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VISUALISATION OF VORTEX FLOWS AROUND

Visualisation of Vortex Flows Around Wings with Highly-Swept Leading-Edges

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ABSTRACT

The separated vortex flows around wings with sharp, highly swept leading edges have been studied using flow visualisation techniques in a small towing tank. The effects of wing planform and wing leading edge shape have been investigated using a series of models with planforms including double-delta and gothic strake/delta combinations. In most cases, the wing vortex system consists of a pair of vortices above each lateral half of the wing. The position of these vortices, and the degree of interaction between them, was a function of the angle of incidence, wing planform and wing leading-edge cross-section shape. Changes in Reynolds number were found to have a significant effect on the flow patterns, although this type of flow with separations occurring at a sharp edge is usually regarded as being relatively independent of Reynolds number effects.

INTRODUCTION

The controlled generation of vortex flows features prominently in the aerodynamic design philosophy of modern combat aircraft. Vortex formation occurs above lifting surfaces with sharply swept leading-edges at moderate to high angles of attack. Typical wing configurations include deltas, modified deltas, and sharply swept strakes combined with slightly swept wings.

Interactions may occur between multiple vortices, or between vortices and parts of the airframe. Although techniques are available for modelling the flow around delta wings and modified delta wings (Hoeijmakers(1983), Smith(1984), Hoeijmakers and Rizzi(1984)), the incorporation of interacting vortices is still at a relatively early stage (Peace(1983)), and an understanding of the fluid mechanics of such interactions is important.

Double-delta wings have been tested extensively in wind tunnels and water tunnels (Brennenstuhl and Hummel(1982), Verhaagen(1983)), as have strake/wing combinations (Frink and Lamar(1981)). In the work described here, the vortex patterns around models in a family of double-delta wings were studied using water flow visualisation techniques in a small towing tank. Tests were also carried out on a family of models incorporating gothic planform strakes combined with delta wings. The effects of wing geometry and Reynolds number on vortex formation and interaction were examined. Full details of the tests are given in Thompson(1985).

EXPERIMENTAL PROGRAM

The experiments were carried out in a small Perspex towing tank, 5 m by 0.3 m by 0.3 m. The towing carriage, mounted on linear bearings running on steel shafts, was driven through a pulley and cable system by a variable speed D.C. motor.

The double-delta models were made of 2 mm thick Perspex sheet, and each had a centreline chord of 150 mm. The leading-edge sweep of the forward half (or strake) of each model was 80 deg, and the leading-edge sweep of the rear half (or wing) varied between 80 deg and 40 deg. One set of models had symmetrically bevelled edges, with an included angle of 30 deg. Each model in a second set had a 30 deg edge bevel on one surface only and could be mounted with either the flat or bevelled surface uppermost. A sting mounting beneath the towing carriage allowed model incidence settings in the range 0-30 deg.

All the gothic strake/delta wing models had the same strake planform. The strake chord and span were the same as those on the double delta models. The wing leading edge sweep varied between 80 deg and 40 deg. Again, two sets of models were used, one set with symmetrically bevelled edges and one set with edges bevelled on one surface only.

The hydrogen bubble technique was used for flow visualisation. Electrolysis between cathodes in the form of narrow strips of aluminium foil cemented beneath each model leading-edge and a brass anode mounted on the towing carriage caused the evolution of small bubbles of hydrogen at the surface of the aluminium. The bubbles were entrained by the flow into the vortex system above the wing where they served to delineate the vortex structure, particularly the vortex cores.

Plan views of the flow patterns were recorded using a camera mounted on the towing carriage and pointing down into the water. A Perspex sled moving on the water surface eliminated surface disturbances in the camera field of view. Illumination was provided by lamps mounted on the towing carriage and shining through the tank sides.

To record patterns in cross-flow planes along a model, a 40 mW argon-ion laser was positioned at one end of the tank with its output beam directed along the tank to the towing carriage and reflected down onto the model. Lenses shaped the beam to produce a thin sheet of light in a plane normal to the direction of motion of the model, and the cross-flow bubble patterns were recorded by a camera viewing the patterns via a mirror mounted behind the model.

