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Review of Vortex Methods for Simulation of Vortex Breakdown

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ABSTRACT

The aim of this work is to identify current developments in the field of vortex breakdown modelling in order to initiate the development of a numerical model for the simulation of F/A-18 empennage buffet. Some attempts at using vortex models for prediction of vortex breakdown were found in the open literature. Their advantages and shortcomings are discussed, allowing the evaluation of their feasibility for the computation of LEX vortex burst. It was concluded that vortex methods are able to simulate an onset of breakdown in simple vortical flows. However, their predictive abilities require further improvement to provide accurate modelling of the temporal and spatial characteristics of the unsteady pressure field past a burst LEX vortex.

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Executive Summary

For the F/A-18 aircraft manoeuvrability at very high angles of attack is achieved through a combination of the wing root leading edge extensions (LEXs) and the placement of twin vertical tails. The highly swept LEXs help to maintain lift during the post-stall flight by generating strong LEX vortices which produce a favourable pressure field over the wings and create an additional 'vortex lift'. However, under certain flight conditions the initially stable LEX vortex cores have a tendency to burst producing a highly disturbed flowfield which impinges on the vertical tails and horizontal stabilisers causing severe buffeting and premature fatigue failures.

Significant efforts have been made during the past decade in an attempt to understand and to predict the occurrence of vortex breakdown. These efforts included a variety of research techniques such as analytical solutions to approximate equations of motion, as well as numerical analysis using finite difference and vortex methods. Although the existing Euler and Navier-Stokes codes can be successfully applied for simulation of vortex breakdown in flow over simple delta wings, they require enormous computational resources to study more complex configurations, such as the complete F/A-18 aircraft.

An alternative to computationally intensive Euler and Navier-Stokes codes are the vortex-based methods that gain economy in computations by concentrating their efforts in the areas of high vorticity gradient. These methods are well suited to simulation of unsteady wakes, as our ultimate aim is to predict buffet pressures on empennage surfaces and evaluate their dynamic response.

The work described in this report intends to identify state-of-the-art and current developments in the field of vortex breakdown modelling. Several attempts at using vortex methods for the prediction of vortex breakdown were found in the open literature. Their advantages and shortcomings are reviewed in detail in order to evaluate their feasibility for computation of LEX vortex burst. Based on the published results, it is concluded that vortex filament and vortex lattice models are able to predict an onset of breakdown and provide a plausible solution for its unsteady behaviour. The results of the work will add to DSTO's existing body of knowledge on vortex breakdown and can assist in the International Follow On Structural Test Project (IFOSTP) fatigue test on the F/A-18 aft fuselage and empennage.

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Contents

1. Introduction

The ability to fly and manoeuvre at a wide range of angles of attack is of prime importance for the modern high performance fighter. For the F/A-18 this ability for controlled flight at high angles of attack is achieved through a combination of the wing root leading edge extensions (LEXs) and the placements of the twin vertical tails.

The highly swept leading edge extensions help to maintain lift during post-stall flight by generating strong LEX vortices which produce a favourable pressure field over the wings and create an additional 'vortex lift'. The twin-tailed configuration of the F/A-18 is designed to make use of these intense vortical flows in order to maintain directional stability of the aircraft at high angles of attack. Such a combination of LEXs and vertical tails provides the aircraft with excellent low-speed, high angle of attack manoeuvrability.

However, apart from the desired increase in the total lift and enhancement of the aircraft manoeuvrability, the use of the LEX vortices brings some serious structural dynamics problems. It appears that under certain flight conditions the initially smooth and stable LEX vortex has a tendency to burst producing a highly disturbed flowfield over the wing that prevents further development of the supplementary vortex lift. Moreover, the highly turbulent wake of a burst vortex then convects downstream and impinges on the vertical tails and horizontal stabilisers causing severe buffeting and premature fatigue failures.

