Computational Fluid Dynamics 5

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Assignment 1 | Flat Plate at Incidence

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LITERATURE REVIEW

Furman et al. conducted experimental investigations on a 65 degree swept delta wing. They used low-speed wind tunnel facilities to obtain results of mean and unsteady surface pressure distributions, as well as mean and turbulent velocity components of the flow field close to the wing surface. Details of the delta wing vortex structure and breakdown phenomenon are discussed and analysed. Vortex bursting leads to specific spectral densities of velocity and surface pressure fluctuations characterised by narrow band distributions associated with the helical mode instability of the vortex breakdown flow field. They place special emphasis on the occurrence of an inner vortex detected for the low Reynolds number and Mach number regime. The inboard vortex results from laminar separation close to the apex due to the spanwise pressure gradient in the area of relatively large thickness while the classical leading-edge vortex progressing from the rear part to the apex is fed from the turbulent shear layers shed at the wing upper and lower side (Furman, Breitsamter 2012).

DELTA WING PHYSICS -Furman, Breitsamter 2012

VORTICES: Flow separates already at low angles of attack at the highly swept leading edges. The separated shear layer rolls up to form a large scale vortex located over each half of the wing. Thus, two strong vortices influence the flow field of the wing upper side. Vortex formation along the leading-edge starts from the rear part to the apex. This primary vortex is fully developed when vorticity feeding extends over the entire leading edge. The vortex cross-flow area reveals a rotational core with an embedded subcore, the latter dominated mainly by viscous effects. The subcore is characterised by high axial velocities, low static pressures and enhanced velocity fluctuations due to the steep gradient in the cross-flow components. The mean velocities on the wing upper surface are strongly increased by the leading-edge vortices resulting in high suction levels. The corresponding suction peaks in the spanwise pressure distribution indicate the track of the vortex axis on the wing surface. Consequently, leading-edge vortices in a fully developed, stable stage create additional lift and an increase in maximum angle of attack which significantly improve the manoeuvre capabilities of high-agility aircraft [1].

LEADING EDGE: Sharp leading edge configurations are often used in delta wing research work because primary separation is fixed and leading edge vortex evolution is less sensitive to Reynolds number effects. Vortex aerodynamics become much more complicated for rounded or blunt leading edge configurations as the position of primary separation varies to a certain extent depending pressure gradient and boundary layer development [2].

VORTEX EVOLUTION: Thus leading edge radius, angle of attack and Reynolds number are the main parameters influencing the onset of vortex evolution as well as as well as position and strength of the primary vortex whereas the angle of attack is the main parameter for the sharp leading edge case only. There is a strong increase in surface pressure when moving in spanwise direction from the station of the primary vortex suction peak to the leading edge. This severe lateral pressure gradient provokes boundary layer separation in that region. The separated boundary layer rolls up by self-induction and creates a small vortex, named a secondary vortex, the rotation of which is opposite to that of the leading edge (primary) vortex. The formation of the secondary vortex depends strongly on the presence of a laminar or turbulent boundary layer. Size and position of the secondary vortex affects the primary vortex location, and thus, the associated suction level.

VORTEX BREAKDOWN: Further, leading-edge vortices are subject to breakdown at high angles of attack. Vortex breakdown is caused by the stagnation of the low-energy axial core flow due to the increase of the adverse pressure gradient along the vortex with increasing angle of attack. This rise in the vortex core static pressure at the wing rear part is caused on the one hand by the recompression in the trailing-edge area. Vortex breakdown is indicated by the rapid expansion of the vortex core accompanied by high velocity fluctuations. Downstream of breakdown, the fluctuation maxima are located in a limited radial range around the burst vortex core. In addition, the breakdown flow exhibits specific instability mechanisms leading to narrow-band unsteady aerodynamic forces.

