Effects of Leading-Edge Radius on Aerodynamic Characteristics of 50° Delta Wings

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The study focuses on the effects of the leading-edge radius on the flow over 50° swept delta wing models. Three models were tested, one model having a sharp leading edge and the other two having a semi-circular leading edge of different radius. The vortical flow on and off the surface of the models was investigated using an oil-flow visualization and a Stereo Particle Image Velocimetry (SPIV) technique. The leading-edge radius is shown to affect the size and location of the vortices and also the vortex bursting location over the models. As a result of this, the leading-edge radius also affects the forces and moment acting on a 50° delta wing.

Nomenclature

\begin{align*}
    b &= \text{semispan} \\
    C_D &= \text{drag coefficient} \\
    C_L &= \text{lift coefficient} \\
    C_m &= \text{pitching-moment coefficient} \\
    c &= \text{root chord length} \\
    r_{le} &= \text{leading-edge radius} \\
    Re &= \text{Reynolds number based on chord length} \\
    s &= \text{local semispan} \\
    t &= \text{wing thickness} \\
    U_\infty &= \text{free stream velocity} \\
    x &= \text{chordwise distance} \\
    x_m &= \text{measurement plane coordinate} \\
    y &= \text{spanwise distance} \\
    y_m &= \text{measurement plane lateral coordinate} \\
    z &= \text{vertical distance from wing surface} \\
    \alpha &= \text{angle of attack} \\
    \beta &= \text{angle of sideslip} \\
    \Lambda &= \text{leading-edge sweep angle}
\end{align*}

Introduction

In recent years much attention is given to designs of unmanned combat aircraft vehicles (UCAV). These are required to have a low structural-weight-to-take-off-weight-ratio, a large surface area to include internal flight systems and be capable of operating at high angles of attack. Concepts of this type of aircraft incorporate a so-called non-slender delta wing, or a delta wing with a leading-edge sweep angle \(\Lambda < 60^\circ\).

The past 50 years, most research was performed on so-called slender delta wings with \(\Lambda \geq 60^\circ\). Over the past years, a reasonably well understanding of the flow phenomena over this type of delta wing has been obtained. The structure of the flow over a non-slender delta wing differs substantially from that over a slender delta wing.\(^1\) A reduction of \(\Lambda\) from, e.g., 65° to 50° results in the formation of the primary vortex closer to the wing surface and consequently a stronger

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interaction between this vortex and the wing boundary layer. Gordner and Visbal\textsuperscript{2} calculate that as a result of this interaction, at $\alpha = 5^\circ$ the primary vortex splits up into two separate regions of vorticity. This so-called dual primary-vortex core structure is confirmed by experiments performed by Taylor et al.\textsuperscript{3} As a result of the strong interaction, the vortex crossflow structure is sensitive to the Reynolds number, which is not the case for the vortex flow over slender delta wings. At higher $\alpha$ the distance between the primary vortex and the wing boundary layer has increased such that only a single primary vortex develops and the cross flow structure becomes similar to that over a slender delta wing.

Another difference is in the development of the vortex core breakdown. On a slender delta wing, bursting is caused by the mutual interaction between the primary vortices over the port- and starboard wing halves. In most experiments,\textsuperscript{4} a spiral-type of breakdown is observed. Compared to a slender delta wing, the primary vortices over a $A = 50^\circ$ delta wing are further apart from each other and the interaction with the surface boundary layer is stronger. Gordner et al.\textsuperscript{5} give a numerical solution for the development of the core flow over such a delta wing at $\alpha = 15^\circ$ and at $Re$ ranging from $2 \times 10^3$ to $2 \times 10^5$. At the lower $Re$, at $x/c = 0.14$ a mean peak axial velocity of $2.91 U_\infty$ is predicted in the core. With increasing $Re$ this velocity decreases to a value of $2.21 U_\infty$. The onset of breakdown is identified by a switch in the core from jetlike to wakelike flow. No flow reversal is predicted as observed on slender delta wings downstream of the breakdown point. The Reynolds number has also an effect on the breakdown location, but not always in the same sense. Associated with this is an effect on the transition of the flow in the breakdown region. Taylor et al.\textsuperscript{3} investigated the variation of the breakdown point with the angle of attack in a water tunnel at $Re = 13,000$. Breakdown was already observed to occur at $\alpha = 2.5^\circ$. The breakdown point moved upstream with increasing angle of attack. In the case of a dual primary vortex structure the outboard vortex was observed to breakdown upstream of the primary vortex. The flow over a $50^\circ$ delta wing was further found to be less steady than that over a slender wing; at low $\alpha$ fluctuations of the order of 50% chord were observed.