Although the fitting of LEX fences has led to a significant reduction of the buffet loads, the search for more effective solutions to the buffeting problem is still under way for current and future generations of fighter aircraft. Any attempt to reduce the severity of such buffet-induced loading and vibration requires further improvement in our understanding of the mechanisms governing the LEX vortex breakdown as it plays a major role in dictating the spectral content of the pressure fluctuations on the tail. Thus, in order to predict the empennage dynamic response during buffet, both temporal and spatial characteristics of the unsteady pressure field of a burst LEX vortex must be modelled accurately.

Although the aim of the work is to predict the F/A-18 LEX vortex breakdown, a more generic geometry such as a delta wing can be used for initial studies. This simple configuration is well suited to the task because it contains all the pertinent physics involved in the development of the leading edge vortex and its subsequent burst. It allows for major characteristics of vortex breakdown to be investigated without computational overheads and undesired geometric influences of such complex configuration as the complete F/A-18 aircraft.

2. Experimental Investigation into Vortex Breakdown

The peculiar and simple looking fluid dynamics phenomenon known as 'vortex breakdown' or 'vortex core burst' has been a subject of intensive theoretical and experimental investigation since the late fifties. Peckham and Atkinson [1] were among the first investigators who encountered the phenomenon of vortex breakdown in their experimental study of flow past a highly swept delta wing. At high incidence they observed breakdown of the pair of vortices formed at the leading edge of a delta wing.

Since then, considerable effort has been spent in an attempt to understand and to predict the occurrence of vortex breakdown. These efforts have included a variety of research techniques such as analytical solutions to approximate equations of motion, numerical analysis using finite difference and vortex methods, small-scale model tests in wind tunnels and water tanks as well as full-scale aircraft flight tests. Despite some progress in the prediction of vortex breakdown, the underlying flow physics of its occurrence and how it causes the tail buffet is still under investigation. Indeed, the mechanism of vortex breakdown is rather complicated and is one of the unresolved problems in fluid mechanics. The flow parameters that affect the vortex breakdown, and the physical process governing the breakdown, are still among of the most challenging fundamental research problems.

An understanding of what the vortex breakdown is and how it can be defined needs to be addressed. According to Benjamin [2], breakdown or bursting is an abrupt and drastic change of vortex structure, generated on leading edges of delta wings. Here, an increase in the angle of attack strengthens the leading edge vortices until eventually a sudden change occurs in the nature of the cores. This sudden change constitutes the vortex breakdown. A vortex filament, which undergoes breakdown, becomes destroyed or at least much diminished in strength and organisation. Upstream of the breakdown location, the vortex filament appears unaffected. Downstream of the breakdown, the flow is disorganised and wake-like but sometimes can recover and develop another breakdown further downstream.

Flow visualisations by Sarpkaya [3] revealed three basic patterns of breakdown: axisymmetric, spiral, and double helix. He performed parametric study of the phenomenon by systematically measuring the relationship between Reynolds number, the position of breakdown, its appearance and the amount of swirling in the flow. Lambourne and Bryer's [4] investigation of flow over a delta wing clearly showed two different patterns of vortex breakdown, namely axisymmetric and spiral, occurring at the same time, see Figure 1. Later, Faler and Leibovich [5] proposed a more detailed classification scheme for vortex breakdown based on their extensive observations and measurements of velocity profiles using a laser Doppler velocimeter. A simple criterion for vortex breakdown was proposed by Escudier and Zehnder [6] who based their findings on extensive flow-visualisation data. See Hall [7] and Leibovich [8] for a review of experimental studies as well as some of the theoretical efforts on vortex breakdown.

Extensive experimental investigations of vortex breakdown have been also carried out at AMRL. Considerable insight into the essential features and nature of vortex breakdown has been gained during these studies. Thompson [9,10] performed water tunnel investigations of vortex flow over both simple delta wings and delta wings of more complex geometry. These studies revealed that the occurrence and axial position of vortex breakdown strongly depend on delta wing geometry and angle of incidence but are only weakly dependent on Reynolds number.

