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VISUALISATION OF VORTEX FLOWS AROUND CANARD CONFIGURATIONS WITH HIGHLY-SWEPT LEADING EDGES

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ABSTRACT

A wing / canard configuration with sharp, highly swept leading edges was tested in a small towing tank. Flow visualisation was used to study the effects of canard position on vortex interactions and vortex breakdown. A canard above or co-planar with the wing delayed wing vortex breakdown. A canard below the wing produced a strong interaction between the wing and canard vortices and could cause early wing vortex breakdown. Depending on its longitudinal position, the low canard could seriously disrupt the wing flow.

INTRODUCTION

In aircraft aerodynamic design, a canard (tail-first) layout can offer some performance advantages over a conventional rear-tail layout (Burns(1985), Nicholas et al(1984)). Critical to canard designs, particularly if they are close-coupled, are the interactions between the canard and wing flowfields. Lifting surfaces with sharp, highly-swept leading edges produce strong vortex flows at moderate to high angles of attack. The use of such surfaces in canard configurations can result in complex interacting vortical flows. Thus proper positioning of the surfaces is critical to the satisfactory design of a canard layout.

Behrbohm (1965) showed how to combine the overall slenderness required for high-speed flight with the high-lift low-speed capability needed for short-field operations, by making use of favourable vortex interference on a close-coupled canard layout for the Saab Viggen fighter aircraft (Karling(1975)). Calarese (1986), Hummel and Oelker (1986), Er-El and Seginer (1985), and Er-El (1988) tested close-coupled canards in wind and water tunnels, using flow visualisation, pressure and velocity surveys, and force and moment measurements to study the effects of vortex interactions.

In the work described here, flow visualisation in water was used to study the interacting vortex systems generated by a close-coupled canard and wing, both with highly-swept leading edges. The effects of canard and wing relative positions on vortex trajectories and vortex breakdown were examined over a range of angles of attack.

EXPERIMENTAL PROGRAM

The experiments were carried out in a small Perspex towing tank, 6 m by 0.3 m by 0.3 m. The towing carriage comprised a baseplate running on linear bearings on shafts beneath the tank, and a gantry mounted on the baseplate and straddling the tank. A variable-speed electric motor drove the carriage through a cable loop and pulley system.

The wing and canard models, both of delta planform, had leading edge sweep angles of 60^o and 70^o respectively. The centreline chord (c) of the wing was 150 mm and of the canard, 75 mm. Both were made from 2 mm thick Perspex sheet, with edges symmetrically bevelled to a 30^o included angle. The models were mounted independently on a single sting. Using sliders and spacers, the canard could be positioned in the wing plane (h/c=0), 0.1c above the wing plane (h/c=+0.1), or 0.1c below (h/c=-0.1). Parallel to the wing plane, the canard could be positioned with its trailing edge up to 0.2c forward of the wing apex (l/c=-0.2) or behind the apex (l/c=+0.2), except in the co-planar case. The incidence setting of the canard and wing were the same. The sting was attached to a strut passing up through the water surface to a pitch and yaw mounting on the towing carriage gantry. The models were tested at zero yaw over an incidence (α) range of 10^o-30^o. Reynolds number (R), based on wing centreline chord, was about 9.5×10^4.

Vortex patterns were made visible using the hydrogen bubble electrolytic technique. Cathodes of aluminium foil strip cemented beneath the wing and canard leading edges gave off small bubbles of hydrogen which were swept into the vortices above the models. The bubbles entrained in the vortex cores delineated them clearly. The bubble patterns were illuminated by lights on the carriage and recorded by still photography and on videotape.

RESULTS AND DISCUSSION

General Flow Features

Fig.1 shows the flow around a typical low-canard configuration with the canard ahead of the wing apex (h/c=-0.1,l/c=-0.1,α=25^o). As with a normal delta wing, the vortex sheet shed by each canard leading edge rolls up to form a vortex above the canard. The vortex starts at the canard apex, trails downstream over the canard trailing edge, moves upwards in the upwash ahead of the wing, and into the vortex system above the wing. A wing vortex, of the same sense as the canard vortex, forms above and inboard of each wing leading

