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MELBOURNE, VICTORIA

Flight Mechanics Technical Memorandum 409

COMPARISON OF FLOW-VISUALISED VORTICES WITH COMPUTED GEOMETRY OVER THIN DELTA WINGS (U)

by

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COMPARISON OF FLOW-VISUALISED VORTICES WITH COMPUTED GEOMETRY OVER THIN DELTA WINGS (U)

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SUMMARY

The vortex flow patterns over thin delta wings were photographed during experiments in a vertical water tunnel making use of appropriate flow visualisation techniques. The flow geometry for these wings was also calculated using the VORSBA vortex flow computer program. A comparison is made between the calculated and experimental results and discrepancies between them are discussed.

DSTO ARL MELBOURNE

POSTAL ADDRESS: Director, Aeronautical Research Laboratory,
P.O. Box 4331, Melbourne, Victoria, 3001, Australia

CONTENTS

1 Introduction

When highly swept delta wings are placed in a fluid flow at high angle of attack, the flow separates from each leading edge of the wing and forms a vortex above the wing. This effect is modelled mathematically by the VORSBA computer program, developed at NLR in The Netherlands.

VORSBA calculates the incompressible inviscid vortex flow about sharp edged wings using the slender body approximation. The highly three dimensional nature of vortex flow is represented by a series of two dimensional problems in a corresponding series of cross-flow planes. To obtain a solution, the mathematical model must be given the wing geometry and a suitable initial estimate for the vortex sheet shape. Both the wing and vortex sheets are defined using segments and are modelled by doublet distributions, although the wing segments can also be modelled by a source distribution. The program is described in detail by Hoeijmakers (Ref.1 and 2). As the problem is highly nonlinear, a second order accurate panel method is used to solve the resulting system of nonlinear equations.

Based on potential flow theory, VORSBA makes no attempt to include any viscous effects and therefore the detailed wing upper surface boundary layer is not modelled. It was of interest to obtain a comparison between the results from the inviscid potential flow model and experimental measurements made under conditions where the viscous effects were likely to be significant. These effects include the presence of laminar boundary layer separation and the formation of secondary vortices.

2 Experimental Technique

2.1 Experimental Facility

The experiments were performed in the vertical water tunnel at the Aeronautical Research Laboratory (ARL) in Melbourne (Ref.3). The tunnel is a recirculating type where the water is pumped from a reservoir tank to the header tank at the top of the tunnel. From the header tank the water goes through a contraction, enters the 250×250 mm working section and finally returns to the reservoir tank. The maximum speed through the working section is about 0.5 m/s.

2.2 Test Models

The wings chosen for the the water tunnel tests were :

1. 70° sweep delta wing
   Length - 150 mm
   Thickness - 2 mm
   3 mm bevel on all edges

2. 80°/70° double delta of the same dimensions as above but with a change in sweep occurring at the 50% chord position.

3. 80°/50° double delta similar to no.2.

The three models are shown on Figs.1a, 1b and 1c.

2.3 Flow Visualisation

2.3.1 Hydrogen Bubble Technique

In order to make the flow pattern visible over the model, the hydrogen bubble technique was used. This technique makes use of the electrolysis, where two electrodes are placed in the water and a potential difference is applied between them. Hydrogen bubbles form at the cathode and oxygen at the anode.

The metal structure of the tunnel was used as the anode in this case and the cathode was a strip of aluminium foil attached to the underside of the wing leading edges. Hydrogen bubbles formed on the foil surface were carried by the flow of water into the vortex system above the wing.

The amount of bubbles formed was increased by the addition of sodium sulphate (Na_2SO_4) to the water in a concentration of 0.05 g/l.

The major problem with the hydrogen bubble technique, especially in a vertical water tunnel, is the effect of bubble buoyancy. With the flow direction being downwards and the bubbles' natural tendency to move upwards against the flow, it is possible for the drag forces and the buoyancy forces on some bubbles to be in equilibrium. This will occur in regions of very low velocity and the stationary effect of the bubbles may mislead the experimenter into assuming that a point of stagnation has been identified. Many bubbles will be trapped in these regions of low velocity and the resulting congestion will disturb the flow there, thus altering the shape of the vortex further downstream. This problem must be monitored when performing experiments and action must be taken to clear the bubbles if congestion of this kind occurs.

