OPPORTUNITIES FOR THE INTEGRATED USE OF MEASUREMENTS AND COMPUTATIONS FOR THE UNDERSTANDING OF DELTA WING AERODYNAMICS

I.A.Gursul
Department of Mechanical Engineering,
University of Bath,
Bath, BA2 7AY,
United Kingdom

M.R.Allan and K.J.Badcock
Computational Fluid Dynamics Laboratory,
Department of Aerospace Engineering,
University of Glasgow,
Glasgow, G12 8QQ,
United Kingdom

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Abstract

This paper considers the current status of delta wing research from the point of view of the potential for using joint experimental and computational studies to advance the subject. After a brief review of the available measurement and numerical methods, delta wing phenomena are considered in the following categories: shear layer instabilities, vortex breakdown, vortex interactions, nonslender vortices, multiple vortices, manoevring wing vortices and vortex/flexible wing interaction. It is concluded that CFD can be very valuable to guide the type amd location of experimental data collected and to enhance the understanding of the data but adding information. Currently CFD requires more datasets

which include boundary layer and field information and which ideally combine different types of data.

1 Introduction

The flow over a delta wing at moderate angles of attack is dominated by two large, counter-rotating leading-edge vortices that are formed by the roll-up of vortex sheets. The flow separates from the leading edge of the wing to form a curved free shear layer above the suction side of the wing, which rolls up into a core. The time-averaged axial velocity is roughly axisymmetric and its maximum can be as large as four or five times the free stream velocity. These large axial velocities are due to very low pressures in the vortex core, which generate additional suction and lift force on the delta wings. A great deal of effort has been focused on the study of these vortices and aerodynamics of delta wings, as summarised in a review article by Lee and Ho [1].

The opportunities for gaining a deep understanding of the behaviour of the vortical flow has been greatly enhanced in recent years due to a revolution in the methods which can provide raw data. These methods can involve experiments using an expanding range of field and surface techniques or Computational Fluid Dynamics (CFD). It has been traditionally the case that these have been used with only very limited interaction, often only involving validation of the computational results using legacy experimental data which might not even be very suitable for the task. However, it is becoming increasingly recognised that if the goal is to improve the understanding of aerodynamics then these methods must be used in a deeper and coordinated way. The purpose of this paper is to give suggestions for how this statement can be realised for delta wings.

2 Tools Available for Aerodynamic Studies

2.1 Experimental Techniques

There are several experimental techniques available for experimental research in delta wing aerodynamics:

1. Steady and unsteady pressure measurements including pressure sensitive paints. These are limited to wing surface measurements and so do not provide information on off-surface flow and the nature of the vortices.

2. Surface flow visualisation. Oil flow visualisation gives an indication of surface streamlines, but only in a time averaged sense. Tufts also give an indication of surface streamlines and can reveal flow separation and reattachment, but are limited with the response time in unsteady flows and can also be intrusive.

3. Off surface flow visualisation (smoke/dye). This can provide useful information on shear layer structures and vortex breakdown, but extra care should be taken in interpreting the streakline patterns in unsteady flows.

4. Multi-hole velocity probes. These can measure three-components of mean velocity, but are intrusive and can cause premature breakdown.

5. Hot-wire anemometry. This can provide unsteady velocity components but can be intrusive.

6. LDV and PIV. These are non-intrusive point and field measurements respectively of velocity vectors in a plane. Seeding of vortical flow near the axis becomes problematic with increasing speed in air flows.

2.2 CFD Techniques

It has been well documented that CFD has developed at a rapid pace over the past 30 years. With developments in algorithms and computers it is possible to simulate complex flows on real aircraft using cheap computers. A recent NATO technical organisation (RTO) working group has examined the predictive capability for vortical flows on generic delta wing configurations (AVT 80) [2].

1. Euler simulations can predict vortex breakdown and vortical interactions when a sharp leading edge is used, fixing the separation point. No secondary separation can be predicted since this is due to boundary layer separation having the effect of shifting the primary vortex closer to the wing leading edge. In addition the strength of the leading edge vortex is strongly dependent on the grid used. However, for sharp leading edges this level of modelling is useful for evaluating qualitative behaviour at a low cost.

2. Unsteady RANS simulations can give good prediction for the secondary separation although the prediction of primary separation and vortex formation for rounded leading edge wings has

not received much attention in the literature. A major problem with URANS is the prediction of the levels of turbulence in the vortex itself which can strongly influence the development of breakdown. Ad-hoc treatments [3] can be used to limit production in regions of high vorticity but the turbulence levels after breakdown are still too high, making the simulation of the helical instability questionable.

3. Detached Eddy Simulation (DES) [4] has been used to overcome this problem by simulating the large scale turbulence in the vortex by Large Eddy Simulation (LES). In the wing boundary layer, where the cost of LES would be prohibitive at realistic Reynolds numbers, the RANS model is used. Some promising results for the prediction of vortex breakdown have been published, indicating the promise of the approach. The disadvantage is that the simulations are more costly in terms of the finer grids needed in the vortex and the small time steps that are required. In addition, the DES gives no improvement over URANS in terms of the vortex formation from rounded leading edges and predicting the influence of transition.

4. Finally, LES and Direct Numerical Simulation (DNS) [5] have been used at low Reynolds numbers to indicate fundamental physics. The cost of these calculations is prohibitive at flight Reynolds numbers because of the grid and temporal resolution required.

CFD predictions have progressed to the point where a current RTO working group (AVT-113) is evaluating the predictions of the flow on the F-16XL aircraft through comparison with in-flight measurements. There are clearly a number of useful tools in the CFD bag with varying cost and predictive capability.