RESULTS AND DISCUSSION

Double-Delta Wings

An example of the vortex pattern over a double-delta wing is shown in Fig. 1, for the 80/60 deg wing at an incidence of 15 deg and a Reynolds number of 100 000. Under these conditions, two vortices form above each lateral half of the model. The fluid separating from the leading edge of the strake rolls up into a spiral vortex system, similar to that which forms over a simple delta wing. The core of this vortex, clearly marked by the hydrogen bubbles, originates from the strake apex. A second vortex forms over the wing, with its core originating at the kink in the wing leading edge.

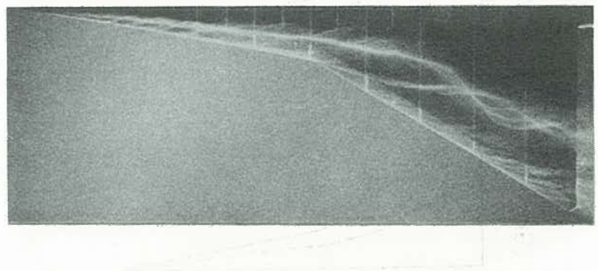

Fig. 1: Vortex pattern over 80/60 deg wing; incidence=15 deg; R=95 000

Fig. 2 shows how the vortex pattern is affected by changes in incidence. At an incidence of 8 deg, the two vortex cores remain separate as they pass downstream over the trailing edge. As the incidence increases, the two vortices begin to interact over the wing. Initially, the strake vortex curves outboard and downwards beneath the wing vortex while the latter remains straight, indicating that the wing vortex is dominating the interaction. As the incidence increases further, the wing vortex core also becomes distorted as it curves inboard above the strake vortex, indicating that the vortices are becoming more evenly matched in strength. The two cores subsequently intertwine and merge as they move downstream. The point at which the two vortex cores first cross as seen in plan view initially moves upstream quite rapidly with increasing incidence, but more slowly at higher angles of incidence.

The strake vortex is initially fed by vorticity shed by the strake leading edge. Downstream of the leading-edge kink this feeding no longer occurs, as the shed vorticity passes instead into the wing vortex. Thus, while the strake vortex remains constant in strength, or may weaken due to viscous effects, the wing vortex gains in strength with increasing downstream distance. The degree to which one or other of the two vortices dominates the interaction depends on the relative strengths of the two vortices and the distance between them at any particular chordwise station. Any change in flow conditions or model geometry which influences either of these factors will affect the interaction process.