A laser light sheet was used to illuminate a plane perpendicular to the flow direction. In order to ensure that enough bubbles pass through the light sheet at any instant for the best possible visual effect, the tunnel speed had to be kept lower than ideal. The lower the speed, the greater the effect of bubble buoyancy and therefore a compromise had to be made between obtaining a good image and avoiding significant buoyancy effects.

2.3.2 Fluorescent Dye

The second method of flow visualisation used was the fluorescent dye technique. This is simply the injection of a dye into the flow via a probe upstream of the model. The probe is aligned in such a way that the dye stream contacts the model at its apex and divides to pass into the two separate vortices above the wing. Again the laser light sheet was used to illuminate the cross-flow plane of interest.

2.3.3 Lighting

The laser used was a Lexel Model 65 air-cooled argon ion laser. A series of lenses were placed along the line of the laser beam to spread the single beam into a light sheet. This was then deflected via a small mirror onto the surface of a spherical mirror which directed the light at the correct angle onto the model.

The vortex cross-section was then photographed via a mirror placed in the wake of the model at an angle of 45° to the water tunnel centreline (see Fig.2). The camera used was an Olympus OM–2N and the film was HP5, developed for 12 minutes in full strength Microphen at 20°C.

3 Flow Computation

Although the water tunnel models did have real thickness, they were originally mathematically modelled by a flat plate of zero thickness. The input files for the calculations were created using the VORSIN input preprocessor (Ref.4) and the procedure used to obtain a solution was as follows :

1. Obtain a convergent solution for a very simple initial vortex shape (ie. 2 panel estimation).
2. Extend this solution to the required vortex sheet length using the automatic sheet extension option.
3. March this solution downstream or vary the angle of attack/sideslip.

To compare the results correctly, the data from the calculation must be transformed into the same co-ordinate system that was used in the water tunnel (see Appendix A). The VORSBA results are always in a plane perpendicular to the wing mid-surface (ie. the x-y plane) whereas the photographs taken during the water tunnel tests show the vortex cross-section perpendicular to the tunnel centreline. In order to make the transformation, it must be assumed that all points on the vortex sheet lie on a ray extending from the wing apex (ie. assume that the flow is conical). This assumption should hold for all wings where the surface itself is conical, however it is not totally correct for wings such as the double deltas. To help compensate for the fact that the double deltas are not conical, all points on the vortex sheet after the mid-chord position will be assumed to have been generated from the point where the aft leading edges intersect with the model centreline (point 0 on Figs. 1b and 1c).

4 Results and Discussion

The first computations were for a 70° delta wing represented as a flat plate of zero thickness. By comparing this result with the test result, it is seen that the two have reasonable agreement for the initial part of the vortex sheet (see Fig.3). Beyond this point the roll up of the experimental vortex is much tighter than the roll up of the computed result and the vortex core is located above and inboard of the theoretical vortex. One possible explanation for this displacement is that it is due to the presence of a secondary vortex extending from the wing upper surface slightly outboard of the primary vortex core. The formation of the secondary vortex follows the separation of the upper surface boundary layer. As VORSBA is purely a potential flow model, this boundary layer behaviour is not modelled. However, it is possible to simulate the effect of the secondary vortex using the potential flow model by specifying the location of the secondary separation line and estimating the initial secondary vortex sheet geometry.

To study the effect of a secondary vortex, another separation point was introduced into the mathematical model located 70 % of the semi-span away from the centreline. A convergent solution was unobtainable for the 70° delta wing so a unit aspect-ratio delta (ie. 76° sweep) was used. When the simple model and the secondary vortex model are superimposed (Fig.4), it can be seen that the secondary vortex flattens out the primary vortex sheet over the initial section of the sheet. It also tends to shift the primary vortex core inboard and upwards and make the core itself roll up in a much tighter manner. A similar trend for the 70° delta could account, at least partly, for the difference between the experimental and computed results.

Another source of discrepancy between the computed and the theoretical results is the fact that the computation so far assumed a zero thickness wing. The mathematical model was given thickness and the same cross-sectional shape as the wing itself to try to obtain a more accurate representation of the vortex shape. It must be remembered that VORSBA assumes a linear relationship between the wing surface co-ordinates at the current station and those at the previous station, in this case the wing apex. Therefore this representation is still not entirely correct as it will have a linear variation in wing thickness from the apex whereas the water tunnel model has constant thickness over the entire length. To represent the experimental model exactly, the amount of computation involved would be considerable, with possible improvements in the final solution being small. The solution for the thick wing was obtained and compared to the flat plate solution (see Fig.5). The initial parts of the vortex sheets are almost identical but the thick wing model shifts the vortex core upwards and slightly inboard, which is the expected effect.