3 Delta Wing Phenomena

3.1 Shear Layer Instabilities

The separated shear layers on a delta wing roll up periodically into discrete vortical substructures as visualised by Gad-el-Hak and Blackwelder [6]. This phenomenon was attributed to a Kelvin-Helmholtz type instability of the shear layer. The origin of these structures has been the subject of controversy as several researchers [7] [8] revealed the existence of stationary small-scale vortices around the primary vortex. The spatially fixed substructures were measured by velocity probes at fixed locations, and were identified as a result of time-averaging the flow. However,such small scale structures are difficult to measure experimentally. PIV and Global Doppler techniques are spatially and temporally limited, whilst LDA and HWA techniques are spatially limited (sampling at a point). Therefore it is not feasible to provide a complete unsteady data set of the flowfield which would be necessary to characterise these structures.

Small scale substructures also require more advanced turbulence modelling than the common Boussinesq-type models. However the relationship of the spatially fixed substructures to observed temporal substructures was recently demonstrated by direct numerical simulation (DNS) [5]. Instantaneous flow visualisation shows the temporal substructures and the transition process with increasing Reynolds number (see figure 1). More interestingly the time-averaged flow visualisation shows isosurfaces of time-averaged axial vorticity, and mean vortical substructures. These results indicate that the *steady* and *unsteady* substructures are not necessarily two separate phenomena. Details of the shear layer structure and transition process need to be investigated further.

In this example the use of DNS has suggested the flow structure and the challenge for experimentalists is to apply their techniques to examine these explanations, especially at high Reynolds number where satisfactory computations become more difficult,

3.2 Vortex Breakdown

At a sufficiently high angle of attack leading edge vortices undergo a sudden expansion known as vortex breakdown (see Figure 2), which was first observed by Werlé in 1954 in a water tunnel facility. Different explanations of the vortex breakdown phenomenon based on hydrodynamic instability, wave propagation, and flow stagnation are summarized in several review articles [9] [10] [11]. It is now generally agreed that this is a wave propagation phenomenon, and there is a strong analogy to shocks in gas dynamics. Concepts of supercritical and subcritical flows based on the wave propagation characteristics seem to play an important role in the understanding of vortex breakdown.

Vortex breakdown has adverse effects on time-averaged performance. For example, the magnitude of the lift and nose down pitching moment decreases after vortex breakdown for slender wings. However, the effects of vortex breakdown are more modest for low sweep angle delta wings [12].

Although a great deal of effort has been focused on the study of the vortex breakdown phenomenon, accurate prediction at high Reynolds numbers remains challenging [13]. Despite higher fidelity modelling and increasing resolution of simulations, core properties (believed to be fundamental in the development of vortex breakdown) are still difficult to predict. In particular the axial velocities in vortex cores tend to be predicted considerably lower than those found in experiment [2] . Prediction of time accurate vortex breakdown is also costly (especially for manoeuvring aircraft where the manoeuvring frequencies are several orders of magnitude lower than frequencies associated with the helical mode instability - see figure 3). The quality of the predictions is also heavily dependent on the realism of the modelling applied with DES showing promise but requiring further detailed scutiny.

In order to be able to further understand the difficulties associated with predicting core properties there are still questions remaining with regard to the structure of the core flow. It is widely assumed that due to viscous effects the core rotates as a rigid body rotation. However it remains unclear whether at high Reynolds number the core is turbulent or laminar and further experimental evidence is needed on this point.

Experimental investigations show that large scatter appears in the vortex breakdown location (see Figure 4, taken from Reference [14]). Geometric variations, tunnel wall effects, support interference, model deformations, Reynolds number, and measurement technique are all possible sources of the large scatter. A further difficulty is that the vortex breakdown location is highly unsteady, exhibiting oscillations in the streamwise direction [15]. These factors significantly affect the usefulness of the experimental data for aerodynamic analysis and design.

It is generally accepted that for a large range of values, breakdown is little affected by Reynolds' number. Tunnel wall influences have been shown by CFD to have an influence on breakdown location [16] [17]. It has also been shown that support structures can promote [18] or even delay [19] breakdown, though the actual influence is likely to be Reynolds number dependent. As such it is recommended that an experimental study be conducted in conjunction with a CFD study. The experimental study should provide accurate flowfield information for realistic upstream and downstream boundary conditions (velocity and pressure profiles), as well as tunnel boundary layer growth data. Useful measurements would include (but are not limited to) wing surface and tunnel wall pressure distributions, and load and moment data for dynamic cases. Flowfield measurements of the vortices would also be required to compare core properties and locations. To obtain results with various model to tunnel ratios, ideally the tunnel geometry should be altered (with artificial walls), as opposed to changing model size. In this way support structure interference would be consistent. If this is not possible and the wing size must vary, the size of the support structure should be adjusted accordingly (for example sting diameter). A useful experimental study would be as follows:

- Select for example a square cross section tunnel.
- Perform measurements for various angles of attack (upstream and downstream pressure and velocity profiles, tunnel boundary layers, wall pressures at selected locations, surface pressure data and flowfield measurements).
- Measure loads and moments for dynamic cases (for example pitching motion).
- Add artificial walls to bring side walls closer.
- Repeat measurements for static and dynamic cases.
- Add artificial walls to bring roof and floor closer
- Repeat measurements for static and dynamic cases.

Such experimental results could be used to validate a similar CFD study. These tests could also be conducted with and without supports for further validation.

There has been less emphasis on the unsteady aspects of vortex breakdown which have an impact on aircraft stability and control, and wing/fin buffeting. The flow downstream of vortex breakdown exhibits a well-documented hydrodynamic instability, called the helical mode instability [20]. Experimentally observed periodic velocity/pressure oscillations correspond to the most unstable normal modes of the time-averaged velocity profiles of the vortex (downstream of breakdown) based on the linearised, inviscid stability analysis. Unsteady flow phenomena relevant to vortical flows over delta wings have been studied in several previous investigations [20] [21] [22] However current knowledge of the unsteady aspects of breakdown is limited to slender wings [23].