Later, Thompson [11] investigated the flow over a $1/48^{th}$ scale model of the F/A-18 aircraft in the AMRL water tunnel, where the effects of engine inlet flow rate, Reynolds number, position of control surfaces *etc.*, on the axial position of LEX vortex breakdown were studied. Further experimental investigation included wind tunnel tests of the flow over the F/A-18 using a $1/9^{th}$ scale model, see Martin & Thompson [12] and Thompson [13]. Despite the substantial differences in Reynolds number, the results of water tunnel and wind tunnel tests showed reasonable agreement regarding the axial location of the vortex breakdown. Also, the trends of the change in the axial position of the vortex breakdown with angle of attack were remarkably similar in both of the above tests.

Results of experimental investigations performed by Thompson, as well as other published studies on flow over delta wings and more complex geometries suggested that the longitudinal location of vortex breakdown is almost independent of Reynolds number. These findings support the proposal that the development of the vortex breakdown can be described in terms of an essentially inviscid, unsteady approach.

Despite all the findings, the fundamental problems of vortex breakdown have not been solved yet. Not only are the causes of vortex breakdown poorly understood, but also the description of the phenomenon itself is uncertain. There is a lack of a precise mathematical definition for this phenomenon that would enable an accurate detection of its occurrence during numerical simulation. Therefore, it would be useful to list some of the descriptions, which demonstrate certain physical characteristics observed when the vortex breakdown occurs. For example, Hitzel [14] defines vortex breakdown as a rapid change of the vortex structure and a corresponding diminishing of the induced suction forces. O'Neil, Barnett, and Louie [15] describe the breakdown effect as the rapid degeneration of a well-defined leading edge vortex into a substantially larger, more diffuse vortical flow region with relatively mild gradients. According to Ekaterinaris and Schiff [16], the phenomenon of vortex breakdown can be defined as a transition of the vortex structure from jet-like to a wake-like flow. A more specific description of vortex breakdown was suggested by Midkavi [17]. He defined the vortex breakdown as the flow structure that results when at some axial location on a vortex filament the axial derivatives are no longer small compared to the inverse of the vortex core size. Thus, at the breakdown region the core size is abruptly increased by an order of magnitude within a distance comparable to the core size.

3. Numerical Simulations

Various attempts have been made to compute leading edge vortex breakdown using rather different numerical approaches. It was found that grid methods experience little difficulty in simulating vortex breakdown and require only proper boundary conditions to obtain a plausible solution. No wonder that the majority of numerical methods for simulation of vortex breakdown developed so far are based on Euler or Navier-Stokes equations.

For example, Hitzel [14] found that the Euler-methods are able to simulate leading edge vortex breakdown quite well despite neglecting viscous effects. As concluded by Hitzel, breakdown is almost independent of Reynolds number and is presumably triggered by adverse pressure gradients, which decelerate the axial flow inside the vortex core. Governed by continuity and the conservation of momentum the vortex core is forced to widen considerably, such that the suction peaks producing the nonlinear lift tend to decline.

Hitzel [14] stated that his prediction of leading edge vortex breakdown was in good agreement with experiment. However, he pointed out that the solution exhibits very high total pressure losses in the vortex-core, and he attributed these losses to numerical errors introduced by the discretisation of the mesh. Furthermore, there were two other vortex-diminishing effects intrinsic to any other grid method. One of these is the decreasing geometrical resolution of the vortex wake. As the vortices leave the wing, they flow into the coarser outer part of the computational domain. The other vortex diminishing effect was caused by the downstream boundary conditions. As recognised by Hitzel, any boundary condition imposes some constant free-flow conditions and, therefore, the vortex must cease to exist at the boundary.

O'Neil, Barnett, and Louie [15] also investigated vortex breakdown over delta wings using Euler methods. They came to the same conclusion as Hitzel that vortex breakdown is governed primarily by inviscid factors. It was found that the occurrence of breakdown-like effects in the Euler solutions had definite trends, and was clearly not a result of arbitrary numerical coincidence. However, their solution also experienced the numerical dissipation induced by artificial dissipation, which is common to all Euler codes.