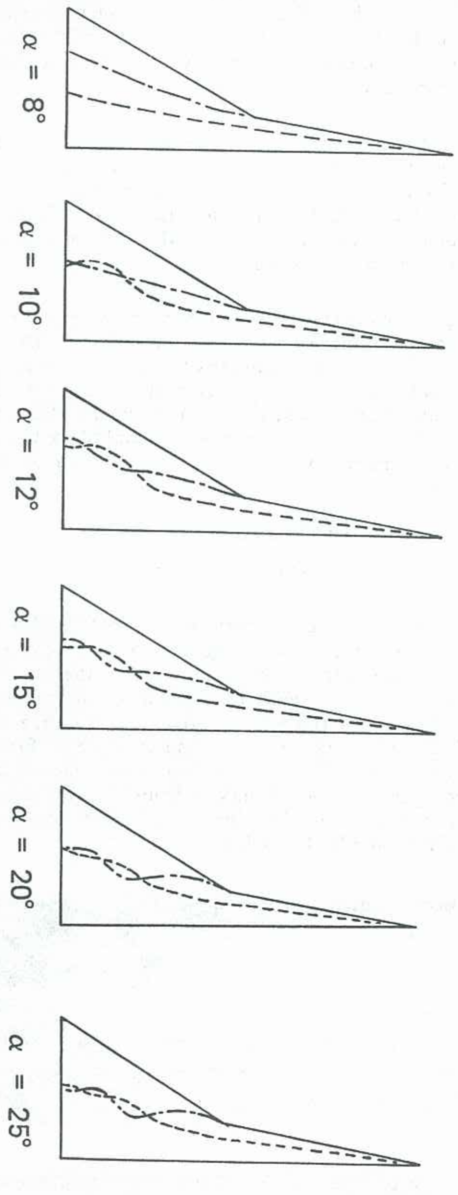

Fig. 2: Effect of incidence on vortex pattern over 80/60 deg wing; R=100 000

Effect of Leading-Edge Kink Angle

The flow patterns over the other double-delta wing models are generally similar to those over the 80/60 deg wing. In general, at a particular incidence, the effect of increasing the leading-edge kink angle from zero is to cause the formation of a separate wing vortex (Fig. 3). The initial spanwise distance between the wing and the strake vortices increases as the kink angle increases. The strake vortex and the wing vortex interact over the wing at low values of kink angle, but the position of the interaction moves downstream past the trailing edge as the kink angle increases.

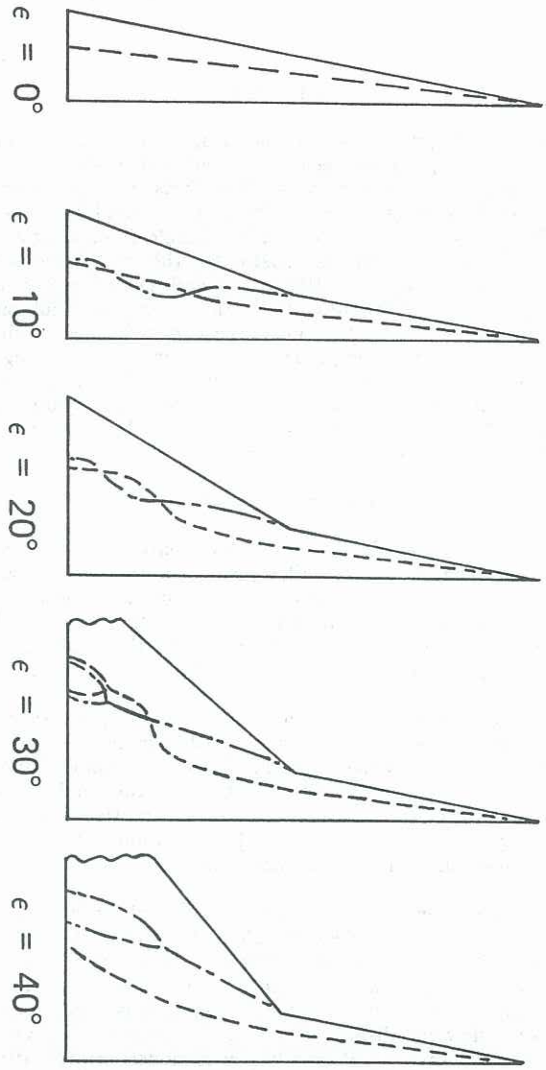

Fig. 3: Effect of leading-edge kink angle on vortex pattern; incidence=15 deg; R=100 000

Effect of Leading-Edge Cross-Section Shape

The results described so far were obtained using models with symmetrically bevelled edges. To investigate the effects of edge cross-section shape on the vortex patterns, the wing models with asymmetrically bevelled edges were tested. Typical results for the 80/60 deg wings at an incidence of 12 deg and a Reynolds number of 100 000 are shown in Fig. 4. Relative to the symmetrically bevelled models, the vortex interaction occurs further upstream, for the model with a lower surface bevel, by about 15% of the centreline chord. In the case of the model with the upper surface bevel, vortex interaction does not occur over the wing at all.

These results indicate that the flow visualisation results obtained using sharp-edged "flat-plate" models must be interpreted with some care, as even the details of the way in which a flat plate is given a sharp edge can have a significant effect on the vortex structure.