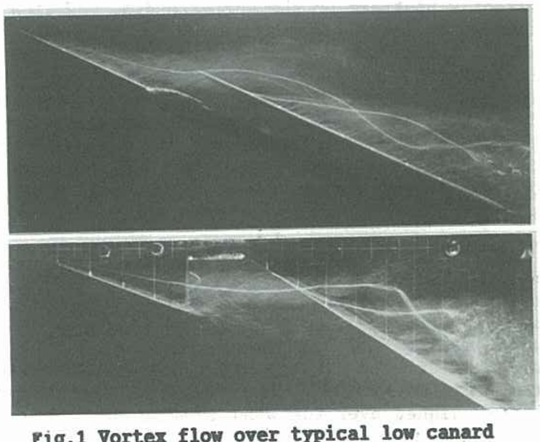

Fig.1 Vortex flow over typical low canard configuration (h/c=-0.1;l/c=-0.1;α=25^o)

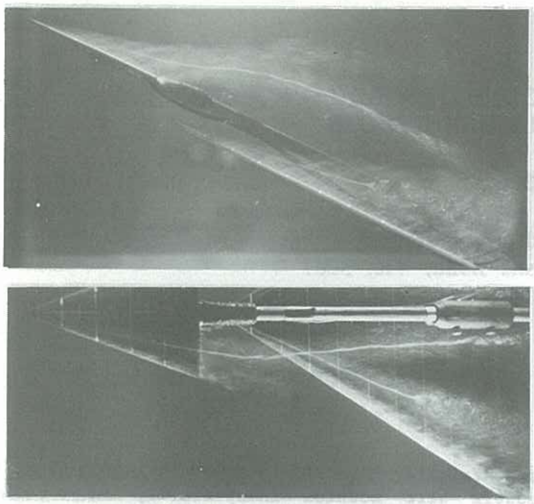

Fig.2 Vortex flow over typical high canard configuration (h/c=0.1;l/c=-0.1;α=25°)

edge, and deflects the canard vortex initially upwards, then downwards and outboard beneath the wing vortex. The wing vortex itself is deflected inboard and upwards by the canard vortex. The canard and wing vortices thus tend to roll round each other. Bursting occurs in each of the canard and wing vortices above the wing, at about 80% chord. Downstream of the bursts, the flowfield is turbulent and the individual vortices are no longer discernible.

The wing vortex does not originate at the wing apex, but at a point on the leading edge at about the 15% chord station. This shift is due to the velocity field inboard of the canard vortex core which suppresses vortex formation above the wing. The effect of the canard on the point of origin of the wing vortex was described by Behrbohm (1965) and Hummel and Oelker (1986) and will be discussed later in more detail.

Fig.2 shows the flow round a typical high canard configuration, with the canard ahead of the wing apex (h/c=0.1,l/c=-0.1,α=25°). Compared to the low canard configuration, the effect of the wing vortex on the canard vortex is less pronounced, due to their greater spacing. Just downstream of the wing apex, the canard vortex is deflected downwards and inboard slightly by the wing vortex. The interaction between the two is not sufficient to cause them to intertwine or merge above the wing. The wing vortex starts at the wing apex, as the influence of the canard vortex flowfield near the wing apex is not sufficient to suppress separation over the forward part of the leading edge.

The wing vortices burst at about 65-70% chord, slightly upstream of the corresponding position for the low canard configuration. At about 70-80% wing chord, the canard vortex cores undergo an expansion in diameter, but the expansion is less abrupt than for the wing vortices. The core structure downstream of the expansion appears to be turbulent. Although differing in appearance from the wing vortex burst, the overall characteristics of the canard vortex expansion seem to indicate that some form of burst has occurred.

Effects of Incidence

For the low canard configuration of Fig.1, the canard vortex passes below the wing for α<12°. At α=12°, the canard vortex passes just above the wing leading edge and merges immediately with the wing vortex. The merged vortex does not burst over the wing. As incidence increases, the canard vortex passes higher over the wing leading edge, as shown in Fig.3, where the canard vortex position in a spanwise plane normal to the wing at 0.25c (x/c=0.25) is plotted in spanwise (y/c) and normal (z/c) co-ordinates. (Similar results are shown for l/c=-0.2, 0.0) Also, the origin of the wing vortex moves upstream, while intertwining and merging of the canard and wing vortices occurs further downstream. Breakdown of the merged vortex occurs over the wing and moves upstream, and at higher values of α breakdown of individual vortices occurs before merging is complete.