Modelling the secondary separation and the wing thickness both tend to shift the computed primary vortex core inboard and upward but the magnitude of the shift still appears to be too small to account for the overall discrepancy between theory and experiment. As the effects of thickness are small, for all other comparisons, the flat plate representation was used for simplicity.

The effect of yaw was also investigated for the 70° delta wing only. From Fig.6 it is seen that yawing the wing through an angle of 10° produces good agreement between theory and experiment for the vortex on the leeward side. However, for the windward vortex, the comparison between theory and experiment becomes progressively worse.

Yawing the wing will reduce the effective sweepback on the windward side and therefore the deviation from the slender body, potential flow assumptions becomes greater. The primary vortex lies closer to the wing surface thus making the effects of secondary separation more significant. The size of the secondary vortex on the windward side of the wing can be seen on Fig.6. The fluorescent dye method was used to visualise the flow in the secondary vortex, the size of which will have an effect on the shape and position of the primary vortex sheet.

Similarly, the effective sweepback on the leeward side is increased thus improving the validity of the slender body and potential flow assumptions. The primary vortex will be further from the wing surface making the secondary separation effects less significant and the agreement between theory and experiment is quite good. A similar trend has been recorded by Verhaagen and Naarding (Ref.5) for a yawed delta wing in a wind-tunnel.

To determine how well VORSBA handles streamwise variations in geometry, two double delta wings were also investigated. The first was an 80°/70° double delta and the second with a more drastic change in sweep was an 80°/50° double delta. For both of these wings, the change in geometry occurred at the 50% chord position.

The discrepancies between the computed result and the measured geometry for the 80°/70° double delta are similar to those for the 70° delta wing. For the double delta, the change in geometry flattens out the initial part of the vortex sheet and although the VORSBA result also includes this characteristic, it is to a much lesser extent (Fig.7). Beyond the 60% chord position, the flattening of the computed vortex becomes almost unnoticeable to the point where it is impossible to detect that a change in the wing sweep has occurred at all.

This is not the case for a more drastic change in sweep as with the 80°/50° double delta. At the 60% chord station the VORSBA result has a definite kink located at the same spanwise position as the kink in the measured vortex (Fig.8). The computed vortex core position is closer to the experimental core in this case than in the previous cases. It is reasonable to say that VORSBA has calculated a good result considering that the 50° sweep angle is a long way from the slender body approximation. After this station, the kinked vortex tends to break into two separate vortices, one originating from the wing apex and the other from the change in sweep. The double branched vortex is illustrated by Thompson (Ref.6). The current version of VORSBA used at ARL cannot deal with such a multiple vortex configuration, and it fails to converge on a solution.

5 Conclusion

The VORSBA computer program is based on the slender body approximation, and it is to be expected that using VORSBA to model a configuration which does not conform to this approximation will not give accurate results. As has been shown in several examples, the correlation between theory and experiment is not good. However for cases where the slender body approximation is a valid one, for example on the leeward side of the yawed delta, the agreement between theory and experiment is excellent.

Because VORSBA is a potential flow model, it does not include any viscous effects such as the upper surface boundary layer. For configurations where the vortex lies close to the wing surface, complicated boundary layer effects will occur and as these are not modelled by the program there will be large discrepancies in the vortex geometry for these cases.

Acknowledgements

The author would like to thank Dr. David Thompson for his help in completing this work. The information regarding the secondary vortex calculations supplied by Dr. Harry Hoeijmakers is also gratefully acknowledged.

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A Transformation Equations

The vortex geometry as calculated by VORSBA is shown schematically on Fig. A1. In order to compare these results with those obtained from the water tunnel tests, the data must be transformed into a plane located at 0 and perpendicular to the velocity vector $\vec{U}_\infty$.

By considering an arbitrary point on the vortex sheet (denoted here on Fig. A1 by point 1) whose co-ordinates are (x, y, z), the pitch and yaw rotations can be viewed and analysed in the directions A and B. These two views are shown on Fig. A2.