Computational simulations can contribute to understanding these flows better. Time-accurate CFD simulations of the helical mode instability can predict buffet frequencies for a range of static and manoeuvring cases. Coupled CFD and structural modelling could also be used to predict whether new aircraft designs would undergo wing / tail buffet, and any possible coupling of fluid / structural instabilities. The prediction of core properties is likely to be crucial however and detailed experimental data is needed to improve the simulations in this respect.

3.3 Vortex Interactions

It was observed in several experiments that the vortex breakdown location over stationary delta wings is not steady and exhibits fluctuations along the axis of the vortices. Subsequently it was discovered that these oscillations are in the form of an asymmetric motion of breakdown locations for left and right vortices [15]. This is demonstrated by plotting the difference and average of left and right breakdowns in Figure 5. The two breakdowns, which are almost mirror images, oscillate in an asymmetric motion. The amplitude of these fluctuations can be a significant fraction of the chord length. These oscillations may be very important for the stability and control of highly manoeuvrable aircraft, and also have important consequences for wing and tail buffeting.

It was also reported [15] that the oscillations of breakdown locations are quasi-periodic. Both flow visualization and pressure measurements at high Reynolds numbers confirmed the existence of vortex interactions. The exact mechanism of this interaction and whether vortex breakdown is an essential part of it remains little understood due to the difficulties of temporal resolution using PIV or spatial resolution with LDA. It was found that the oscillations become larger and more coherent as the time-averaged breakdown locations get closer to each other when the angle of attack or sweep angle is increased.

Asymmetric oscillations of breakdown location have been observed computationally with symmetric computational domains. Oscillations have been seen both with Euler simulations [2] and higher fidelity DES simulations [2] and potentially such simulations can provide a great deal of understanding of these interactions. For example, studying cases without vortex breakdown may highlight if breakdown plays an important role in vortex interactions. Careful examination of the apex region and the mid plane of the computational domain may also provide insight into where the interactions start to occur and how they could proceed into asymmetric motions of breakdown location. Such studies are impossible to achieve experimentally. Experiments have a crucial role to play in validating the predictions in the sense of breakdown movement (from visualization), core properties and frequencies (from surface measurements or LDA).

Although this kind of interaction is more of a concern for slender wings, evidence of such interactions at a relatively low sweep angle of $\Lambda = 60^o$ was reported recently [24]. Wing tip accelerations occurred in an asymmetric structural mode for a slightly flexible delta wing when vortex breakdown occurred on the wing. Time-accurate CFD simulations could provide evidence of the underlying reasons for the instability and guide detailed flowfield measurements to further the understanding.

3.4 Nonslender Vortices

Much of our knowledge of vortex flows is related to slender vortices. There is very little known about the structure of vortices over nonslender delta wings ($\Lambda \leq 55^o$) and unsteady flow phenomena. Figure 7 shows an example of flow visualisation for a $\Lambda = 50^o$ delta wing, where a dual vortex structure is identified. Both PIV measurements [25] and DNS calculations [26] confirmed that both vortices have the same sign of vorticity.

It has been found that nonslender wings (with sweep angles as low as 40^o) at angles of attack as low as a few degrees can produce strong vortical flows. An example of surface flow visualization for $\alpha = 2.5^o$ is shown in Figure 8 for a $\Lambda = 50^o$ delta wing, where the secondary separation and reattachment lines are visible. For $\alpha = 15^o$, there is a change in the curvature of the secondary separation line around the midchord, which is presumably due to the vortex breakdown. Figure 9 shows root mean square values of fluctuating velocity together with the surface streamline pattern obtained from velocity measurements close to the wing surface. For $\alpha = 15^o$, the signature of vortex breakdown starting around 40% of the chord length is visible. However, for $\alpha = 20^o$, it is not the breakdown, but the reattachment of the shear layer which produces unsteadiness near the wing surface. Reattachment of shear layer, vortex breakdown, and stall over wings with rounded leading-edges are very complex and can benefit from numerical simulations for better understanding of the general flow topology which can then guide detailed measurements. Such numerical studies are problematic due to the difficulty in accurately predicting the (non-fixed Reynolds number dependent) separation location over rounded leading edges. However, it is unknown to what extent the vortical structures are dependent on the accurate prediction of the separation location. Again experiments focussing on the leading edge region to provide detailed velocity and turbulence data for separation onset would provide valuable validating data for the predictions. Also, there is a need to understand separated and vortical flows at nonzero roll angles for nonslender wings. Recently, it was discovered that nonslender delta wings can exhibit wing rock phenomenon [27].

3.5 Multiple Vortices

Another area that has received little attention is the interaction of multiple vortices such as those found on double delta wings (see Figure 10). Interactions of multiple vortices, complex vortex patterns, coiling-up and merging, vortex breakdown, and unsteady interactions are highly challenging vortical flows. These aspects are even more complex and challenging for manoeuvring aircraft. This is a particularly interesting area in which CFD can provide much needed understanding since the entire unsteady flowfield can be visualised and studied. Experimental flow visualisation techniques can be applied for static cases though this is harder for manoeuvring cases. As such time accurate CFD simulations would be able to track core motions, examine vortex interactions, highlight interaction induced vortex breakdown, as other phenomena currently poorly understood. Location of interesting phenomena with CFD would also have the advantage of guiding experimentalists in finding measurement locations of interest.

