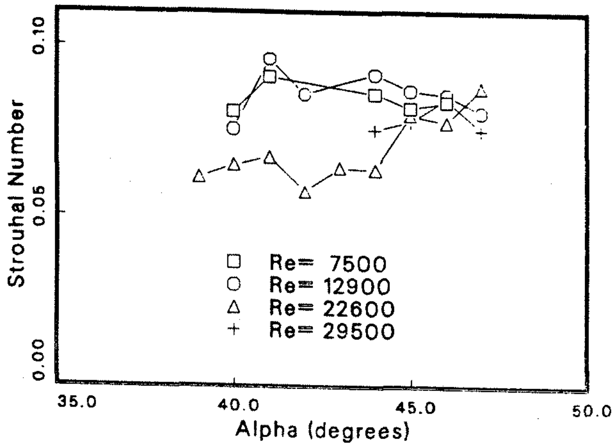

Figure 2. Strouhal number vs. incidence for several Reynolds numbers - Wing number 4.

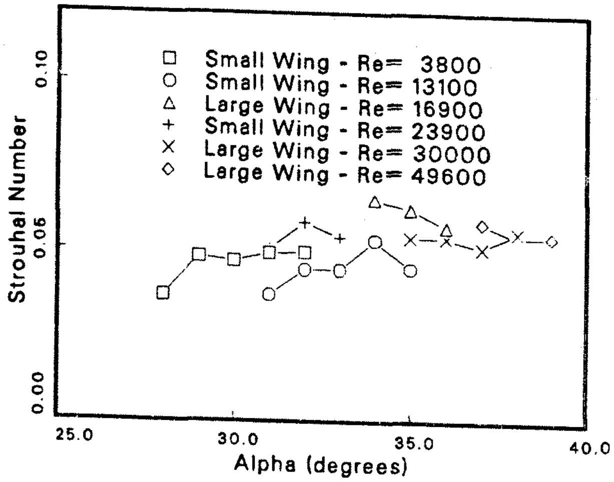

Figure 3. Strouhal number vs. incidence for several Reynolds numbers - Wings 1 and 2.

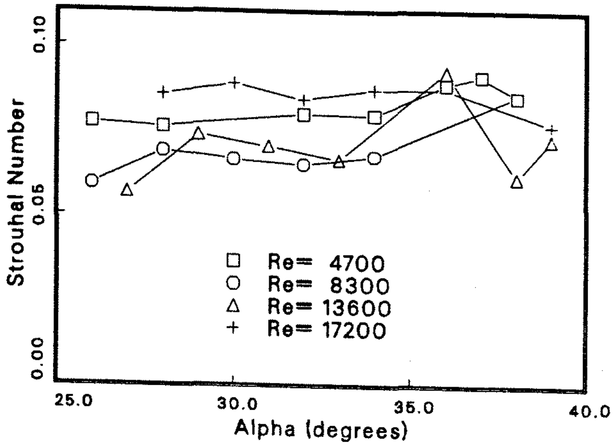

Figure 4. Strouhal number vs. incidence for several Reynolds numbers - Wing number 3.

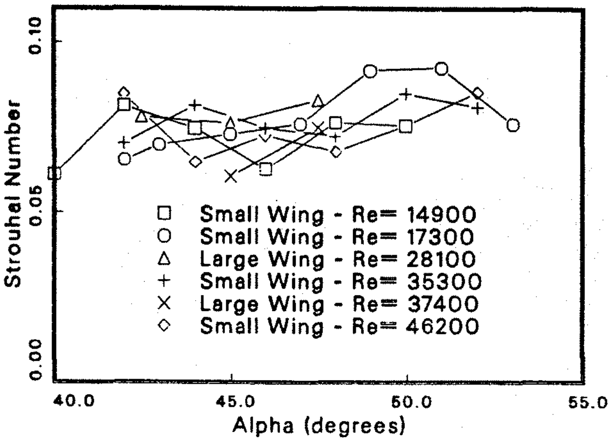

Figure 5. Strouhal number vs. incidence for several Reynolds numbers - Wings 5 and 6.

In Figures 1 to 5, it has been possible to show only a selection of the results obtained and it has not been practical to mark the boundaries between the various types of flow behaviour, however, in Table 2 and Figure 6 we give information, derived from the complete set of data, about these boundaries. The zones which are referred to in the table and figure are defined as follows: in Zone 1 only fore-and-aft oscillations occur, Zone 2 is the changeover region and in Zone 3 only side-to-side oscillations occur. For incidences before Zone 1 small movements only were seen and for those after Zone 3, the bluff-body wake prevails.

MODEL	1	2	3	4	5	6
Start of Zone 1	28-31°	31-34°	26-28°	38-40°	40-42°	40-42.5°
Start of Zone 2	28-31°	31-34°	32-37°	42-44°	47-48°	*
Start of Zone 3	28-32°	31-35°	37-38°	44-46°	49-52°	*
End of Zone 3	33-37°	37-40°	38-39°	47-48°	54-55°	*

TABLE 2

* Results for Wing 6 are incomplete, owing to restrictions on the incidence which could be used, because of the model size.

As regards the correlation between Sr - α graphs for the geometrically similar planforms of different sizes, the small amount of information available on Wing 6 compares well with that for Wing 5, as we see in Figure 5 and this holds also for the data in Table 2. However, comparing the Sr - α graphs shown, for Wings 1 and 2, in Figure 3, we see that, although they seem to form one set, the graphs for the larger wing (Wing 2) begin approximately where those for the smaller wing (Wing 1) finish; that is, the boundaries of the various zones are moved to higher values of α.

