The Discrete Vortices from a Delta Wing

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Introduction: The Classical View

THE flow over delta wings at an angle of attack is dominated by two large bound vortices that result from the flow separation at the leading edge. The classical view of these vortices is sketched in Fig. 1a and has been discussed by Hoerner and Borst[1] among others. With a sharp leading edge at an angle of attack α, the flow is separated along the entire leading edge forming a strong shear layer. The shear layer is wrapped up in a spiral fashion, resulting in the large bound vortex as sketched. These vortices appear on the suction surface and increase in intensity downstream. The low pressure associated with the vortices produces an additional lift on the wing, often called nonlinear or vortex lift, which is particularly important at large angles of attack. As sketched in Fig. 1a, small secondary vortices also appear on the wing near the points of reattachment as a result of the strong lateral flow toward the leading edge.

Experimental Approach

Two delta wings with leading edge sweeps of 45 and 60 deg were used in the present investigation. The root chord of both wings was 25 cm, and the chord Reynolds number varied in the range of 1.3×10^4 to 3.5×10^5. The 45 deg delta wing had a NACA 0012 profile at each spanwise section. The wing was made of two aluminum pieces with grooves on the inner surface of each for dye passage and storage. The 60 deg delta wing had a flat surface with a sharp leading edge.

The wings were towed at speeds, U_∞, ranging from 5 to 140 cm/s through the 18 m long, 1.2 m wide, 0.9 m deep water channel described in Ref. 2. The wings were sting-mounted to a carriage riding on two tracks mounted along the top of the tank. During towing, the carriage was supported by an oil film which insured a vibrationless tow, having an equivalent freestream turbulence of about 0.1%.

Food color and fluorescent dyes were used in the present investigation to visualize the flowfield in and around the delta wing. The food color dyes were illuminated with conventional flood lights. The fluorescent dyes were excited with sheets of laser light projected in the desired plane. To produce a sheet of light a 5 W argon laser (Spectra Physics, Model 164) was used with a mirror mounted on an optical scanner having a 720 Hz natural frequency (General Scanning, Inc.). A sine-wave signal generator, set at a frequency equal to the inverse of the camera shutter speed, drove the optical scanner to produce light sheets approximately 1 mm thick.

Dye sheets or dye lines were seeped into the boundary layer through a system of slots and holes on the suction side of the wing. The slots were 0.2 mm wide and were milled at a 45 deg angle to minimize the flow disturbance. The holes were 0.4 mm in diameter and were spaced at 1 cm center to center. Ciné films were obtained using two 16 mm cameras towed with the wing. The first was mounted over the wing and above the water surface, and the second camera was located behind the wing and underwater.

Vortex Formation

The present research was undertaken to determine and examine the structure of the shear layer at the leading edge. Brown and Roshko[3] showed that in free shear layers originating at a splitter plate between two streams of differing velocity, the flowfield contains discrete vortices. Winant and Browand[4] further showed that the growth of such shear layers is the result of a pairing process between two neighboring vortices. They showed that the mutual induction of one vortex on the other caused them to begin to rotate around each other and merge to form a single vortex of a larger diameter. The process repeated itself until inhibited by the physical constraints of the flow apparatus.

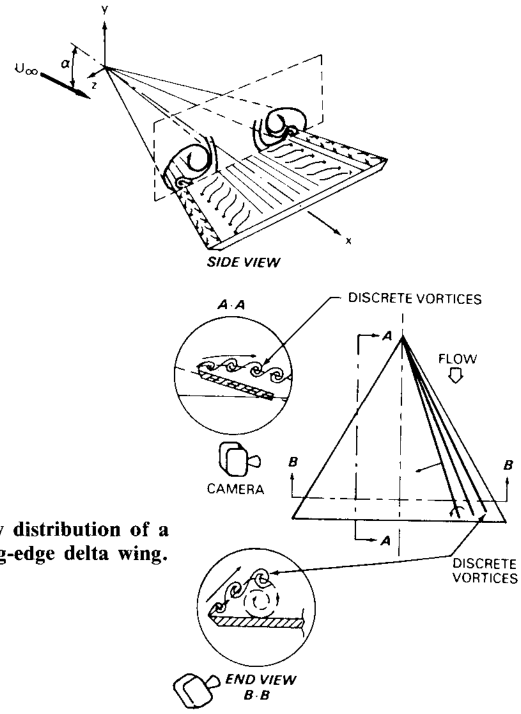

Fig. 1 Flow distribution of a sharp leading-edge delta wing.