Initially the point (x, y, z) is at position number 1 and the wing apex is at $\hat{1}$. In both views these two points form a triangle with point 0 which is the position about which the wing will be rotated. The wing is pitched through angle α so that the triangle $1, 0, \hat{1}$ becomes $2, 0, \hat{2}$. This is followed by a yaw through angle β which generates triangle $3, 0, \hat{3}$. The line that joins point 3 (the wing apex) to the point $\hat{3}$ cuts the original y–z plane at a point (x, y'', z''). This is the transformed coordinate and is defined using the following expressions.

$$y'' = \frac{y\cos(\beta+\eta)}{\cos\eta} - \frac{y\sin(\beta+\eta)}{\cos\eta}\tan\varsigma$$

where

$$\eta = \arctan(\frac{z}{y}\sin\alpha)$$

$$x' = x\cos\alpha$$

and

$$\tan\varsigma = \frac{\frac{y\cos(\beta+\eta)}{\cos\eta} - x'\sin\beta}{x'\cos\beta + \frac{y\sin(\beta+\eta)}{\cos\eta}}$$

$$\Rightarrow y'' = \frac{y}{\cos\eta}\left\{\cos(\beta+\eta) - \sin(\beta+\eta)\left[\frac{\frac{y\cos(\beta+\eta)}{\cos\eta} - x\cos\alpha\sin\beta}{x\cos\alpha\cos\beta + \frac{y\sin(\beta+\eta)}{\cos\eta}}\right]\right\}$$

Also,

$$z'' = z\cos\alpha - \frac{y\sin(\beta+\eta)}{\cos\eta}\tan\gamma$$

$$tan\gamma = \frac{z\cos\alpha - x'\cos\beta\tan\alpha}{x'\cos\beta + \frac{y\sin(\beta+\eta)}{\cos\eta}}$$

$$\Rightarrow z'' = z\cos\alpha - \frac{y\sin(\beta+\eta)}{\cos\eta}\left\{\frac{z\cos\alpha - x\cos\beta\sin\alpha}{x\cos\alpha\cos\beta + \frac{y\sin(\beta+\eta)}{\cos\eta}}\right\}$$