3.6 Manoeuvring wing vortices

The spectrum of unsteady flow phenomena over stationary delta wings is shown in Figure 3 as a function of dimensionless frequency [15]. Also shown is the frequency range of aerodynamic manoeuvres for current fighter aircraft. Future unmanned aircraft could be highly manoeuvrable and flexible, with the capability of performing extreme manoeuvres at high g (with a 30g vehicle envisioned). At such high reduced frequencies, there is the possibility of a coupling of aerodynamic manoeuvres with vortex instabilities. For highly manoeuvrable aircraft configurations, nonlinear unsteady aerodynamics presents major challenges for the development of flight control laws.

The dynamic response of leading edge vortices and breakdown is important for flight of unmanned aircraft. For a pitching delta wing, both the formation of leading-edge vortices [28] and vortex breakdown [29] [30] show hysteresis and time lag compared with respect the quasi-steady case. This time lag, which is important for the stability and control of aircraft, has also been observed for other types of wing motion, such as plunging and rolling. The time lag of vortex breakdown is much larger than that of vortex formation. Although it is common to all unsteady flows regardless of the type of unsteady motion [31], the mechanism of hysteresis and time lag is not well understood. The dynamic response of vortex breakdown is strongly linked to the adverse pressure gradient along the vortex axis [30], which cannot be measured experimentally and which as previously mentioned, is hard to obtain with CFD.

As CFD simulations has become more realistic the opportunity to couple CFD and flight mechanics has been exploited. A great deal of experimental data is available for 1 Degree of Freedom (DOF) motion around the roll axis of a delta wing, when a highly swept delta wing exhibits wing rock (see for example figure 11). CFD has been able to predict the wing rock phenomenon of highly swept wings with Euler, laminar, and RANS models of the flow. For a $\Lambda = 65^o$ delta wing rolling about its x-(body)axis, RANS simulations have been performed [32]. In this case the experimental results were *contaminated* by mechanical friction between the sting and the support structure. As such, instead of the experimental results exhibiting an aerodynamically damped oscillation, the model stopped at non-zero roll angles for various initial roll angles. CFD simulations were able to reproduce such behaviour if mechanical friction was added, though the choice of mechanical friction model was governed by comparison with experiment.

As an extension to the 1 DOF roll cases discussed it is also currently feasible to perform multiple degree-of-freedom (rigid body motion) simulations with CFD. Multiple degree of freedom experimental studies are uncommon and problematic due to the support structures required to move freely (though as discussed mechanical friction remains a problem) and in any direction. Coupling CFD and flight mechanics in such a way will allow virtual studies of new aircraft configurations in regimes which are usually avoided due to highly non-linear aerodynamics. However, experiments with simplified free response cases are required to allow evaluation of the influence of modelling induced effects on the rigid body dynamics.

3.7 Vortex / flexible wing interaction

Because of unusual designs and high rate motions for future aircraft, wing flexibility could become an issue. Coupling of unsteady, separated and vortical flows with flexible wings may result in limit-cycle-oscillations or control problems. For flexible delta wings, vortex/wing interaction (see Figure 6) may lead to limit cycle oscillations, where the vortex acts like an aerodynamic spring [33]. Unsteady flow phenomena may interact and couple with structural vibrations. As it is very difficult to simulate aeroelastic phenomena experimentally due to model scaling requirements, validated computational simulations may be very useful for this kind of multidisciplinary and challenging engineering problem. CFD simulations have the advantage of being able make predictions at real flight conditions with structural models representing the full aircraft behaviour.

4 Conclusions

For experimentalists, with the current capabilities of CFD and the assumptions it employs, CFD should be primarily used as a tool to build on measurement opportunities. Ideally an iterative process should be used, using CFD to highlight areas of interest either before or after experiments. As a greater understanding is gained of the flowfield, further experiments or CFD simulations could be done which would provide a much more detailed picture of the flowfield. Due to the temporal limitations of PIV and the spatial restrictions of LDA, using CFD to focus (and also understand) the measurements is seen as particularly advantageous. Since delta wing flows are particularly susceptible to facility interference an accurate tool for predicting tunnel interference is required. A suitably validated CFD method would be able to provide details of combined tunnel wall, tunnel boundary layer, and support structure interference effects. The tool would also be applicable to all facilities and all tests.

For the CFD practitioners more detailed high quality data is required, especially in boundary layers. There is little insight to be gained from validating an expensive DES simulation with force and moment data. Instead to validate models high quality flowfield data is required, especially in vortical flows where the understanding of off surface flow features is of vital importance. Similarly as the effects of facility interference often contaminate experimental results, modelling the entire experiment is required for fair comparisons. As such details of freestream flow properties, supports, tunnel boundary layers etc are required to provide better boundary conditions for the simulations. Ideally, combinations of different types of data is required. For example in delta wing flows vortex behaviour is of importance in predicting the response of an aircraft to manoeuvres. Given the time lags associated with vortex breakdown and its effect on the loads and moments experienced by the aircraft, it is vital to know the off surface flow as well as the loads and moments and surface pressure distributions for validation purposes. Such combinations of data are rare or non-existent!

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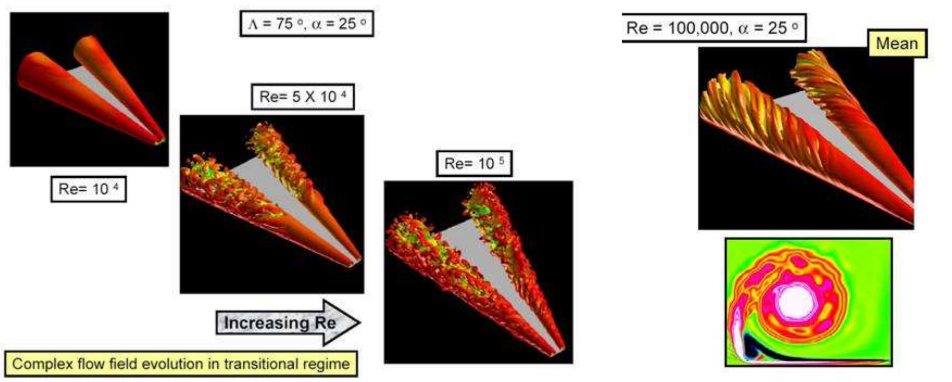