Figure 2 shows the plane view of the 60 deg, sharp leading edge delta wing at an angle of attack of $\alpha = 10$ deg and a Reynolds number of 1.3×10^4 based upon the root chord. The flow is from top to bottom, and the flowfield on the left side of the wing is visualized using a dye slot at the leading edge. Note that the dye sheet has alternating dark and light regions near the leading edge and extending along it. Although these regions become more obscure as they are wrapped up into the large vortex structure, they do indicate that a substructure is present in the flowfield.

A cross-sectional view of the same flowfield is found in Fig. 3. The flow is partially out of the plane of the photograph, and the left side of the flowfield has been visualized with a fluorescent dye excited with a vertical sheet of laser light perpendicular to the axis of the primary leading-edge vortex. It is apparent that the dye rolls up into regions of strong concentration immediately after separation. Although the geometry of the shear layer is much more complex in the present case, the observed phenomenon is similar to that of Winant and Browand.[4] On the accompanying movies, the dye injected near the leading edge was observed to immediately roll up into discrete vortices‡ separated by a very thin braid of dye. With some background lighting in addition to the laser sheet, the vortices were seen to be parallel to the leading edge and extended along the entire edge, as seen in Fig. 2. The trajectory of the vortices followed the general outline of the large bound vortex. As they followed this course, two vortices would begin to roll around each other and merge to form a single larger vortex. This process was observed to repeat itself until either the dye passed out of the sheet of laser light or the large bound vortex broke down and the dye became too diffuse.

The best attack angle to observe this phenomenon was in the range of 10-15 deg. At angles below 5 deg, the pairing process seemed to be inhibited by the proximity of the solid boundary.

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‡The roll-up consisted of a discrete concentration of dye which was assumed to be a vortex following the results of Winant and Browand.[4]

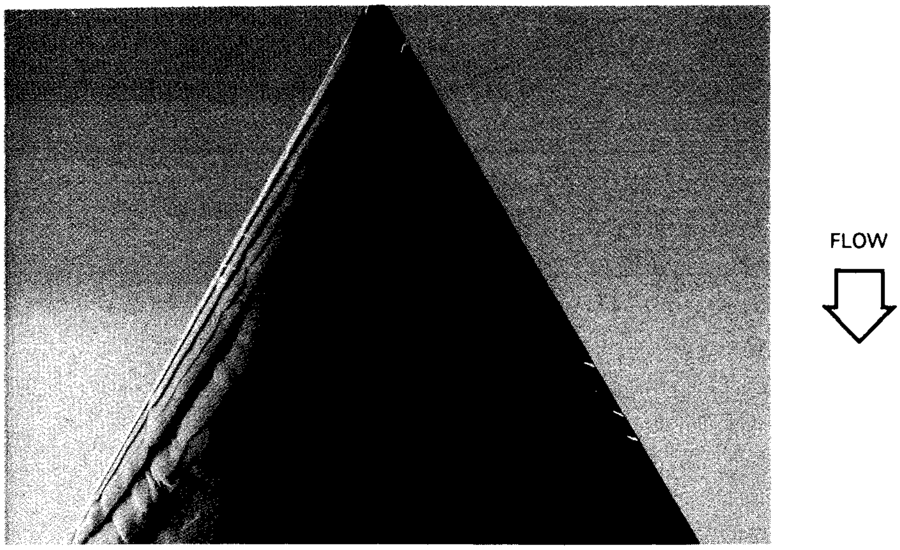

Fig. 2 Top view with delta wing at fixed angle of attack $\alpha = 10$ deg.