[1] C. Breitsamter, Strake effects on the turbulent fin flowfield of a highperformance fighter aircraft, in: W. Nitsche, H.-J. Heinemann, R. Hilbig (Eds.), Notes on Numerical Fluid Mechanics, in: New Results in Numerical and Experimental Fluid Mechanics II, Contributions to the 11th AG STAB/DGLR Symposium, **Berlin, Germany, vol. 72, Vieweg Verlag, 1999, pp. 69–76**

[2] J.M. Luckring, Reynolds number, compressibility, and leading-edge bluntness effects on delta-wing aerodynamics, in: Proc. 24th Congress of the International Council of the Aeronautical Sciences,

VALIDATION REFERENCES:

- Free stream turbulence intensity <0.4%.
- Uncertainty in the temporal and spatial mean velocity distribution is <0.6%
- Uncertainty in free stream direction is <0.2.
- Static pressure variations < 0.4%.

	Sim	Exp
Root chord length (m), c_r	0.1	0.980
Wing Span (m), b	0.088	0.914
Swept Angle (°), φ	65	65
Aspect Ratio		1.865

- Investigation carried out at 3 angles of attack (13/18/23).
- Corresponding Mach numbers for each (0.07/0.14)
- Corresponding Reynolds based on the mean aerodynamic chord are 10^6 and 2x10^6.

Pressure Sensors:

- 177 pressure orifices / 44 unsteady pressure sensors.
- Positioned at 5 chordwise positions x/c_r = 0.2, 0.4, 0.6, 0.8 and 0.95. Could obtain data using probes in STARCCM+ from the same points for comparison.

RESULTS AND DISCUSSION -Furman, Breitsamter 2012

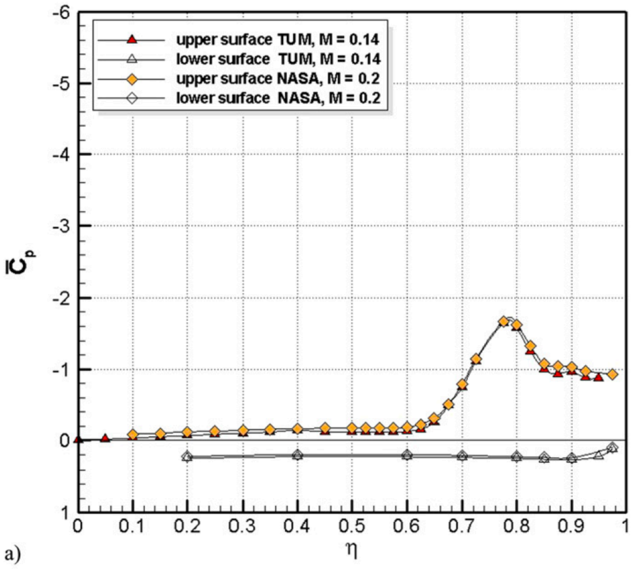
Surface Flow:

The leading edge (primary) vortex starts from a turbulent separation at the wing rear part, with the turbulent shear layers of the wing upper and lower side rolling up along the leading edge. The roll-up process does not reach the apex at this angle of attack (13) but progresses up to the wing front part. There, a laminar boundary layer is present. Transition is indicated by an outboard shift of the separation line of the secondary vortex. Further, a laminar separation exists near the apex close to the symmetry plane. This three-dimensional separation bubble is caused by the pressure increase when the flow has turned around the leading edge contour of the relatively thick wing section of the apex region.

Downstream Flow

Downstream, the inboard separated flow forms a small inner vortex favoured by the positive lateral pressure gradient between the primary vortex suction area and the local suction minimum at the symmetry plane. The inboard vortex rotates in the same direction as the leading edge (primary) vortex. Separation and attachment line of the inboard vortex lie closely together and can be clearly seen in the oil flow picture. The inboard vortex extends over the entire chord length to the wing rear edge. Further tests have shown that the trajectory and strength of the inboard vortex depends strongly on angle of attack (strength of primary vortex and adverse lateral pressure gradient) and Reynolds number (area of laminar flow). Therefore, this phenomenon is only visible at certain Reynolds numbers in the medium angle of attack range.