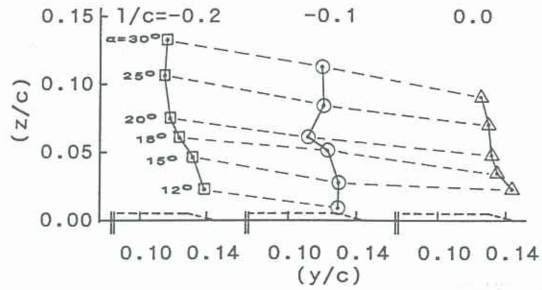

Fig.3 Effect of incidence on canard vortex position over wing at x/c=0.25 (h/c=-0.1)

Incidence changes have less effect on the high canard configuration of Fig.2, and the flow pattern remains similar to that shown. The canard vortex trails downstream well above the wing, the wing vortex originates at the wing apex, and the wing and canard vortices do not intertwine or merge over the wing. As incidence increases, bursts appear in the wing and canard vortex cores and move upstream.

Incidence effects on a typical mid-canard configuration (h/c=0.0,l/c=-0.1) share features of both the high and low canard flow patterns, depending on the angle of incidence. In general, the canard vortex passes above the wing leading edge and is deflected downward by the wing vortex, but there is no intertwining or merging of the vortices. The wing vortex origin is displaced outboard along the leading edge. Breakdown occurs in all vortices as incidence increases.

Effect of Canard Longitudinal Position

The vortex pattern over a low canard configuration (h/c=-0.1,α=18°) remains similar to that in Fig.1 as the longitudinal position of the canard is varied from l/c=-0.2 to l/c=0.0. The canard vortex passes closer to the wing leading edge, as shown in Fig.3, and merging of the canard and wing vortex cores occurs earlier. Bursting of the vortices over the wing also occurs.

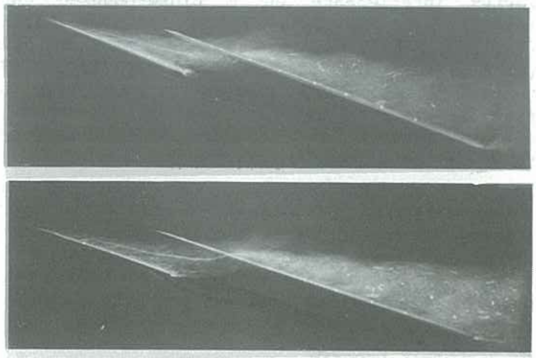

Fig.4 Canard vortex impacting wing leading edge (h/c=-0.1;l/c=0.1(top),0.08(bottom);α=18°)

For l/c=0.1, the vortex pattern changes. Under the influence of the wing flowfield, the canard vortex bursts near the canard trailing edge, and the expanded canard vortex core strikes the wing leading edge (Fig.4). The wing vortex starts near this point, but bursts almost as soon as it has formed. For l/c=0.2, the canard vortex bursts at about 80% canard chord. The turbulent flow downstream of the burst strikes the wing leading edge and causes disordered flow over the wing, with no evidence of the formation of a wing vortex.

The behaviour of the canard and wing vortices as the canard trailing edge is moved aft past the wing apex is sensitive to the actual canard position. As l/c increases from zero, the burst in the core of the merged canard and wing vortices moves rapidly upstream towards the wing leading edge. A situation is reached where the canard vortex remains unburst right up to the wing leading edge, but the wing vortex bursts just behind the leading edge. This is shown in Fig.4, with the canard at l/c=0.08.

The effects of canard longitudinal position on the vortex patterns over a high canard configuration are less apparent than for the low canard configuration. For $-0.2 \le l/c \le 0.2$, the flow pattern remains similar to that in Fig.2, apart from slight changes in vortex burst position.

For the mid-canard configuration, the flow patterns are more like those of the high canard than those of the low canard. As the canard is moved downstream, limited intertwining occurs between the canard and wing vortices, but there is no merging.

Effect of Canard Vertical Position

In Fig.5, the vortex patterns for three different canard vertical positions (h/c=-0.1,0.0, and 0.1) are compared, for l/c=-0.1 and $\alpha=20^o$. The most obvious changes occur between the low and mid-canard configurations, as the degree of interaction between the wing and canard vortices decreases markedly. The shift of the wing vortex origin away from the wing apex also decreases as the canard is raised relative to the wing.