Figure 1: Instantaneous flow showing the transition process with increasing Reynolds number (left); and time-averaged flow showing mean vortical substructures (right) [5]

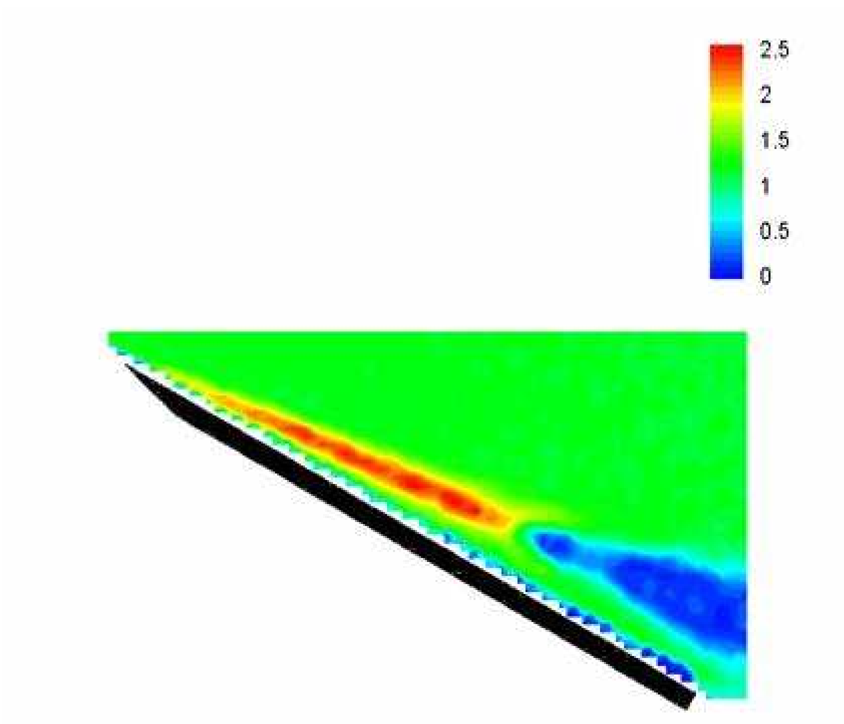

Figure 2: Magnitude of velocity measured by PIV over a slender delta wing showing the time-averaged structured of vortex breakdown.

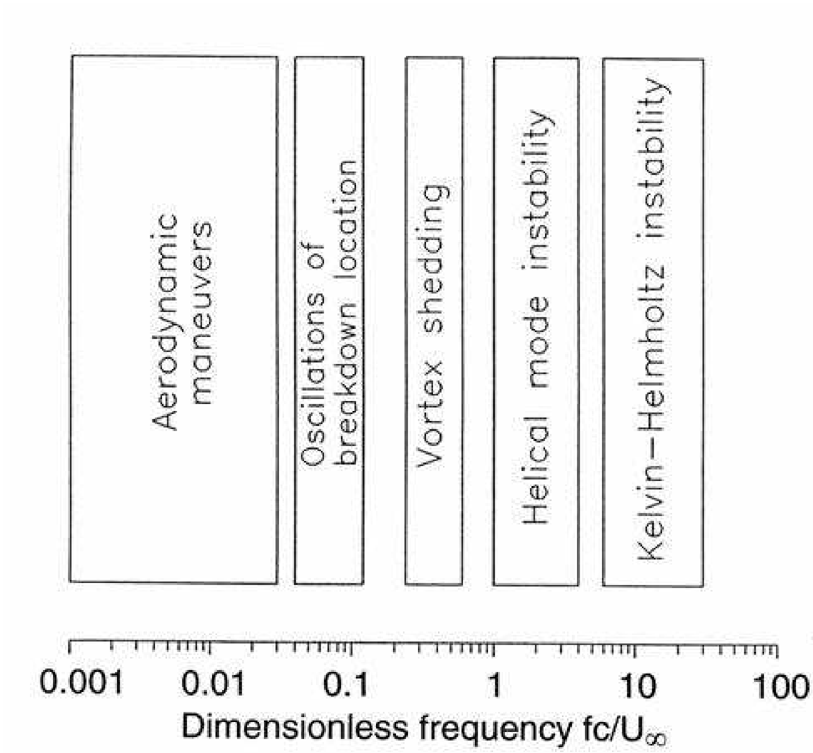

Figure 3: Spectrum of unsteady flow phenomena over delta wings as a function of dimensionless frequency [15]