*Compares pressure distribution results with NASA



a)

Overall the comparison shows an excellent agreement between NASA and TUM steady pressure distributions. It illustrates the comparability in the measured quantities despite the differences in free stream, wind tunnel and model conditions.

But a notable difference is present for the case with the rounded leading-edge at AOA (13) with respect to the span wise position and intensity of the primary vortex suction area (Talk in report about how not having a rounded plate causes different results with ref to the rounding – see highlight below). This case, which is characterised by the partly developed leading edge vortex, is already sensitive to minor changes in Reynolds number and Mach number. The TUM tests match the Reynolds number of the NASA tests but the latter conducted at a slightly higher Mach number, also associated with a higher free stream velocity. This difference in flow conditions correspond to a lateral shift of the primary vortex in direction to the leading edge along with an increase in vortex induced suction. It matches the trend that increasing the Mach number at constant Reynolds number promotes the onset of blunt leading-edge vortex separation.

Turbulent flow field:

The differences in the mean pressure suction peaks between the cases of sharp and rounded leading-edges cannot be quantified in sufficient detail due to the limited spatial resolution related to the spacing of the pressure tabs. However, compared to the case of sharp leading-edges, it can be clearly stated that the primary separation is retarded for the rounded leading-edge resulting in a primary vortex suction area which is located closer to the leading edge.

Vortex Bursting

If an increase in angle of attack does not cause an increase in the primary vortex suction peak comparing stations of x/cr = const, then the leading edge vortex may experience breakdown. This criterion fails if the primary vortex detaches from the wing surface and thereby reduces its influence on the pressure distribution at the same time as the breakdown location passes the trailing edge upstream. The detachment of the vortex axis for strong leading edge vortices present at this delta wing planform, is only observed at angles of attack beyond the ones investigated here. Therefore, the described breakdown criterion is applicable.

Turbulence Intensity

The turbulence intensity pattern exhibits an annular concentration of local rms maxima. This turbulence structure is a characteristic feature of spiral vortex breakdown which is related to Reynolds stress numbers above 10^4 [3]. ... . That means the vortex breakdown has started to influence the surface pressure fluctuations. The narrow band concentration of turbulent kinetic energy at burst flow conditions reflects the helical mode instability of the vortex breakdown flow.

[3] C. Breitsamter, Unsteady flow phenomena associated with leading-edge vortices, Progress in Aerospace Sciences 44 (1) (2008) 48–65.

CONCLUSIONS

1. For medium angles of attack, a new phenomenon was found for delta wings with straight leading-edge depending on strongly on Reynolds number. In addition to the classical primary vortex an inboard vortex occurs close to the wing surface. This phenomenon appears stronger for the rounded than for the sharp leading edge. While the primary vortex develops from the trailing edge towards the apex with increasing angle of attack and therewith starts here from a turbulent separation, a laminar separation occurs at the wing surface in the region of the apex close to the symmetry plane. The flow is attached around the leading edge, but the pressure increases towards the symmetry plane of the wing causing laminar separation in the inboard area. Downstream, the three-dimensional separation bubble transform to a spatially small and weak vortex, which is situated close to the wing surface along the entire chord length.
2. At high angle of attack, vortex breakdown dominates the wing flow associated with a characteristic annular region of local turbulence maxima surrounding the strongly expanded core of the burst primary vortex. Further, a narrow band concentration of turbulent kinetic energy takes place. During the upstream movement of the breakdown location the turbulent flow field affects more and more the wing surface flow, thereby increasing the surface pressure fluctuations which also show coherent structures and significant concentrations in a certain frequency range.
3. Measurements of the boundary layer allow the quanitification of the time averaged velocities as well as of the turbulent normal and shear stresses close to the wing surface. For the Reynolds numbers investigated here and medium angles of attack, a turbulent boundary layer starts to develop at approximately 20% to 30% of the root chord for the attached flow of the inner part of the wing. Under the primary vortex, the boundary layer becomes thinner by a factor of 2 to 5 due to the strong accelerated flow. (Furman 2012)