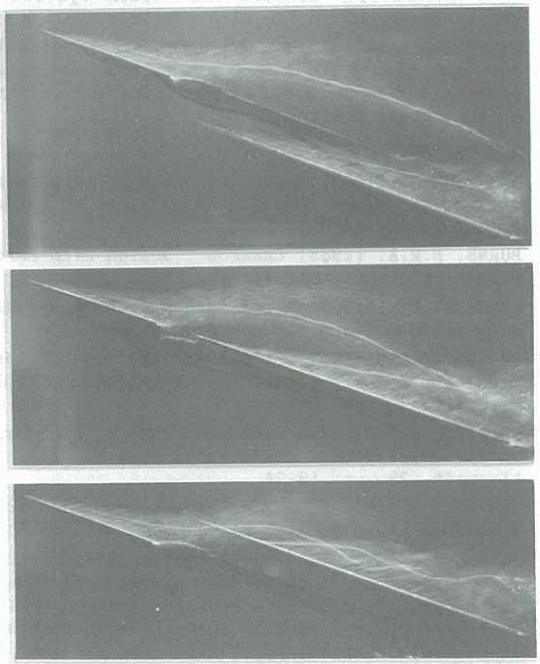

Fig.5 Effect of canard vertical position on vortex flow (h/c=0.1(top),0.0(middle), -0.1(bottom);l/c=-0.1;$\alpha=20^o$)

Flow near Wing Apex

As has been noted above, there are some conditions, under which the canard vortex displaces the origin of the wing vortex from the wing apex to a point outboard along the wing leading edge. For many configurations, no clear flow pattern could be discerned in this apex region. However, for a low canard configuration with l/c=0.05 and $\alpha=30^o$, there appeared to be a flow structure originating from a point on the wing lower surface, upstream of the wing vortex origin. This structure looked like a vortex core which curled up and around the leading edge into the wing vortex system. A similar flow pattern was observed at $\alpha=25^o$.

By careful adjustment of a light on one side of the towing carriage and a camera on the opposite side, it was possible to photograph the flow beneath the apex. Fig.6 shows a photograph taken at $\alpha=30^o$ and $R=5.2 \times 10^4$. There appears to be a vortex beneath the wing leading edge, with its core starting at or near the wing apex. This part of the leading edge

Fig.6 Apex lower surface vortex and wing vortex (h/c=-0.1;l/c=0.05;$\alpha=30^o$;R=5.2x10^4)

is immersed in the strong downwash and sidewash field inboard of and beneath the canard vortex. This velocity field maintains attached, outboard-moving flow over the wing upper surface. Separation occurs at the leading edge and the separated flow rolls up to form a small vortex beneath the leading edge. Near the point where the canard vortex core passes close to the wing leading edge, the local flowfield at the leading edge changes from a downwash to an upwash. The flow separating at the leading edge now forms the familiar vortex system above the wing. The underside vortex curves sharply upwards, passes round the leading edge, and into the vortex systems above the wing. Fig.7 (taken from a videotape) shows the canard vortex as well.

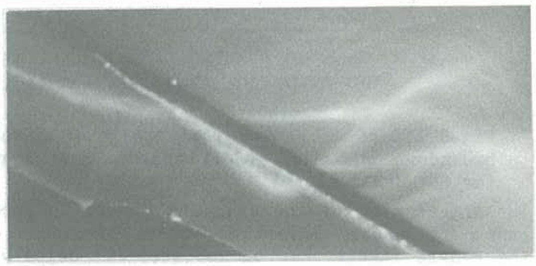

Fig.7 Canard, wing and apex lower surface vortices (h/c=-0.1;l/c=0.05;$\alpha=30^o$;R=5.2x10^4)

Effect of Canard on Vortex Breakdown

It is apparent from the flow patterns described so far that the relative positions of the wing and canard have a marked effect on the occurrence of breakdown within the wing and canard vortices. In Fig.8, measured positions of wing vortex breakdown are plotted against incidence for several values of longitudinal canard position, for each of the three vertical canard positions tested. Also included are lines showing breakdown for the wing alone case.

For the high- and mid-canards, breakdown occurs further downstream than is the case for the wing alone. The shift is quite substantial. For example, at $\alpha=20^o$ the breakdown typically moves downstream from about 40% wing chord to the trailing edge. The actual longitudinal position of the canard has a lesser effect. The most forward position (l/c=-0.2) causes the smallest breakdown shift, but the difference in shift magnitude between the most forward and most aft canard positions is only some 20% of wing chord.

The longitudinal position of the low canard is much more critical. The most forward position produces a breakdown shift of about the same magnitude as the high and mid-canards. However, as the low canard is moved aft, the breakdown shift is considerably reduced, particularly at the lower angles of incidence. In fact, a low canard can reverse the breakdown shift, causing the wing vortex to burst further upstream than it would over the wing alone. The incidence at which the reversal occurs increases as the canard is moved aft. As discussed above, when the canard trailing edge is moved aft past the wing apex, the interaction of the canard vortex and the wing leading edge causes the wing vortex to burst almost as soon as it forms. Thus the most upstream vortex breakdown positions plotted in Fig.8 for the low canard at l/c > 0 correspond closely to the points of origin of the wing vortices.