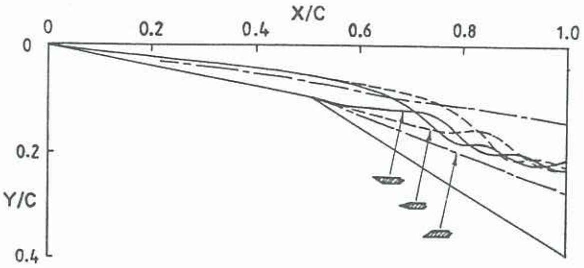

Fig. 4: Effect of leading-edge cross-section shape on vortex pattern over 80/60 deg wing; incidence=12 deg; R=100 000

Effect of Reynolds Number

It is a common assumption that separated vortex flows where primary separation occurs at a sharp leading edge are relatively insensitive to Reynolds number. This assumption provides the justification for flow visualisation tests in water at Reynolds numbers in the range 1 000 to 10 000, some two or three orders of magnitude less than usual wind tunnel and flight values. One objective of the tests described here was to investigate the validity of the assumption.

Fig. 5 shows the vortex positions above the 80/60 deg wing in the towing tank at an incidence of 12 deg, for Reynolds numbers of 8 400, 16 000 and 92 000. For the two highest Reynolds numbers, the most noticeable effect is that the point at which the strake and wing vortex cores cross over moves downstream with increasing Reynolds number. This trend appears to be continued in the wind tunnel results of Brennenstuhl and Hummel(1982) for a similar planform model at a Reynolds number of 1.5 million.

At a Reynolds number of 8 400, there appears to be no separate wing vortex, and the flow separating from the leading edge rolls up into a single vortex above each wing half. This is confirmed by the vortex cross-sections shown in Fig. 6. The cross-sections are at the chordwise station of x/c=0.6, for Reynolds numbers of 7 100, 15 000, 30 000 and 52 000. At the lowest Reynolds number, the sheet of bubbles is continuous from the leading edge into the strake vortex core with no indication of a wing vortex outboard of the strake vortex. At a Reynolds number of 15 000 the wing vortex is present, and becomes larger as the Reynolds number increases further. Similar effects were observed for other models in the series.

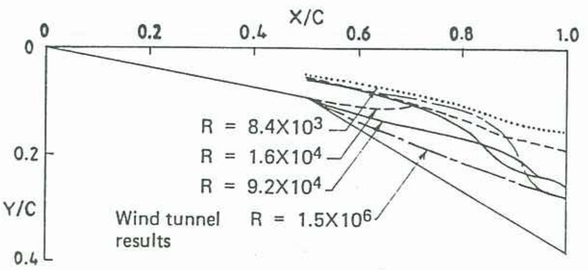

Fig. 5: Effect of Reynolds number on vortex pattern over 80/60 deg wing; incidence=12 deg; wind tunnel results from Brennenstuhl and Hummel(1982)

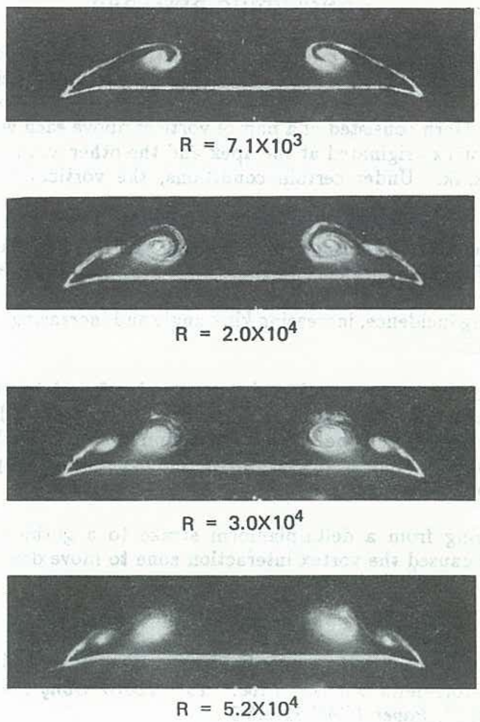

Fig. 6: Effect of Reynolds number on vortex cross-sections above 80/60 deg wing; incidence=12 deg; x/c=0.6