1. For a delta wing with a rounded leading edge, the prediction of the onset of the primary leading edge separation is the most essential problem. The position of this separation point can be predicted too much upstream or too much downstream or (by accident?) at the correct position. Depending on this, the agreement between numerical and experimental results can be very good or less good. One uncertainty parameter which was found for these test cases is the unknown transition, which can have a strong effect on the solution. So transition modeling should be further promoted. Another difficulty is the effect of the Reynolds number at delta wings with round leading edges. This effect also can be under- or over-predicted.
2. At higher incidence, the correct prediction of vortex break down is also a very difficult task. In the numerical solution, vortex break down occurred at earlier angles of attack compared to the experiment. This may be due to an under-prediction of the axial velocity in the vortex core. Either there is still a deficit of the existing turbulence models for a proper treatment of vortical flow, or RANS methods are overstrained and DES methods are required for the correct prediction of vortex break down.
3. Summarizing it can be stated, that not for all presented test cases the experimental results could be predicted in detail correctly, but anyhow detailed numerical flow analysis gave an essential insight into the complex flow structure of the double vortex system at round LE and the numerical calculations helped to design the PIV experiments (W. Fritz 2012)

Narayama – 9 Types of flow over delta wing

1. Flow with primary separation at the leading edge, secondary and tertiary separation.
2. Flow with primary separation at the leading edge with a cross flow shock beneath the vortex and secondary separation.
3. Flow with primary separation at the leading edge with chock-induced secondary separation.
4. Fully attached flow with embedded shock wave.
5. Flow attached at the leading edge with inboard shock induced separation
6. Mixed flow with a shed vortex

7. Flow with leading edge bubble and shock
8. Flow with primary separation at the leading edge with a centreline shock in between the vortices.
9. A type of flow with a leading edge bubble which we have called type 1a and which occurs at very small angles of attack and close to the SS boundary has also been observed.

*The dependence of these flow types on both freestream and geometrical parameters has been well established experimentally.

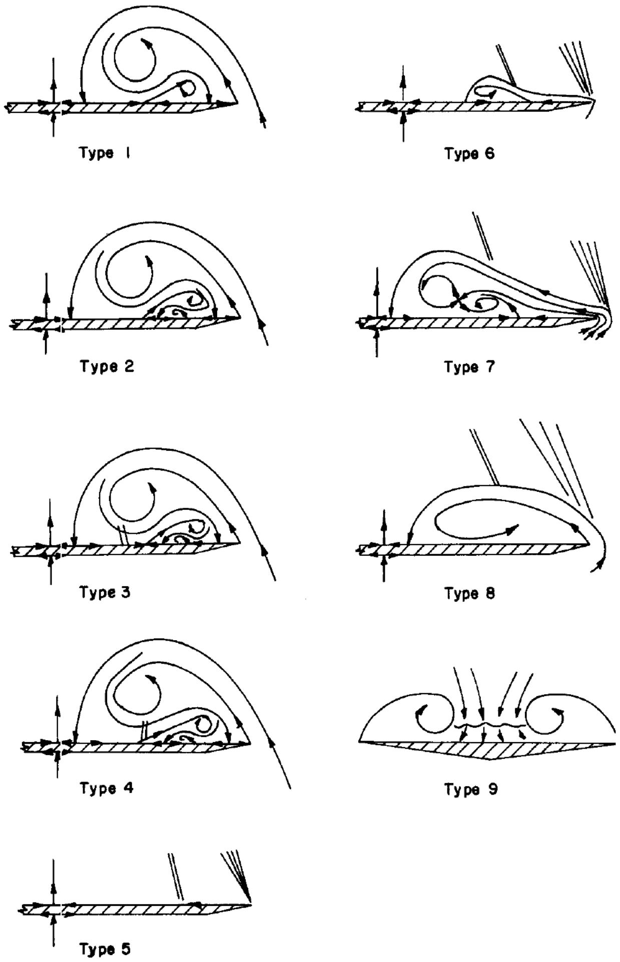


Fig. 15. Schematic cross flow patterns of different types of flow.