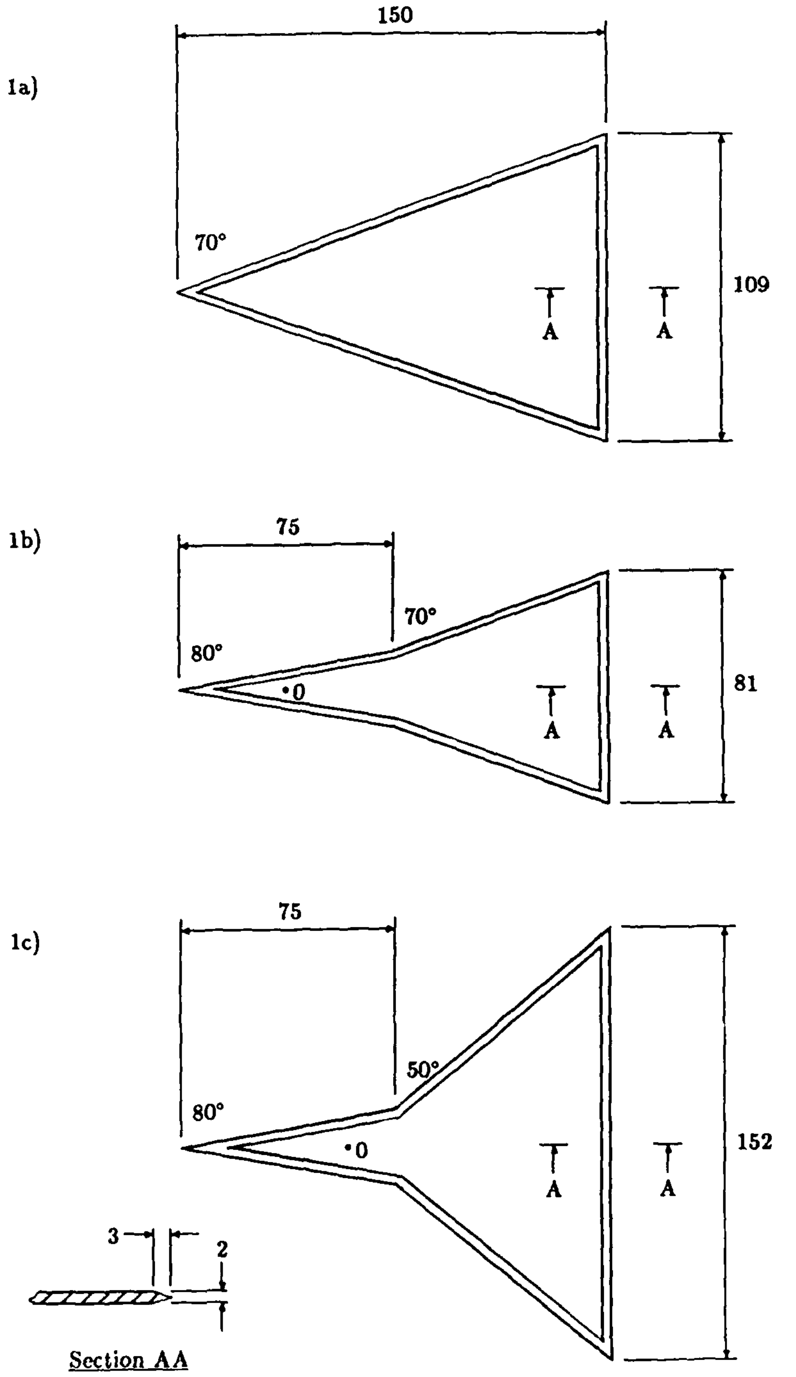


Figure 1 – Water tunnel models

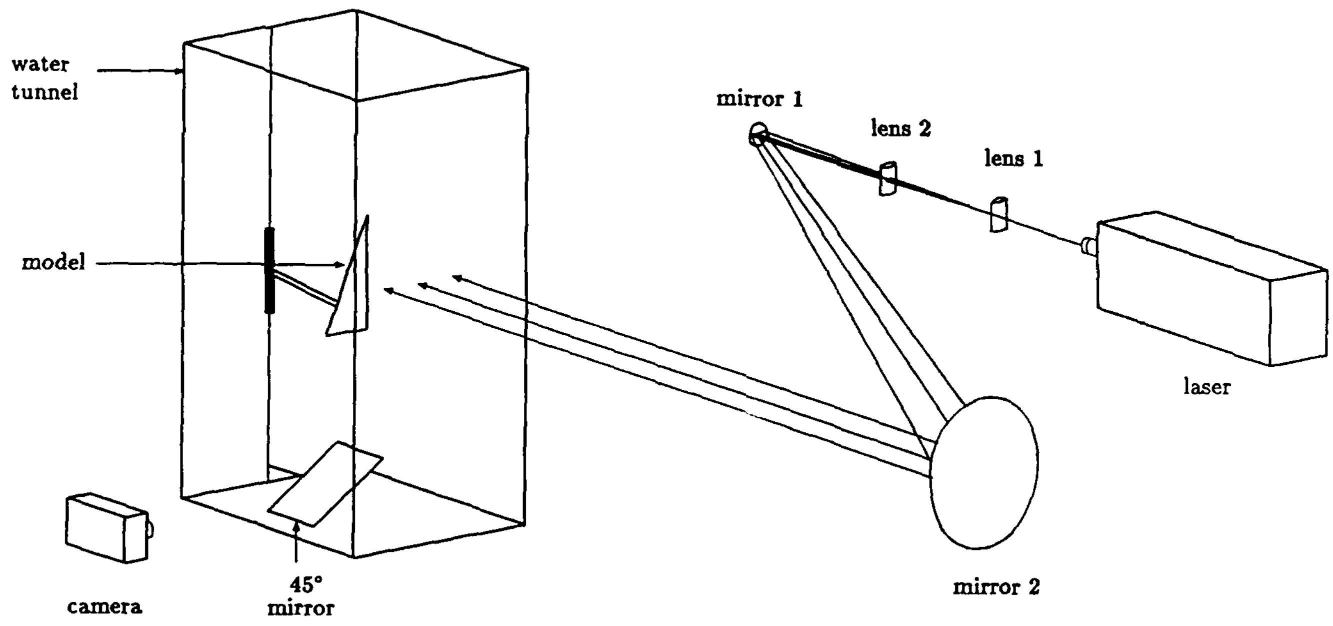
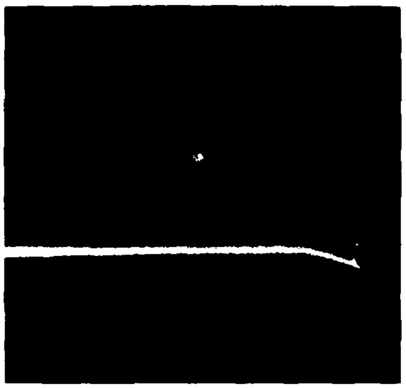
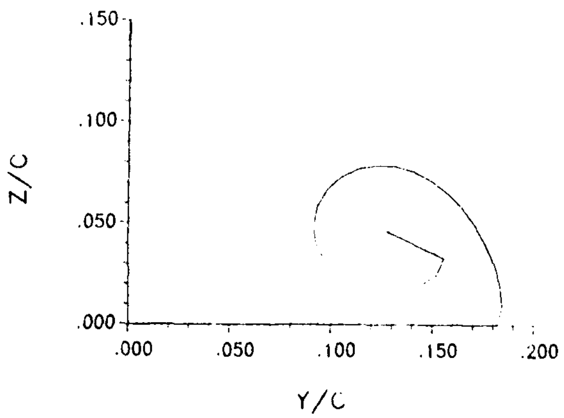