Shear layer instabilities in the flow separating from the leading edge and oscillations in the flow downstream of the vortex breakdown location have a large effect on the structural mode frequencies of a delta wing. One of the objectives of the present research project is to gain more insight into the cause of these instabilities. The availability today of advanced flow field measuring techniques such as PIV opens a way to study unstable flow phenomena, both qualitatively and quantitatively. This technique is therefore applied in the present research.

In the present research project special attention is paid to the effects of the leading-edge radius on the structure and instabilities of the vortex flow. In the majority of wind tunnel experiments, delta wing models have been tested with sharp edges. This has been done to fix the boundary-layer separation at these edges and to reduce Reynolds number sensitivity effects. Realistic applications, however, often have blunt edges.\textsuperscript{6} In Section I a short overview is given of the effects of the leading-edge shape on the aerodynamic characteristics of a delta wing. While much is known on the effects of the edge shape on the flow over a slender wing, still little data is available on the effects on the flow over a non-slender delta wing.\textsuperscript{1} To help obtain more data on these effects, a series of three small-scale $A = 50^\circ$ delta wing models was constructed. One model has a “sharp” leading edge, while the other two models have a semi-circular edge of increasing radius. As a start, a number of flowfield tests was performed in a small open wind tunnel. The prime objective of these tests was to develop a SPIV setup suitable for measuring in detail the flowfield over the models. The second objective was to obtain a first insight into the effects of the leading-edge radius on the flow on and off the models. In the paper, surface oil-flow results as well as cross flow velocity vector and vorticity data are presented. In addition, balance data are presented that were recently obtained on a series of larger models. The balance measurements were performed in a large closed-circuit low-turbulence tunnel.

I. Effects of leading-edge shape on delta wing characteristics

The effects of the leading-edge shape on the aerodynamic characteristics of a slender delta wing ($A \geq 60^\circ$) are known from a number of experimental and numerical studies.\textsuperscript{7,14} The studies show that the edge shape affects the origin and location of the primary-separation line, the size and position of the primary vortex and through mutual interaction with the wing boundary layer the generation of a secondary vortex and possibly a tertiary vortex. At certain conditions, on a delta wing with a symmetrically rounded leading edge a second primary vortex is found inboard of the primary vortex.\textsuperscript{13} The size and strength of the primary vortex tends to reduce with increasing leading-edge radius $r_{le}$. Associated with this is a reduction of the induced surface-pressure suction peak. Balance measurements show that an increase in $r_{le}$ decreases the lift only slightly, but reduces the drag significantly. The latter is due to the increased suction at the edges. This results into a higher lift-to-drag ratio, hence a better performance of the delta wing at subsonic speeds. Contrary to a sharp leading edge, however, on a rounded edge the location of the primary-separation line and separated flow structure are
sensitive to the Reynolds number. The edge curvature also affects the location of the bursting point over the wing; an increase in $r_e$ is found to move the bursting point in a downstream direction.

As far as the effects of the leading-edge radius on the flow over a non-slender delta wing are concerned, little data is available.\(^1\) Balance data does suggest that, compared to a slender delta wing, the shape of the leading edge of a non-slender wing has a substantial effect on the measured lift and on the stall behavior, in other words, on the strength and location of the vortices and their breakdown location.

II. Experimental Setup

The research project is carried out at the Aerodynamics Group of the Department of Aerospace Engineering of the Delft University of Technology (TUD) in the Netherlands. The research was started with a series of small-scale models. These were tested in an open wind tunnel in order to have an easy access to the models and SPIV equipment. The results obtained on these models show that certain flow details are not resolved. To improve resolution, recently a series of three times larger models have been constructed that are tested in a large closed-circuit tunnel. The first tests performed with these models are the balance measurements described below.