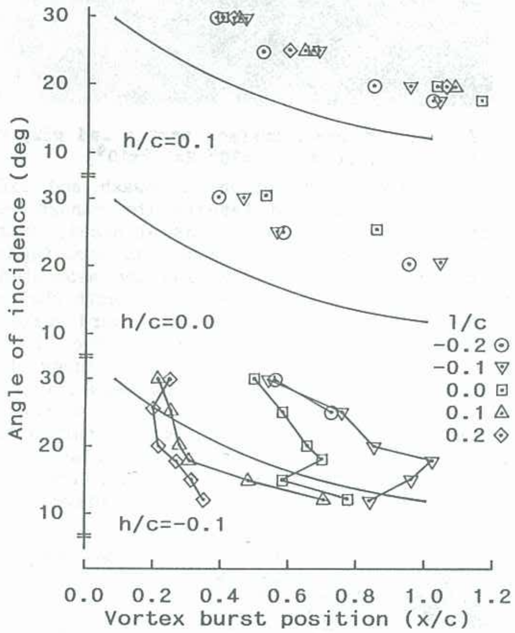

Fig.8 Effect of canard position on wing vortex breakdown position. (Solid lines show results for 60^{o} delta alone)

The interaction of the wing and canard in general has a favourable effect on vortex breakdown over the canard itself. For an isolated 70^{o} delta wing, vortex breakdown moves upstream with increasing incidence, crossing the trailing edge at $\alpha \approx 22^{o}$. For almost all the configurations tested, except for the aft positions of the low canard, the canard vortices burst well downstream of the canard trailing edge. This favourable effect was noted also by Behrbohm (1965) and Hummel and Oelker (1986).

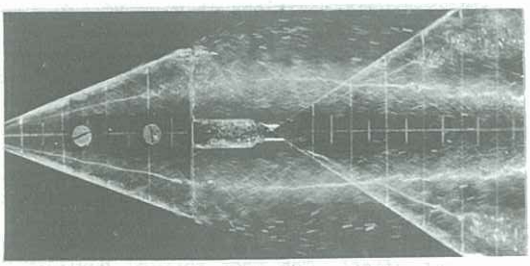

Fig.9 Bursting and re-forming of canard vortices ($h/c=0.0; l/c=-0.2; \alpha=30^{o}; R=9.6x10^{4}$)

An unusual effect was noted in the canard vortices over the mid-canard configuration, with the canard in its most forward position ($h/c=0, l/c=-0.2$), at $\alpha=30^{o}$. This was the apparent re-formation of the canard vortex cores downstream of breakdown points. This was observed at $R \approx 9.5x10^{4}$, but was photographed in more detail at $R=4.5x10^{4}$ and $\alpha=30^{o}$, as shown in Fig.9. In this case both canard vortices burst over the canard, near its trailing edge. The cores appear to re-form just ahead of the wing leading edge, then burst again over the wing. Hummel and Oelker (1986) observed a similar phenomenon in their water tunnel tests. The re-forming of the canard vortex cores is due presumably to the favourable pressure gradients experienced by the vortices in the flow ahead of the wing. The restoration of a burst vortex by a favourable pressure gradient in a closed tube has been described by Harvey (1962).

CONCLUDING REMARKS

The formation and interaction of vortices above a canard/wing configuration where canard and wing both had sharp, highly-swept leading edges were studied using flow visualisation techniques in a small towing tank. In general, the canard vortex system interacted with the wing vortex system to a degree dependent on the relative positions of the two surfaces.

The most extensive interaction occurred with the canard beneath the wing plane. In this case, the canard vortices intertwined and merged with the wing vortices, with the details of the interaction depending on the longitudinal position of the canard. Forward positions of the low canard delayed wing vortex breakdown, at least at higher angles of incidence. This favourable effect was reduced as the canard was shifted aft, and in its rearmost positions the low canard could seriously disrupt the wing vortex flow.

A canard above or co-planar with the wing produces less interaction between the vortex systems, and delays breakdown in the wing vortices.

Other features of the flow successfully visualised for some canard positions include vortex formation beneath the wing apex, and bursting and re-forming of the canard vortices.

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