Since the Euler equations cannot describe the flow structure in the core of the vortex, they give only an indication as to the occurrence of a sudden change which can be denoted as breakdown. The more comprehensive Navier-Stokes codes include analysis of the viscous-inviscid flow inside the core and in the vortex flow surrounding the core. Thus, it is reasonable to expect that the Navier-Stokes solutions would provide a more detailed description of the flow structure that would allow making a more reliable conclusion about the occurrence of the breakdown.

Hence, Ekaterinaris and Schiff [16] studied the vortex breakdown on a 75 degrees swept delta wing using Navier-Stokes code. They reported that the vortex breakdown first appeared on the wing at 32 degrees angle of attack. The flow with the vortex breakdown was computed within a 57 x 54 x 70 point cylindrical grid using zonal method. The calculated shape of the vortex breakdown had a closed front end, indicating the tip of a bubble-type breakdown, which then expanded downstream of the burst point with the bubble remaining open in the wake region. At a higher angle of attack of 40 degrees, the flow was very similar to that obtained at 32 degrees, but the burst point was located further towards the apex and the burst area was larger.

As reported by Ekaterinaris and Schiff, the predictions of vortex breakdown were strongly affected by the resolution of the computational grid. For example, using a coarse grid of 33 x 50 x 15 points for calculations of the flow field over the same delta wing at angles of attack above 35 degrees, vortex breakdown was not observed at all. Also, in the calculations with the coarse grid resolution, the position of the burst point was predicted to be further downstream and the extent of the vortex breakdown was much smaller than calculated with the fine grid resolution. This study of Ekaterinaris and Schiff also revealed the strong effect of the adverse axial pressure gradient on the vortex breakdown. It was shown that eliminating the effect of the adverse axial pressure gradient by excluding the wake region from the computations, vortex breakdown was not predicted. An additional investigation involved the search for the possible existence of unsteadiness in the region downstream of the tip of the bubble type breakdown. As was reported by the authors, no sign of unsteadiness was observed in the region downstream of the vortex burst point and solutions of Navier-Stokes code converged to a steady state. This is quite surprising and contradicts experimental observations showing that, in almost all cases, vortex breakdown is an essentially unsteady phenomenon.

The results of Ekaterinaris and Schiff regarding the steadiness of the obtained solution put a question about time accuracy of this type of code as the simulation of the unsteady behaviour of the vortex breakdown is crucial for buffet modelling. Obviously, in order to capture the complex flow patterns in the breakdown region and to obtain a truly unsteady solution, a high resolution of the grid is required. Thus, important features of the flowfield past a burst vortex can only be evaluated with very high grid resolution that requires substantial computing resources that are at the very limit of capabilities of modern supercomputers.

4. Modelling the Vortex Breakdown by Vortex Methods

An alternative to grid-dependent Euler and Navier-Stokes codes are the vortex methods, which simulate the unsteady fluid flow under an assumption of nonlinear dynamics of vorticity. Here, the inviscid motion of the vorticity is given by the local fluid velocity, which in turn is determined kinematically from the vorticity field. The evolution of the vorticity can be tracked numerically in a Lagrangian or hybrid Euler-Lagrangian reference frame. Thus, it is very convenient to consider inviscid fluid dynamics in terms of concentrated vorticity regions, which induce motion on each other as an alternative to pressure-velocity considerations.

One of the advantages of the vortex-based methods is their ability to concentrate computational effort in the areas of high vorticity gradient, which is particularly suitable for simulations of vorticity dominated flows, such as vortex flow past a LEX. Besides the economy in computation, another advantage of vortex methods over Euler methods is in the way the initial vorticity is introduced. For example, Hitzel [14] states that "in Euler-calculations usually the start conditions already introduce vorticity... A proper natural evaluation of the vorticity however should start from zero evolving to the flight-velocity to simulate the real time-dependent build-up of the flow." Within the vortex approach, this is performed by modelling the flow from the very beginning and tracking a continuously developing vortex wake, which is not bound by a computational domain or grid. This eliminates the vortex diminishing effects and does not require an initial introduction of vorticity as found in Euler codes.