Models and Flow Facility used for SPIV and Flow Visualization Tests

Three models of a $\Lambda = 50^\circ$ delta wing were manufactured of 7-mm thick anodized Aluminum. Figure 1 shows the wing planform and the different leading-edge shapes that were selected. It should be remarked here that in principle various edge-shape combinations are possible, such as symmetrical edges, edges beveled on the upper surface, etc. For the present research project, edges with a bottom-surface bevel are chosen in order to keep the upper surface of the models as flat as possible. Wing I has a “sharp” leading edge of 0.50 mm radius, yielding an $r_e/c$ ratio of 0.0042. The edge is beveled on the bottom side at 18°. Wing II has a semi-circular leading edge of 1.75 mm radius ($r_e/c = 0.0149$) and wing III a semi-circular edge of 3.50 mm radius ($r_e/c = 0.0298$), being half the model thickness. The radius of the rounding at the model nose equals that of the leading edge. The models have a square trailing edge and a thickness-to-chord ratio $t/c = 0.06$. The flow on and off the models has been investigated at a constant $U_\infty = 20$ m/s, yielding a $Re = 2.0 \times 10^5$, based on chord length. An oil-film technique was used to visualize the boundary-layer flow on the leeward surface at $\alpha = 5^\circ$, 7.5°, 10°, 12.5°, 15° and 22.5°. A SPIV technique was used to survey the flow over the models at the same free stream velocity, but due to the limited time available for the measurements, data was acquired at only $\alpha = 5^\circ$ and 15°. The models were tested in an open-jet type tunnel with a nozzle cross section of 40 x 40 cm\(^2\). The maximum airspeed in this tunnel amounts 30 m/s.

SPIV Technique

Figure 2 shows the SPIV setup. The models were positioned at about a chord length distance from the tunnel nozzle. The models were screw mounted to a sting that was connected to a ($\alpha$, $\beta$) traversing system. The laser sheet was normal to the starboard leading edge. One CCD camera was positioned normal to this sheet, while the
The second camera was at an angle of about 56° with the sheet. As shown in Figure 3, the measurements have been performed in two planes normal to the starboard leading edge. The two planes cross the leading edge at 50% and 70% root chord and are denoted \( x_m = 0.5 \) and 0.7, respectively, where \( x_m \) is the measurement plane coordinate. A lateral coordinate \( y_m \) is defined normal to the leading-edge.

The SPIV technique requires a calibration procedure to obtain the mapping function between the image coordinates and the physical space. This was obtained by using a two-level calibration pattern plate and the evaluation of the mapping function was made by DAVIS 7.1 software.

**Flow Seeding and Illumination**

A SAFEX Fog generator produced liquid droplets of approximately 1 µm in diameter, which were introduced into the wind tunnel flow downstream of the centrifugal fan of the wind tunnel.

A QUANTEL CFR 200 Nd:YAG laser emitted double light pulses of 200 mJ energy with a duration of 7 µm at a repetition rate of 30 Hz. Through optics, the laser beam was converted into a 2 mm thick and 20 cm wide light sheet.

**Imaging Recording and Data Processing**

Two CCD cameras of 1376 x 1040 pixels were used to record the flow field. The two cameras are equipped with 65 mm focal length lenses and Scheimpflug adapters. Both lenses were equipped with daylight filters in order to reduce the background light in the PIV images. A cross correlation method was used to obtain the velocity vector field from the reconstructed images.

Each flow field measurement contained 200 records acquired at 5 Hz with a pulse separation time of 2 µs. The flow is therefore not time resolved. Each image pair was analyzed with the La Vision Davis 7.1 software, applying the window deformation iterative multigrid technique\(^{15}\) with a final window size of 32 x 32 pixels and an overlap factor of 50%. For visualization purposes only, the velocity vector field is low-pass filtered with a 3 x 3 Gaussian Kernel.

**Oil Flow Technique**

The direction of the boundary-layer flow on the leeward surface of the models was visualized using an oil-flow technique. The oil mixture consisted of titanium dioxide and kaolinum powder (china clay) mixed with kerosene and pure oleic acid fluid. The mixture was applied on the surface of the models at freestream velocity. When dry, the surface flow pattern was photographed using a digital camera.

**Wall Interference**

Interpolation of the numerical predictions for the wall interference correction of a delta-type wing in a rectangular wind tunnel\(^{16}\) indicates that the upflow angle correction for the small models is of the order of 1.5° at \( \alpha = 15° \). The models are actually positioned at a chord distance from the tunnel exit. The upflow effects can therefore be expected to be less strong.