Figure 2 – Experimental set-up



Experimental vortex



Computed result

Figure 3. Comparison between experimental and computed vortex shapes for a 70° delta wing at the 50% chord position; $\alpha = 20°, \beta = 0°$

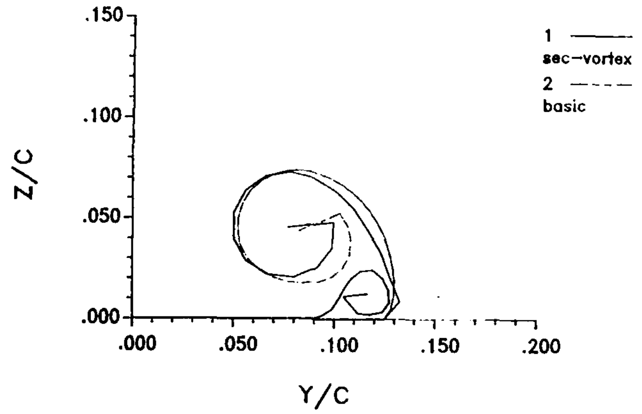


Figure 4. Effect of simulated secondary vortex on a unit aspect-ratio delta wing at the 50% chord position; $\alpha = 20°, \beta = 0°$

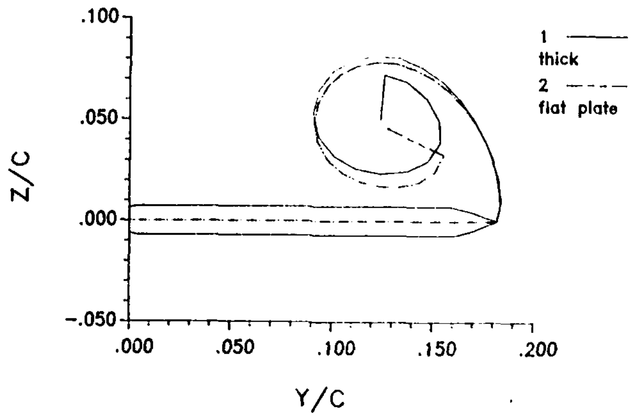
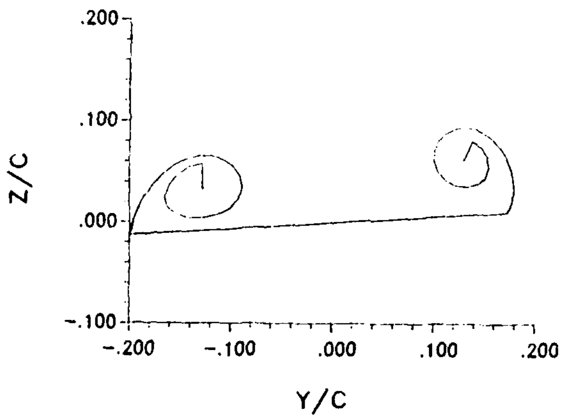


Figure 5. Effect of simulated wing thickness on a 70° delta wing at the 50% chord position; $\alpha = 20°, \beta = 0°$