Despite the simplicity and robustness of vortex methods, they have not received as much attention as a tool for modelling vortex breakdown as their counterparts - Euler methods. Only a few attempts at their application to the breakdown problem were found in the open literature. Each of these methods is discussed below in detail, in order to evaluate their advantages and shortcomings and to conclude on their feasibility for vortex burst modelling.

4.1 Vortex Filament Method

One of the first attempts to attack the vortex breakdown problem by vortex-based method was undertaken by Nakamura, Leonard & Spalart [18], who utilised the vortex-filament method in their simulations. This method seems to be well suited to the simulation of vortex breakdown, in that computational elements are simple straight filaments and are required only for the vorticity-containing fluid in and near the flow region where vortex breakdown is occurring.

As pointed out by the authors, it was clearly desirable to analyse the vortex breakdown problem numerically with a three-dimensional capability. According to experimental observations, even an axisymmetric-type vortex breakdown includes three-dimensional motion. It was also argued that in the vortex filament method rapid changes in the flow pattern with three-dimensionality could be represented with minimal error due to numerical dissipation.

The vortex filament method as used by Nakamura *et al.* does not explicitly include the effect of viscous diffusion and, therefore, does not account for the effect of Reynolds number on the mechanism of breakdown. However, in the authors' opinion, the process of breakdown itself occurs rapidly and is therefore dominated by nonlinear inviscid phenomena, well described by the dynamics of the vortex-filament method. As argued by the authors, the primary role of Reynolds number is in shaping the internal structure of the vortex core upstream of the breakdown. Thus, the upstream velocity profiles within the vortex and the amount of swirling in the flow can be reproduced by proper choice of the filament geometry and strength. In this way, the method can reflect changes in Reynolds number, and provide results comparable to those experimentally observed.

A flow with a simple analytical expression, where vorticity sharply declines with the distance from the axis was chosen for the purpose of simulation. Such an expression, often used for unbounded swirling flow was assumed to approximate velocity profiles, as obtained in experiments on vortex breakdown inside a pipe. The principal vorticity region was represented by multiple vortex filaments, and an axial velocity component was induced by a spiral winding of the filaments. Thus, the breakdown region consisted of helical vortex filaments, which rotate and translate with fixed, predetermined velocities. Required upstream axial and theta velocity profiles were simulated by adjusting the pitch and circulation of the helical filaments. An accuracy check was performed for a cylindrical flow with simple analytical functions for the velocities. As the authors stated, the method is able to simulate the flow field to any degree of accuracy by increasing the number of filaments.

A similar approach was used by Del Prete [19] for simulation of vortex breakdown using the vortex filament method. However, she used only parallel longitudinal vortex filaments upstream with no axial velocity component interacting with a vortex ring to produce a structure suggestive of vortex breakdown.

One could argue here that fundamental differences exist between the experimental flow inside the pipe and the unbounded flow assumed for the simulation. However, as argued by Nakamura *et al.*, despite the differences between these two configurations, the essential ingredients remained for vortex breakdown in unbounded flow, as stable vortex breakdowns can be produced inside the pipe with or without a divergent wall.

Due to insufficient knowledge about the initial disturbance necessary to produce vortex breakdown, several three-dimensional perturbations were applied in order to evaluate the response. As was shown by preliminary calculations [18], a small amplitude disturbance on a vortex with no axial flow resulted only in weak travelling waves, but a large amplitude disturbance caused breakdown similar in the appearance to a wave breaking. In fact, it is proved experimentally that vortex breakdown is quite sensitive to the type of disturbance and that changes in breakdown pattern occur even if the same upstream conditions are maintained.