**Models and Flow Facility used for Balance Measurements**

The planform and edge shapes of the larger models are shown in Figure 4. The models were manufactured of 20-mm thick anodized Aluminum, have a chord length of 0.360 m and a span of 0.600 m. Wing I has a sharp leading edge of about zero radius. The bottom edge is beveled at 16°, which is slightly less than the bevel angle of the smaller models. Wing II has a semi-circular leading edge of 5.0 mm radius (\( r_{le}/c = 0.0139 \)) and wing III a semi-circular edge of 10.0 mm radius (\( r_{le}/c = 0.0278 \)), being half the model thickness. The radius of the rounding at the nose equals again that of the leading edge. The models have a square trailing edge and a thickness-to-chord ratio \( t/c = 0.056 \). The models were tested in the Low-Turbulence-Tunnel (LTT) of the Department of Aerospace Engineering of TUD. This is a closed-circuit tunnel with an octagonal test section 1.80-m wide, 1.25-m high and 2.60-m long. Most tests were conducted at an airspeed of about 50 m/sec, yielding a chord Reynolds number of about 1.2 million, but in order to be able to study possible \( Re \)-effects, for some \( \alpha \), in addition, data were acquired at \( Re = 0.50, 0.97, 1.75 \) and 2.17 million. Each model was suspended through a streamlined strut that was connected to a six-component balance system overhead of the test section (Figure 5). To avoid interference of the strut with the vortex flow, the wings were tested inverted, i.e. with their flat leeward surface facing down. In literature, it is common to present data of delta wings with their leeward surface facing up. This surface is then called the "upper" surface. This terminology is also used in the present paper.
Static time-averaged force-and-moment data were obtained using the six-component balance system. The data were taken at geometric $\alpha$ up to 27 deg. The data were corrected for the elastic deformation of the strut and the balance system under aerodynamic load. Dummy measurements were performed to determine strut/model interference effects. The lift and drag coefficients $C_L$ and $C_D$ are based on freestream dynamic pressure and wing area. The pitching-moment coefficient $C_m$ is, in addition, based on chord as reference length. This moment is given relative to the strut/model pivot location $P$, marked in Figure 4.

As far as tunnel-wall-interference corrections are concerned, existing theories estimate corrections that can be applied for delta wings only if $\alpha$ is less than 25 deg, and if vortex breakdown does not take place over the wing. The theory developed by Hsing and Lan has been used here to obtain an idea of the order of magnitude of the wall corrections. Based on this theory, at the present test conditions the upflow angle is estimated to be $0.5^\circ$ at $\alpha = 5^\circ$ and to increase to about $2.7^\circ$ at $\alpha = 25^\circ$. Based on the same theory, the blockage is estimated to be of the order of 4% at low $\alpha$ and to increase to about 6% at $\alpha = 25^\circ$. The blockage correction has been applied to the dynamic pressure used to non-dimensionalize the balance data.

No special tests were carried out to determine the repeatability of the balance data. Comparison of data taken at identical ($\alpha$, Re) combinations indicate a maximum uncertainty in $C_L$ and $C_D$ of 0.5% and in $C_m$ of 1.3%.

### III. Test Results

#### Oil-flow visualization

Figure 6 shows the oil-flow pattern on the starboard leeward surface of small-scale model I at $\alpha = 5^\circ$, 10°, 15° and 22.5°, respectively, for $Re = 2.0 \times 10^5$. At $\alpha = 5^\circ$, the flow separates at the leading edge forming a primary vortex that attaches at the primary-attachment line $A_1$ located at about 0.5 s. The outboard directed boundary layer separates at the secondary-separation line $S_2$. Outboard of this line a secondary-attachment line is visible, suggesting the presence of a tertiary vortex. The secondary-separation line is straight up to the trailing-edge. At $\alpha = 10^\circ$, an outward bending of the secondary-separation line is visible upstream of the trailing edge. This outward bending is supposed to be due to an enlargement of the primary-vortex footprint caused by breakdown. The actual breakdown of the vortex core can be expected to occur at a short distance upstream of the bending point of $S_2$. At $\alpha = 15^\circ$, the outward bending point has moved upstream to about $x/c = 0.3$. The bending point at this $\alpha$ reasonably well correlates with the location of the bursting point computed at identical conditions by Gordnier et al. At $\alpha = 22.5^\circ$, the primary-vortex footprint is distorted by a fully turbulent boundary layer. The bursting occurs now near the apex.