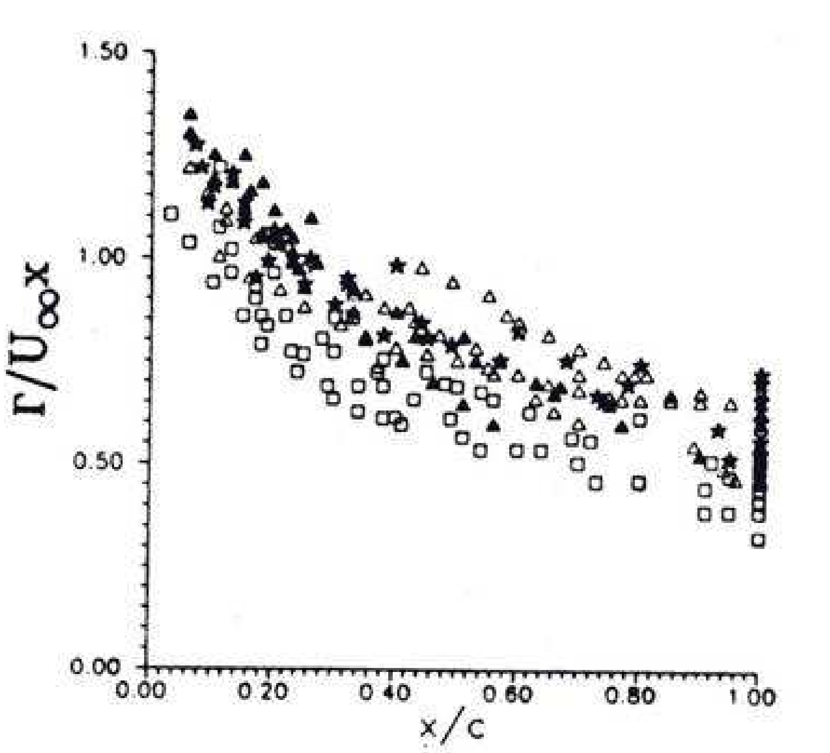

Figure 4: Scatter of vortex breakdown location in different facilities (from [14])

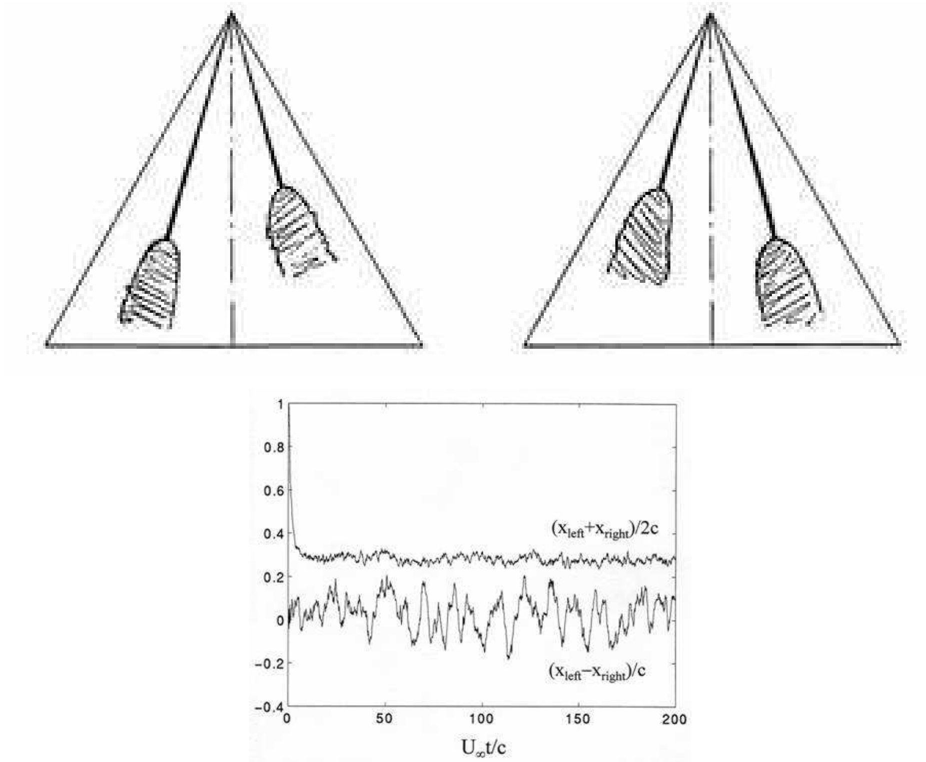

Figure 5: Time history of average and difference of breakdown locations showing asymmetric oscillations.

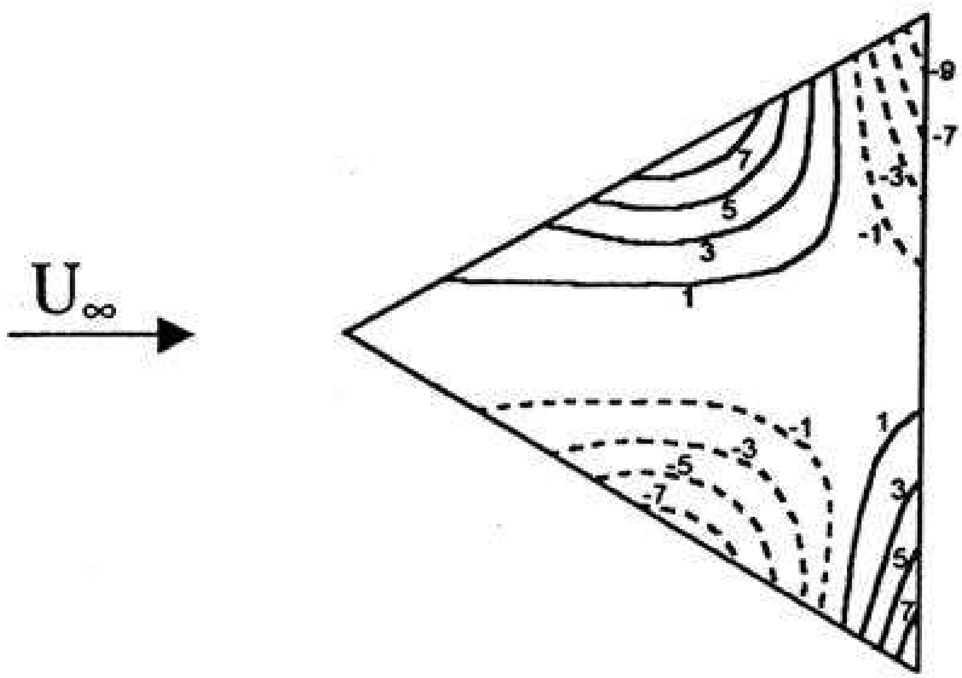

Figure 6: Asymmetric structural mode for a slightly flexible delta wing when vortex breakdown occurred on the wing.