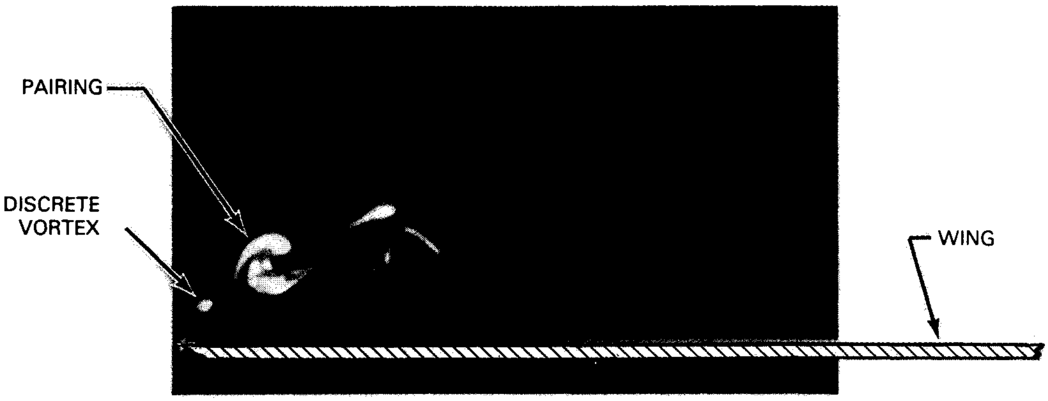

Fig. 3 View with a vertical sheet of light perpendicular to axis of primary leading-edge vortex.

At large angles of attack, the flow was more turbulent and masked the observed phenomenon. It is not clear from the present experiments if the primary vortex was only the cause of the secondary vortices by setting up the initial shear layer, or if it was possibly the result of several mergings of the secondary vortices.

The discrete vortices were also observed on the 45 deg, blunt leading-edge delta wing. Ciné films were used to determine the natural shedding frequency, f_0, by counting the number of vortices passing a fixed position near the leading edge per unit time. The data are shown in Table 1. The shedding frequency was independent of the wing's sweep angle and leading edge shape. At constant U_∞, the observed number of vortices shed per unit time tended to decrease as α increased. At constant α, the measured frequency is proportional to the square root of the towing speed. A least squares fit of the data in Table 1 yields the empirical relation:

$$f_0 = 1.3\sqrt{U_\infty}; \quad \alpha = 15 \text{ deg}, R_c = 1.25\times10^4\text{-}3.33\times10^5$$

or

$$f_0 c/U_\infty = 1625/\sqrt{R_c}$$

If the vortices are shed at a constant Strouhal number, this would imply that the length scale also increases as the square root of the velocity. Since the frequency is very sensitive to slight changes in the shear layer, this result may have been influenced by increasing the dye flow rate at higher velocities in order to improve the visual image.

The principal result of this Note is that the classical large vortices on delta wings originate as a series of smaller vortices shed from the leading edge of the airfoil. They rotate around each other and pair to form larger vortices while simultaneously moving downstream. The vortices have paired at least three times before reaching the trailing edge of the wing at the Reynolds number range used in the present investigation. Although laboratory experiments with simpler geometry indicates that more pairing and growth would occur at higher Reynolds numbers, it is felt that the discrete vortex shedding and pairing process will also be important in the dynamics of the larger primary vortex structure.

Table 1 Shedding frequency dependence upon angle of attack and flow speed

$U_\infty = 10$ cm/s							
α, deg	5	10	15	20	25	30	40
f, Hz	4.0	2.7	4.2	3.2	2.6	2.8	2.2
$\alpha = 15$ deg							
U_∞, cm/s	5	10	20	40	80	130	140
f, Hz	3.0	4.2	5.7	7.6	12.4	15.0	15.4

Acknowledgments

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References

[1]Hoerner, S. F. and Borst, H. V., *Fluid Dynamic Lift*, L. A. Hoerner, Brick Town, N.J., 1975, pp. 18.1-18.20.

[2]Gad-el-Hak, M., Blackwelder, R. F., and Riley, J. J., "On the Growth of Turbulent Regions in Laminar Boundary Layers," *Journal of Fluid Mechanics*, Vol. 110, Sept. 1981, pp. 73-95.

[3]Brown, G. L. and Roshko, A., "On Density Effects and Large Structure in Turbulent Mixing Layers," *Journal of Fluid Mechanics*, Vol. 64, July 1974, pp. 775-816.

[4]Winant, C. D. and Browand, F. K., "Vortex Pairing: the Mechanism of Turbulent Mixing-Layer Growth at Moderate Reynolds Number," *Journal of Fluid Mechanics*, Vol. 63, 1974, pp. 237-255.

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