Figure 7 shows the oil-flow pattern on wing II and III for $\alpha = 15^\circ$. Compared to wing I (Figure 6c), on wing II the outward bending of $S_2$ occurs more downstream. The outward bending on wing III is again downstream of that on wing II. This suggests that an increasing $r_e$ will delay vortex breakdown. Renac et al observed a similar tendency on 60° swept delta wings and Huang et al on 65° swept delta wings.

As far as the onset of the primary separation is concerned, in the $\alpha$-range tested here the primary separation on all three models was observed to start at the apex and not at some distance downstream from this point. The latter was observed...
by Konrath et al\textsuperscript{19} over a $\Lambda = 65^\circ$ delta wing with symmetrically rounded edges. Figure 8a and b show the flow patterns on wing I and III, respectively, for $\alpha = 10^\circ$. Figure 8c shows the surface-pressure distributions at the same $\alpha$ obtained by Konrath et al with PSP (Pressure-Sensitive-Paint) on their 65$^\circ$ delta wing with a sharp (left-) and a symmetrical leading edge with radius $r_{le}/c = 0.001$ (right-hand picture). The suction peaks induced by the primary vortices are clearly visible. On the sharp-edged delta wing the suction starts at the apex, while on the wing with the rounded leading edge suction can be seen to develop more downstream at $x/c = 0.6$.

Figure 9 shows the effect of $\alpha$ on the chordwise location of the outward bending point of $S_2$ for all the three wings. The data points were determined from the oil-flow patterns with an accuracy of $\pm 0.03$ $c$. The outward
bending point moves upstream with increasing $\alpha$. The increase in $r_{le}$ delays the outward bending of $S_2$, which is indicative for a delay in the occurrence of vortex breakdown. With respect to wing I, on wing II vortex breakdown occurs at a 0.10 $c$ to 0.30 $c$ more downstream location. From wing II to wing III, the rearward movement of the bursting point is less strong. Cummings et al.\textsuperscript{20} compute the flowfield over a $\Lambda = 50^\circ$ UCAV configuration with rounded leading edges at a $Re$ of the order of $10^5$. There is a correspondence between the computed upstream movements of the bursting point over the UCAV configuration with $\alpha$ and the upstream movement of the $S_2$ bending point over wing III.

Taylor et al.\textsuperscript{3} investigated the flow over a $50^\circ$ delta wing model in a water tunnel at $Re$ ranging from 4,300 to 34,700. The model had a bottom-edge bevel of $45^\circ$, which is much larger than the bevel angle of the present models. In the range of $Re$ tested, an upstream progression of the vortex bursting location was
observed, which is interesting keeping in mind the insensitivity to $Re$ of vortices and their bursting location over slender delta wings. In addition, with increasing $Re$ an outboard shift of the vortex trajectory was observed. The observations in the water tunnel further suggest a less abrupt transition from coherent to broken vortex core at the higher $Re$.

Figure 11. Effects of $Re$ on balance data of Wing I (left-) and Wing III (right-hand plots)
Balance data

Figure 10 shows plots of balance data obtained on the larger models. The leading-edge radius can be seen to affect the level and slope of the coefficients. The level of $C_L$ decreases with increasing $r_le$. Note that for wing III with the symmetrically rounded edges $C_L = 0$ at $\alpha = 0^\circ$. The other two wings have edges that are beveled on the bottom side. The negative camber associated with this yields a positive $C_L$ at $\alpha = 0^\circ$. The $C_L$ of sharp-edged wing I increases linearly with $\alpha$ up to $5^\circ$. Beyond this angle, the slope of the $C_L$-curve reduces due to the occurrence of vortex burst over the model. The range of linear $C_L$-curve extends when the edges are rounded off. A strong lift loss can be noted at $\alpha$ beyond $20^\circ$ when the burst approaches the apex. As was noted in the former figure, the occurrence of burst is delayed when the edges are rounded off. This explains why, compared to the other two wings, the delay in the strong lift loss on wing III takes place at large $\alpha$.