Note: For a delta wing with blunt leading edges, leading edge separation starts near the wing tip and moves upstream towards the apex with increased angle of attack. Thus, on a blunt wing, the lee side flow is characterised by a flow which is separated along part of the leading edge and attached over the rest. Interestingly such non-conical behaviour occurs inboard of the leading edge also; in particular, inboard shock induced separation starts near the trailing edge and moves upstream with increase in angle of attack.

REYNOLDS: Evidence suggests that the primary effect of Reynolds number is to delay separation to higher angles of attack on a blunt wing, while its effect on a sharp wing is relatively less since separation is fixed to the sharp edge.

VORTICES: Streamwise vortices have been observed as the flow charges from leading edge attached to separated and also when the lee side boundary layer changes from laminar to turbulent.

VORTICE BURST: At higher angles of attack, the vortices burst. The burst starts at the trailing edge and moves towards the apex with increasing angle of attack (Narayama 1996).

C. Breitsamter, 2008

Unsteady flow phenomena around the leading edge of delta wings.

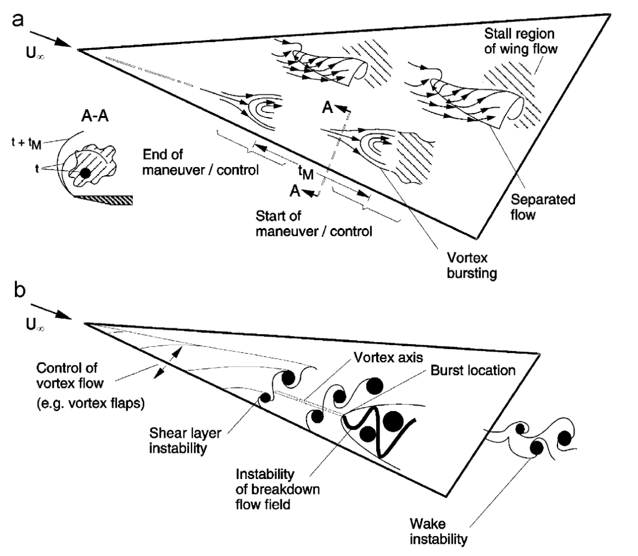
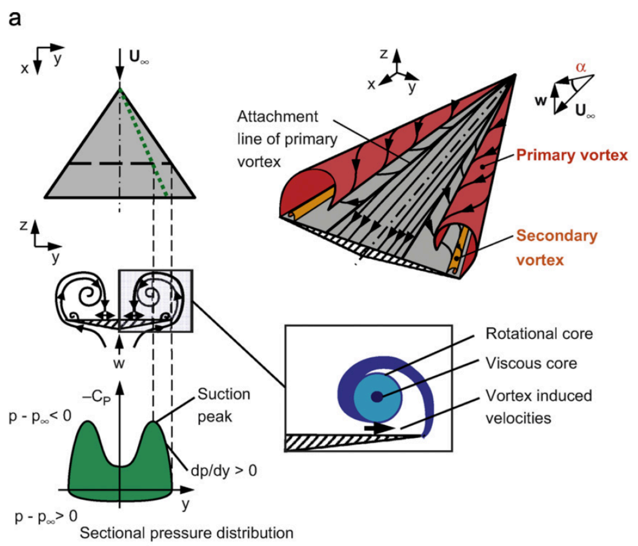


Fig. 1. Unsteady flow phenomena on delta wing configurations: flow features associated with time scales of $tU_\infty/c_r \gg 1$ (a) and flow features associated with time scales of $tU_\infty/c_r \leqslant 1$ (b).