Solutions were obtained for two types of initial disturbances: axisymmetric and three-dimensional (sine wave), with experimental data serving as upstream conditions. Filament configurations and calculated axial- and theta-velocity contours, obtained in [18] are presented in Figure 2, Figure 3 and Figure 4. All these plots show the breakdown of the vortex, including a rapid change in the vortex core, followed axially by a recovery zone and then a second breakdown. One vortex breakdown was similar in both cases and was axisymmetric. The other vortex breakdown was axisymmetric for axisymmetric disturbances and three dimensional for three-dimensional disturbances. The latter case agreed with the experimental observations where an axisymmetric vortex breakdown is followed by a spiral-type breakdown. It was suggested by Nakamura *et al.* that each type of vortex breakdown might need a different three-dimensional initial perturbation.

As reported in [18], when an axisymmetric disturbance was applied, a remarkable vortex swelling was observed in the downstream region where the initial disturbance had a flow reversal, see Figure 2. At later times this swelling moved downstream having vortex filaments elongated in the axial direction. Just downstream of this region a narrow region with small pitch can be observed. A central region, which appeared devoid of filaments due to the elongation and straightening of the filaments, was observed in the middle of the breakdown region. This region then moved upstream and, as the authors concluded, was a manifestation of the axisymmetric vortex breakdown.

It may be also noted that another low-velocity region appears near the downstream boundary, which apparently manifests the occurrence of a second breakdown, see Figure 3 and Figure 4. It is often observed experimentally that axisymmetric vortex breakdown is followed by a second breakdown of the spiral type. However, in this case the axisymmetric initial disturbance appeared to produce only an axisymmetric flow.

In the case of a three-dimensional perturbation it was observed that, in general, the breakdown pattern was similar to that caused by an axisymmetric disturbance. However, the three-dimensionality remained at later times, but only near the downstream boundary. The shape of the first breakdown appeared to be axisymmetric, but the second breakdown was distorted, not axisymmetric, and appeared to be rotating around the longitudinal axis. According to the authors, it was indicative of a vortex breakdown of a spiral type in agreement with experimental observations.

Also, it was noticed that differences in the filament configurations between axisymmetric and three-dimensional disturbances persisted in time but remained confined to the downstream end of the computational domain. At later times most of the filaments in both cases became very disordered near the downstream boundary showing the existence of a highly turbulent wake of a burst vortex. However, the vortex filament method is not well suited for simulating such kinds of wakes as some of the filaments can become overlapped, producing unrealistically high induced velocities. Here, the use of a more comprehensive technique such as vortex particle or vorton method would be required in order to reproduce different scales of turbulence in the wake of a burst vortex.

4.2 Unsteady Vortex Lattice Method

An attempt to determine if a vortex lattice method could compute the bursting of a leading edge vortex was undertaken by Lorey [20]. In this study, he applied an unsteady three-dimensional vortex panel method to simulate the flow over a unit aspect ratio delta wing. The method was a hybrid of a vortex panelling method which described the lifting surface, and a vortex lattice method which was employed to model the development of the unsteady vortex wake. The method utilised triangular elements, or panels, on which the surface vorticity is piecewise linearly varying, to model the lifting surface. Quadratically varying vortex cores are placed at the edges of the wing in order to generate a nonzero vorticity there. The unsteady wake was modelled as a vortex sheet, composed of discrete vortex cores, which emanate from the edges of the wing.

The simulation of the flow past the delta wing was performed by starting the fluid flow impulsively, allowing for a continuously developing wake. One of the distinctive features of the method, as used by Lorey, was its wake-splitting algorithm, which controls the distance between adjacent vortex cores in the wake, as it is convected downstream. In order to sustain a continuous distribution of wake cores, additional cores were added between those that have moved sufficiently apart. The strengths of the added cores were determined from the conservation of circulation within the wake.

The results of flow simulation past the delta wing were presented for 20.5 and 30 degrees angle of attack, see Figure 5 - Figure 10. According to experimental data, the vortex breakdown does not occur over a delta wing with an aspect ratio of one at 20.5 degrees angle of attack. Therefore, this flow case was calculated as a baseline. A case of 30 degrees of angle of attack was used to determine if the panelling method could predict the vortex bursting. In order to establish if vortex bursting occurred, the criteria established by O'Neil *et al.* [15] were used, which describes the breakdown as degeneration of the leading edge vortex combined with relatively mild gradients.