As far as the drag coefficient is concerned, the increase in $r_le$ results in a lower level of $C_D$. This is due to an increase in the leading-edge suction. There is an interplay between the vortex lift and leading-edge suction; on sharp-edged wing I, the vortex lift will dominate resulting in a large $C_L$. Rounding off the edges will increase the edge suction at the expense of the vortex lift. The overall effect on the $C_L$-to-$C_D$ ratio is that up to $\alpha = 6^\circ$ wing I has the largest ratio, while beyond this angle wing III dominates with the largest ratio at $\alpha = 10^\circ$.

An effect of $r_le$ can also be noted on the pitching-moment coefficient $C_m$; the level of this coefficient increases with $\alpha$ and decreases with increasing $r_le$. A strong decline can be observed again at $\alpha$ beyond $20^\circ$. The decline is delayed and less strong when the edges are rounded off.

Figure 11 shows the effects of $Re$ on the balance data of wing I and III. The data was acquired at $\alpha$ from $5^\circ$ to $25^\circ$, in steps of $5^\circ$, and at $Re$ ranging from 0.50 to 2.17 million. The effects on $C_L$ and $C_D$ for the two wings (and for wing II, not

![Figure 12. The vortex flow over wing I at $\alpha = 15^\circ$; $x_m = 0.5$ a) the instantaneous and b) time-averaged velocity-vector distribution, c) the instantaneous and d) time-averaged axial-vorticity distribution.](image)

Figure 12. The vortex flow over wing I at $\alpha = 15^\circ$; $x_m = 0.5$ a) the instantaneous and b) time-averaged velocity-vector distribution, c) the instantaneous and d) time-averaged axial-vorticity distribution.

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shown here) are almost identical. The $C_L$-$Re$ plots show that the lift coefficient tends to increase by 6 - 8% when $Re$ increases from 0.50 to 0.97 million, but at larger $Re$ the increase in $C_L$ is smaller to nil for $\alpha$ up to and including 15°. At $\alpha = 20°$ and 25°, the $C_L$-curves shows a slight decrease with increasing $Re$. The $C_D$-$Re$ plots show that the drag coefficient is hardly affected by $Re$. The variations are within the accuracy of the balance measurements. As for the pitching-moment coefficients, the $C_m$-$Re$ plots show a decrease of 8 – 10% at $\alpha = 5°$ and 10° when $Re$ increases from 0.50 to 0.97 million, but at larger $Re$ the variation in $C_m$ is nil for $\alpha$ up to and including 10°. At $\alpha = 20°$ and 25°, the gradient of the $C_m$-$Re$ curves can be seen to steadily decrease with increasing $Re$.

The effects of $Re$ on the balance data of the three models are rather small and are expected to be mainly due to changes in the vortex bursting location. The sensitivity of $Re$ on the latter location has been noted earlier.3,5

SPIV results

The velocity-vector fields over the three smaller models were measured in the planes at $x_m = 0.5$ and 0.7 at a constant $Re$ of $2.0 \times 10^5$. For this preliminary investigation the flow field data was acquired in planes perpendicular to the leading edge and at a sufficient distance from the apex in order to be able to resolve the vortex crossflow structure. The data was taken at $\alpha = 5°$ and 15°. The data for the first $\alpha$ were presented earlier in Ref. 21 and will not be repeated here. The data showed that an increase in $r_{le}$ reduces the size of the small and flat primary-vortex core that exists at this low $\alpha$.

In the following, the data is discussed obtained for $\alpha = 15°$. Only the velocity-vector distributions and the axial-vorticity distributions calculated from the velocity-vector fields are presented here. The distributions of the velocity component normal to these planes will be presented in a later paper.