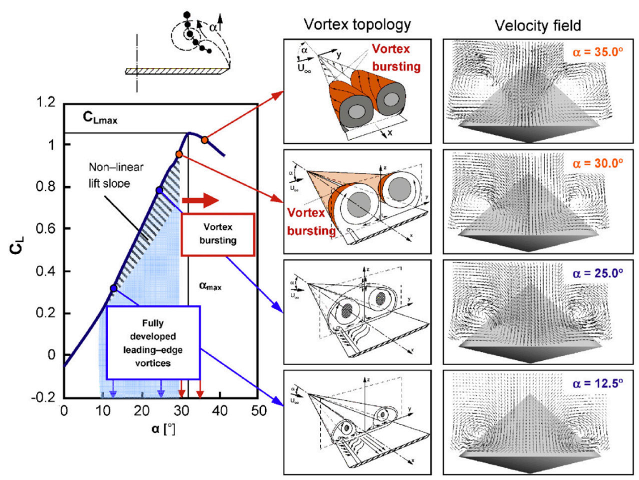
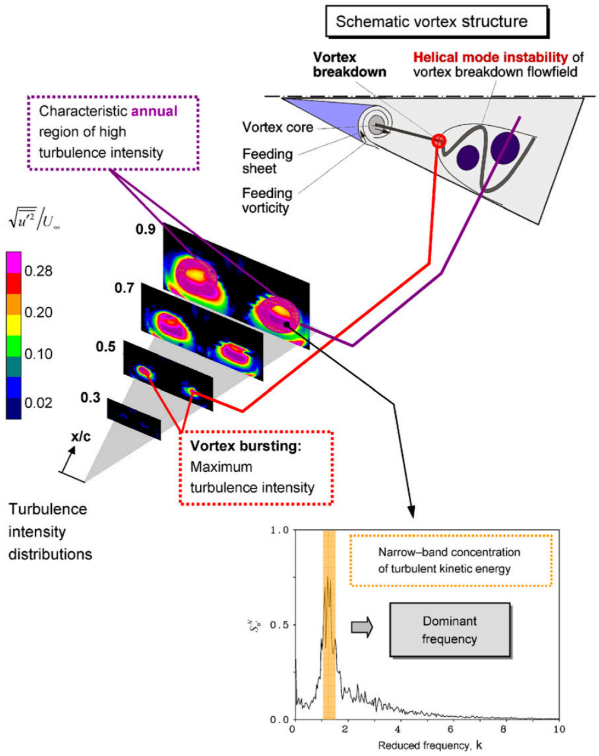


Fig. 6. Typical delta wing lift polar and flow field topology as function of angle of attack; $\varphi_W = 76°$, $U_\infty = 37\,\mathrm{m/s}$, $Re_{l\mu} = 1.07 \times 10^6$.



LIT. REV. APPLICATION: Modern fighter aircraft are subject to high angle of attack manoeuvres extending the flight envelope to the stall and post-stall regime [4].

LEADING EDGE VORTICES: The leading edge vortices improve significantly the high angle of attack performance because of the additional lift and an increase in maximum angle of attack. At high angle of attack, the phenomenon of leading edge vortex bursting over the wing planform is of specific interest. The transition from stable to unstable core flow, evident by the rapid change in the axial velocity profiles from jet to wake type, leads to extremely high turbulence intensities at the breakdown positon and to increased turbulence levels further downstream. Such unsteady aerodynamic loads often excite the vertical tail structure or even the wing structure in their natural frequencies, resulting in increased fatigue loads, reduced service life and raised maintenance costs.

[4] Herbst WB. Future fighter technologies. AIAA J Aircraft 1980;17(8): 561–6.