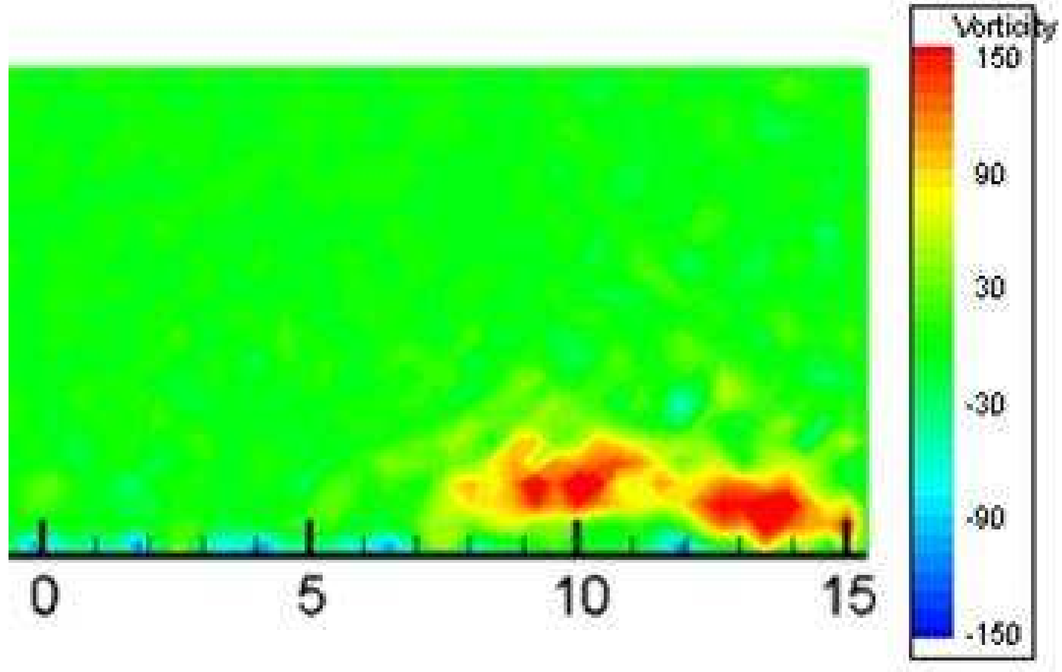

Figure 7: Flow visualisation of vortices over a nonslender delta wing with a sweep angle of $\Lambda = 50^o$ (left). Dual vortex structure (of the sane sign of vorticity) in a cross-flow plane exists upstream of vortex breakdown (right), $alpha = 15^o$.

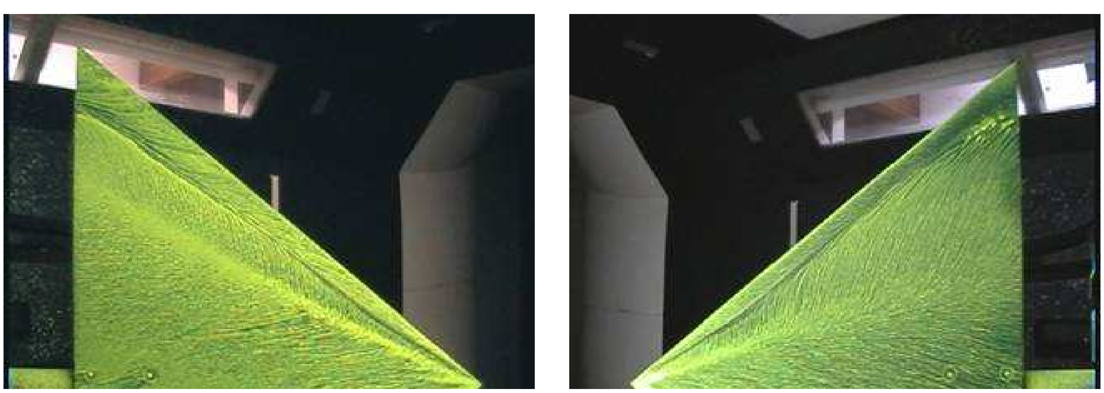

Figure 8: Surface flow visualisation for $\Lambda = 50^o$ for $\alpha = 2.5^o$ (left) and $\alpha = 15^o$ (right).