Effect of Strake Planform

The effect on the flow of changing the strake planform is illustrated in Fig. 7, which compares the vortex trajectories for the 80/60 deg and gothic/60 deg wings, at an incidence of 15 deg and a Reynolds number of 100 000. The most obvious effect of the change from the delta to the gothic planform is that the position of the interaction between the two vortices is shifted downstream by about 10% of the centreline chord. The most likely reason for this shift is the increased separation between the wing and strake vortices in the vicinity of the leading edge kink. The strake vortex from the gothic planform strake lies further from the wing surface than is the case with the delta strake vortex. Also, the gothic strake vortex is likely to be initially stronger than the delta strake vortex, and thus travel further downstream before being affected by the wing vortex.

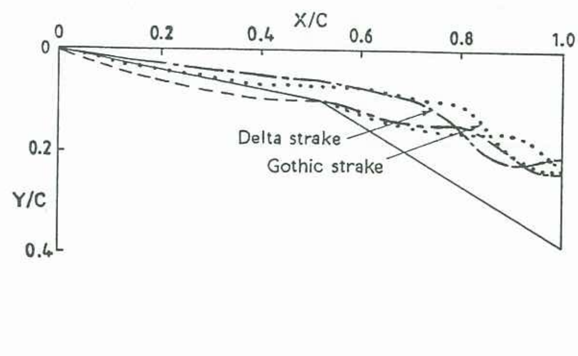

Fig. 7: Effect of strake planform on vortex pattern over 60 deg delta wing; incidence=15 deg; R=95 000

CONCLUDING REMARKS

The formation and interaction of vortices above double-delta wings and gothic strake/delta wings were studied using flow visualisation techniques in a small towing tank. In general the flow pattern consisted of a pair of vortices above each wing half. One vortex originated at the apex and the other at the leading-edge kink. Under certain conditions, the vortices interacted above the wing.

The location of the zone of interaction was found to be a function of angle of incidence, leading-edge kink angle, and Reynolds number. In general, the interaction moves downstream with decreasing incidence, increasing kink angle and increasing Reynolds number.

Leading edge cross-section shape was also found to affect the vortex system structure. In particular, on models with an upper surface bevel, the vortex interaction zone occurred further downstream than is the case with the other edge shapes, and the vortices were closer to the wing upper surface.

Changing from a delta-planform strake to a gothic-planform strake caused the vortex interaction zone to move downstream.

REFERENCES

Brennenstuhl, U; Hummel, D (1982): Vortex formation over double-delta wings. *Proc.* 13th *ICAS Congress (Seattle 1982), Paper ICAS*-82-6.6.3

Frink, N T; Lamar, J E (1981): Analysis of strake vortex breakdown characteristics in relation to design features. *J. of Aircraft* **18**, 252-258.

Hoeijmakers, H W M (1983): Numerical computation of vortical flows about wings. *NLR MP* 83073*U*

Hoeijmakers, H W M; Rizzi, A (1983): Vortex-fitted potential solution compared with vortex-captured Euler solution for delta wing leading-edge vortex separation. *AIAA* 2nd *Applied Aero. Conference (Seattle* 1984*), Paper AIAA*-84-2114

Peace, A J (1983): A multi-vortex model of leading-edge vortex flows. *Intl. J. for Numerical Methods in Fluids* **3**, 543-565.

Thompson, D H (1985): A visualisation study of the vortex flow around double-delta wings. *ARL Aerodynamics Report* 165

Verhaagen, N G (1983): An experimental investigation of the vortex flow over delta and double-delta wings at low speed. *Deflt U. of Tech., Dept. of Aerospace Eng., Report LR*-372