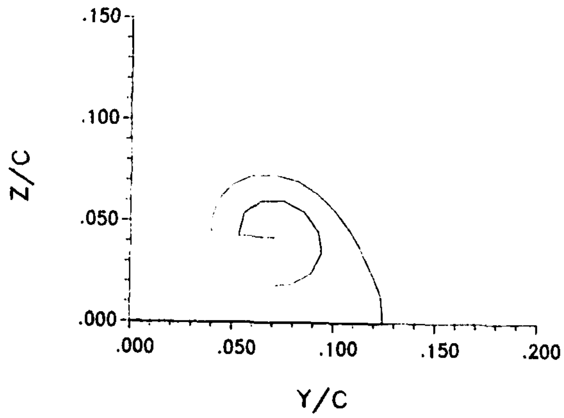
Experimental vortex



Computed result

Figure 6. Comparison between experimental and computed vortex shapes for a 70° delta wing at the 50% chord position; $\alpha = 20°, \beta = 10°$

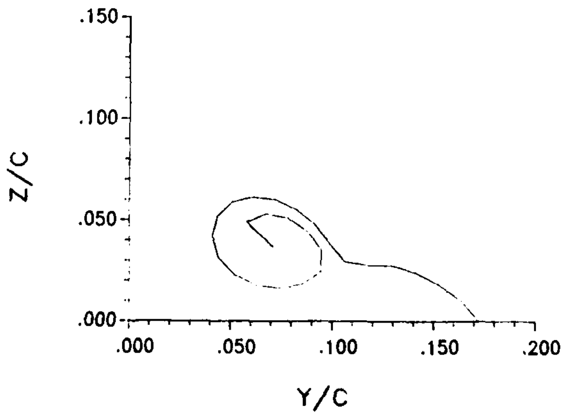
Experimental vortex



Computed result

Figure 7. Comparison between experimental and computed vortex shapes for a 80°/70° double delta wing at the 60% chord position; $\alpha = 20°, \beta = 0°$

Experimental vortex



Computed result

Figure 8. Comparison between experimental and computed vortex shapes for a 80°/50° double delta wing at the 60% chord position; $\alpha = 20°, \beta = 0°$