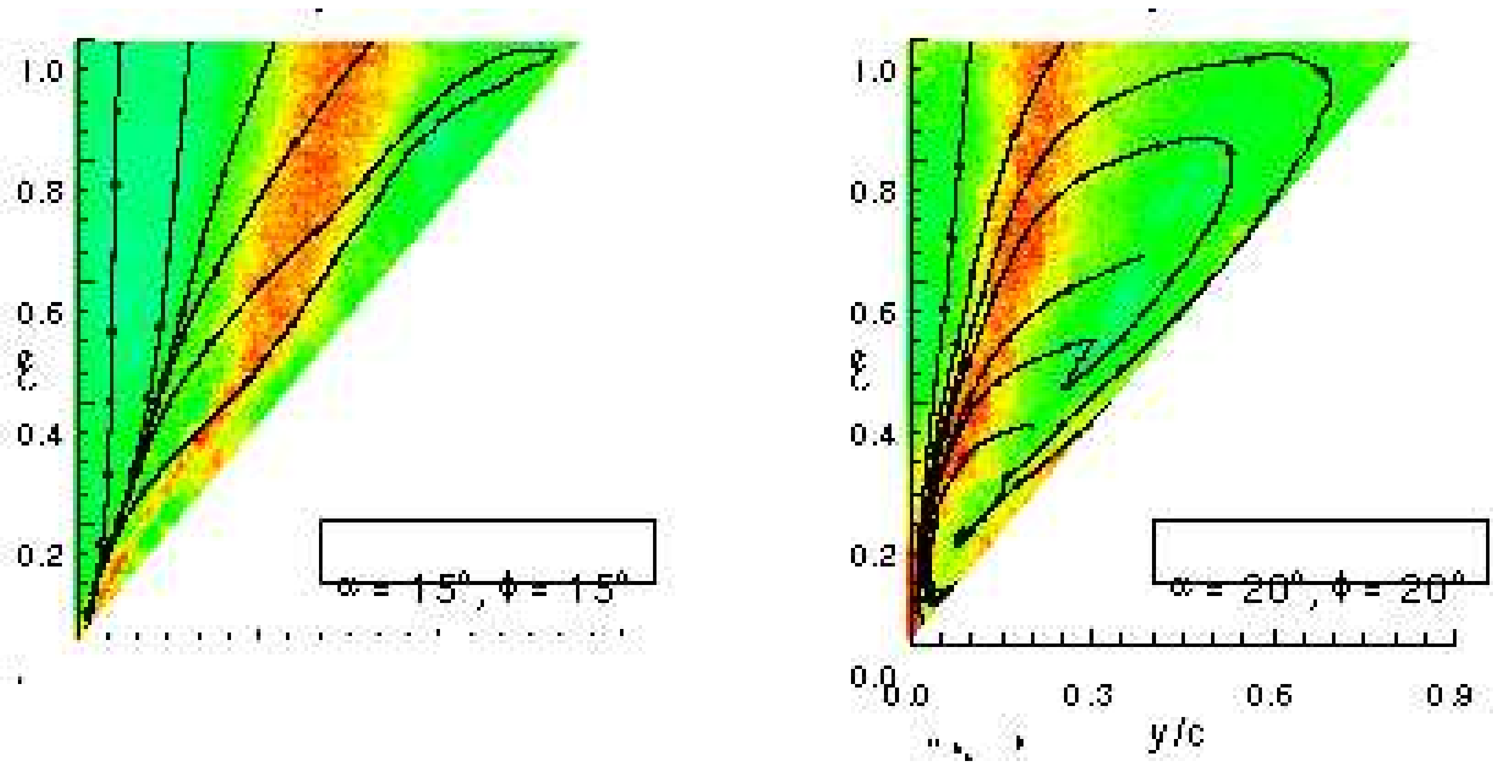

Figure 9: RMS value of fluctuating velocity together with the surface streamline pattern obtained from velocity measurements close to the wing surface.

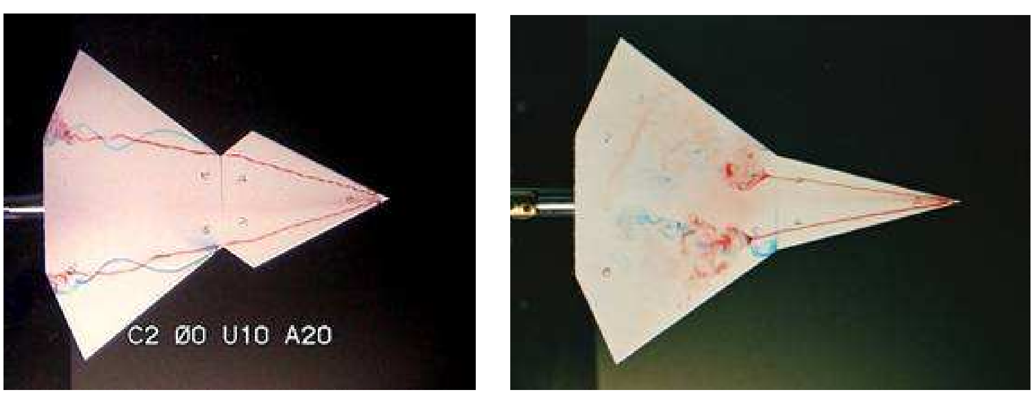

Figure 10: Interaction of multiple vortices originating from strake and wing, showing coiling-up and vortex breakdown.

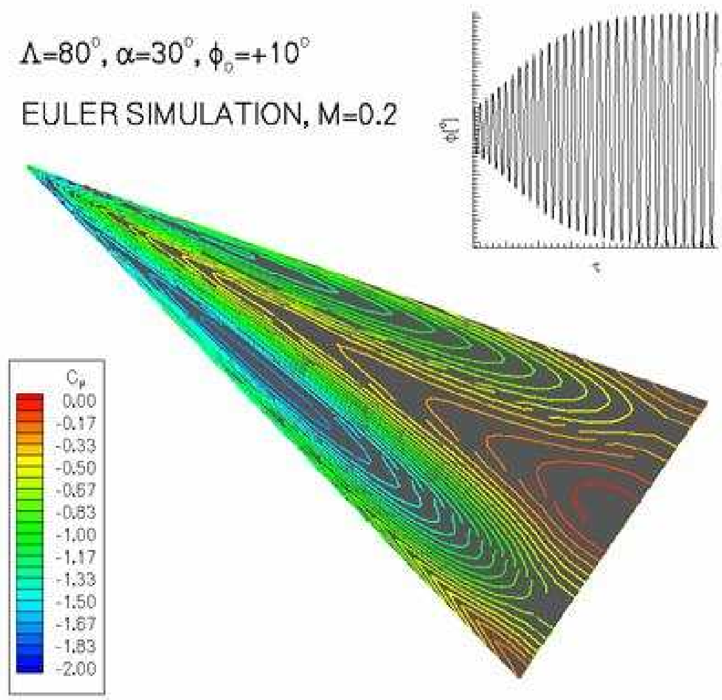

Figure 11: Upper surface pressure distribution and roll history from Euler simulations of the wing rock phenomenon