Figure 13. The vortex flow over wing II at $\alpha = 15°$; $x_m = 0.5$ a) the instantaneous and b) time-averaged velocity-vector distribution, c) the instantaneous and d) time-averaged axial-vorticity distribution.
Figure 12 shows plots of the instantaneous and the time-averaged vector and axial-vorticity distributions over sharp-edged wing I at $x_m = 0.5$. The data is plotted versus $y_m - y_{mle}$, where $y_m$ is the lateral coordinate in the measurement plane and $y_{mle}$ the value of the coordinate at the wing leading edge. The vector plots show that the vortex core has a more or less elliptical shape. The instantaneous vector plot represents one out of the 200 recordings of the vector field. The time-averaged vector field shows a dark contour. Outside of this contour the flow spirals inward towards the contour, at the inside of it the flow continues to spiral towards the vortex axis. It is not known whether this contour is associated with the core extension downstream of the bursting point. According to Figure 9, on this wing breakdown occurs upstream of the measuring station. The vector fields suggest the presence of a secondary vortex. Resolution was too low to resolve a tertiary vortex, if present. The instantaneous axial-vorticity distribution gives evidence of the free shear layer rapidly breaking up into a highly turbulent flow. This type of flow exists in the wake behind the vortex breakdown point. The time-averaged distribution is smooth and shows no separate vortical substructures.

Figure 13 shows the data for wing II. Compared to wing I, the vortex core is significantly smaller and located closer to the wing surface. The vector plots show no contour dividing the inner and outer primary-vortex flow. According to Figure 9, vortex burst now occurs downstream of the measuring station. The axial-vorticity distributions show a more stable structure and a slight increase in the level of the vorticity in the free shear layer near the leading edge.

Figure 14 shows the data obtained for this wing in the measuring plane $x_m = 0.7$. Compared to the $x_m = 0.5$ station, the vortex cross-sectional size has almost doubled due to the greater distance from the apex, and due to the effect of vortex burst which now occurs upstream of the measuring plane. This flow phenomenon explains the chaotic instantaneous vector field and the more diffuse vorticity distribution. The vector field shows a limit cycle contour, where the streamlines inside the contour spiral outward and the streamlines outside the contour spiral inward. Visbal \cite{Visbal2010} calls this a stable limit cycle in a sequence of crossflow topologies associated with vortex breakdown.

Figure 14. The vortex flow over wing II at $\alpha = 15^\circ$; $x_m = 0.7$ a) the instantaneous and b) time-averaged velocity-vector distribution, c) the instantaneous and d) time-averaged axial-vorticity distribution.
Figure 15. The vortex flow over wing III at $\alpha = 15^\circ$; $x_m = 0.5$  a) the instantaneous and b) time-averaged velocity-vector distribution, c) the instantaneous and d) time-averaged axial-vorticity distribution.

The data at the $x_m = 0.7$ station of wing I and III were presented earlier and show developments with respect to the $x_m = 0.5$ station similar to those noted above.$^{23}$

Figure 15 shows the data at $x_m = 0.5$ for wing III. Compared to wing II, the vortex core is again smaller and closer to the wing surface. The vector plots show an inward spiraling vortex flow whose structure is not affected by vortex breakdown. The axial-vorticity distributions show a smooth development and another increase of the vorticity magnitude in the free shear layer.

Figure 16 shows the effects of the leading-edge radius on the location of the oilflow pattern lines $A_1$, $S_2$, and on the lateral and vertical location of the vortex axis, as determined from the time-averaged velocity-vector distributions at $x_m = 0.5$. The primary
A preliminary study is presented of the effects of the leading-edge radius on the flow over three $\Lambda = 50^\circ$ delta wing models.

The oil-flow visualization shows a clear effect of the leading-edge radius on the location of the secondary-separation line; a larger radius delays the outward bending of the secondary-separation line, which is indicative for a delay in the occurrence of vortex bursting over the models.

The balance data shows that the leading-edge radius affects the level and slope of the forces acting on the wings. Changes in the slope of the curves are caused by vortex burst displacements. At $\alpha$ beyond $20^\circ$, vortex burst takes over the entire wing and results in a strong lift loss, especially, when the edges are sharp. The effects of the Reynolds number on the balance data are rather small and expected to be caused again by small movements of the vortex breakdown point.

The SPIV data shows that a larger leading-edge radius reduces the size and strength of the primary vortex and moves this vortex outboard and closer to the wing surface. In addition, a slight increase in the level of the axial vorticity in the free shear layer is noted at a short distance from the leading edge. This suggests that the leading edge shape affects the direction of the local vorticity vector. Some vector fields show flow dividing contours that may be associated with the occurrence of vortex breakdown.

The preliminary SPIV data were obtained in only two cross flow planes. Currently, data are acquired in planes covering a larger portion of the models. This data will be used to determine the location of the vortex breakdown point and will be reported in a subsequent paper.

References