This is confirmed in Table 2. This shift cannot be due to differences in Re since one of the graphs for Wing 2 is at a lower Re than one of the Wing 1 set. We conclude that the discrepancy is due to geometrical differences between the models. Examination of the apex of each model under a microscope showed that Wing 1 is considerably more blunt than Wing 2, leading us to surmise that, although the results for the planform lie along one band of values, the exact position of the start of the oscillations etc. depends on the detailed geometry of the point, which is reasonable, since this must fix the degree of disturbance introduced into the vortex core at the outset.

Examination of the other models revealed that Wing 3 was particularly blunt - even more than Wing 1. This explains why the zone boundaries for Wing 3 overlap those of Wings 1 and 2, instead of being nearer to those of Wing 4 as we would expect and also, possibly, why the total range covered by this wing is noticeably longer than those of its neighbours.

The above conclusions have been taken into account in preparing Figure 6, which shows estimated boundaries for the various zones for wings with sharp apexes, plotted together with the boundary marking incidence for breakdown at the trailing edge (see, e.g., reference 13).

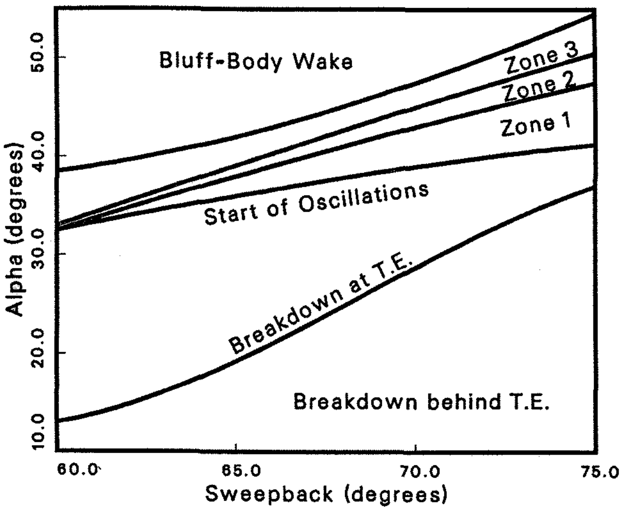

Figure 6. Flow-regime boundaries for sharp-pointed delta wings.

We may give a tentative, somewhat incomplete explanation of the above phenomena as follows. The positions of the breakdowns over the wing seem to be fixed by a balance between the conical-flow conditions generated at the apex and the pressure rise required towards the trailing edge to ensure fulfilment of the Kutta-Joukowski condition there. As the incidence increases and the pressures generated in the conical flow become lower, the influence of the trailing edge extends further forward, driving the breakdowns forward over the upper surface.

When the vortex breakdowns are far back and, therefore, far apart, they hardly influence each other. However, as they approach the apex, they move closer together and this is no longer true. Each breakdown causes a free stagnation point to appear on the vortex axis, with a dividing stream surface reminiscent of that produced by a source in a uniform stream, so that a pressure rise is induced in front of the breakdown, followed by a region of falling pressure as flow speeds up round the sides of the dividing stream surface. If some disturbance now moves one breakdown forward of its partner, the forward one finds itself in an adverse situation and tends to move further upstream and the rearward one experiences the reverse and tends to move further downstream. This continues until each breakdown has moved out of the immediate influence of its partner and finds itself once more dominated by the global effects mentioned above and away from its undisturbed position, to which it is now forced to return, generally overshooting and continuing the above process in reverse to complete a cycle and so on. This constitutes the fore-and-aft oscillation.

At still higher incidences, the vortex strength before breakdown increases and the separation of the breakdowns decreases, such that if one vortex lifts off the wing slightly, due to a disturbance, it is able to sweep the opposite vortex across and under, being itself lifted up in the process by the displacement effect of the fluid being entrained from the latter, which is effectively "swallowed". Since the two closely-locked vortices effectively nullify each other, a new vortex can establish itself on the side of the "swallowed" one, which appears to have "sprung back" to its place from under the other vortex, which also reestablishes itself. The new vortices take up positions such that the one on the side of the original "swallowed" vortex is now slightly higher above the wing, allowing the process just described to be repeated in reverse. This constitutes the side-to-side oscillation. Occasionally the two vortices remain "locked together" at one side for a period of time, because the "swallowing" vortex remains sufficiently dominant to continue absorbing the newly-formed vortex sheet from the other side, so preventing a new core from establishing itself.

The final stages occur when the vortex sheets leaving the wing leading edges immediately behind the apex become disrupted before they have time to form recognizable cores.

Conclusions

Oscillatory relative movements of the vortex-breakdown positions on the two sides of delta wings have been found to occur at very high incidences when the breakdowns are very close to the apex, just before complete disruption of the vortex system and its replacement by a disorganised bluff-body wake occurs. Initially, the oscillations consist of fore-and-aft movements changing to a more complicated side-to-side motion at the later incidences, just before the final disruption.

The results, which were obtained using wings of different sizes and planforms, tested over a velocity range from about 10 to 60 cm/s, correlate fairly well using the Strouhal number, varying little with Reynolds number or incidence. Typical values of Sr vary from about 0.05 for 60 degree sweepback wings to about 0.07 for sweepbacks of 65 degrees and more.

The demarcation incidences between the various stages were found to be very sensitive to the degree of sharpness of the wing point, bluntness tending to shift the whole process to lower values.

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