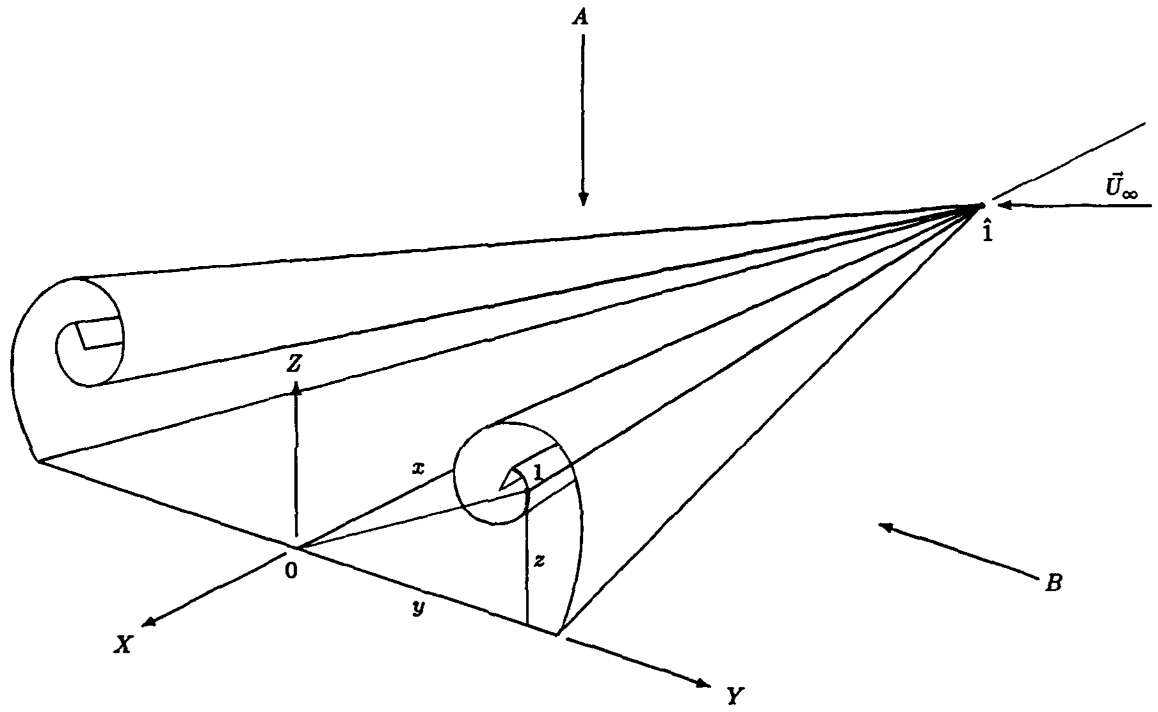


Figure A1 – Schematic roll--up of vortex sheet

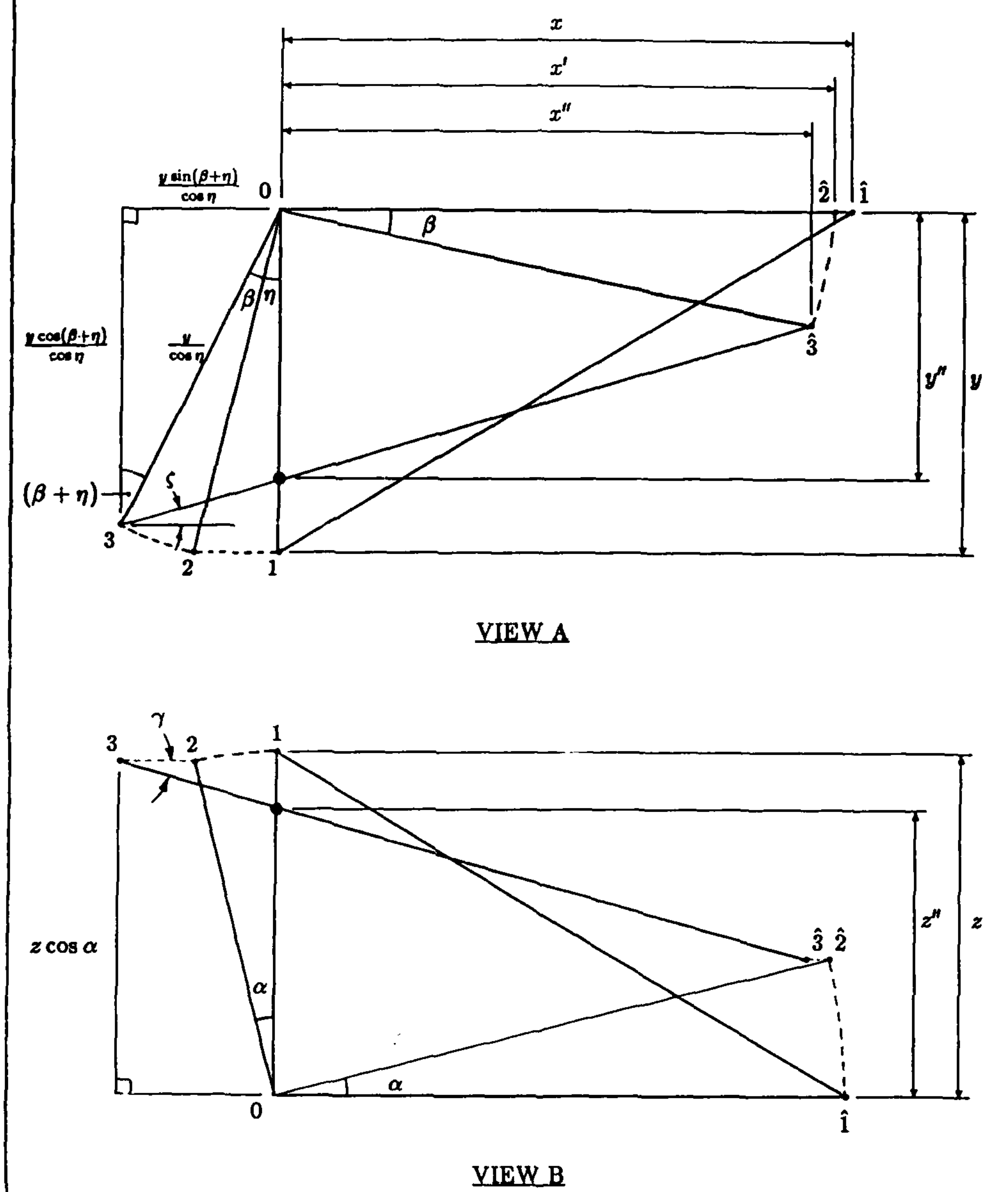


Figure A2 – Transformation from VORSBA to water tunnel co–ordinates

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