As reported by Lorey, both calculations were carried out to produce one chord length of wake. The vortex sheets generated off the leading and trailing edges of the airfoil were used as the flow visualisation of the wake. Figure 5 and Figure 6 show the wake mesh at this time for the 20.5 and 30 degrees angle of attack, respectively. As one can see, the panelling method computed both the leading edge and the trailing edge vortices typical of the flow over delta wings. Figure 7 and Figure 8 provide a hidden line picture that provides a clear view of the leading edge vortices and the destruction of the wake mesh for the 30 degree angle of attack in the area, where the leading and trailing vortex systems meet and combine.

For the 20-degree angle of attack, the leading edge vortex wake expands in a continuous manner as it is convected downstream. However, at 30-degree angle of attack, the leading edge wake shows a perturbation and enlargement of the vortex approximately at the two-thirds chord position. According to Lorey, this fits the description of vortex breakdown provided by O'Neil *et al.* [15]. However, further investigation into the surface pressure gradients in the spanwise direction was performed to verify this conclusion.

Figure 9 and Figure 10 show the coefficient of pressure distribution in the spanwise directions for 20.5 and 30 degrees angle of attack, as obtained in [20]. The length in the spanwise direction was normalised by one-half the local span. The pressure distributions were presented at one half, two-thirds, and five-sixths chords and at the trailing edge. As concluded by the author, these curves are typical of the trends investigated experimentally under similar conditions over delta wings. As one can see, the rise in the curves is the enhanced lift provided by the suction induced by the leading edge vortices. A peculiar decrease in the coefficient of pressure, or decrease in lift, was found at the two-thirds chord position at 30 degrees angle of attack. This corresponded to the chordwise location of the vortex perturbation. However, as concluded by the author, these sharp gradients in the pressure coefficient contradict the vortex breakdown criteria of O'Neil *et al.*

In an attempt to find out if the sharp pressure gradients would diminish as time proceeds, the calculations were continued for another ten time steps, or one-third chord length. As reported by Lorey, it resulted in severe wake degeneration behind the wing. However, the leading edge wake still retained its structure over the wing and the vortex perturbation and enlargement was still evident implying the existence of vortex breakdown. But the pressure gradient at the two-thirds chord position, at an angle of attack of 30 degrees, had not diminished, and had actually increased with the additional amount of wake.

Also, a qualitative comparison between wake cross-sections in the vicinity of the breakdown location was accomplished for 20.5 and 30 degrees angle of attack, see [20]. It appeared that the only distinction between the different angles of attack was the magnitude of the leading edge vortex. Again this led to the conclusion that vortex breakdown was not simulated in the 30 degrees angle of attack calculation. However, it is admitted by the author that a more detailed investigation would be required to make a certain conclusion on the occurrence of the breakdown by using flow visualisation of the burst vortex. This could be done by inclusion of Lagrangian points or numerical dye within the flowfield, which would provide further insight into topology of the vortex wake.

According to Lorey, a possible explanation of the failure to predict vortex bursting was the splitting method employed. The process traced the spanwise distance of the wake elements and split the elements in the spanwise direction, if warranted. This was based on the premise that the wake was continuously diverging. However, the wake elements were also elongated in the chordwise direction. The area most susceptible to this stretching was in the leading edge vortex. The author's suggestion was that the algorithm splitting the wake in the chordwise direction should be included before further analysis of vortex breakdown is undertaken.

Another reasonable suggestion would be the implementation of a higher order convection scheme of the wake nodes. The intermixing of the leading edge and trailing edge vortices induced excessively high velocities of the wake nodes, resulting in the deterioration of the wake mesh. A second order convection scheme could possibly eliminate this deficiency.

4.3 Semi-Empirical Vortex Methods

Considerable difficulties encountered during the numerical simulation of vortex breakdown prompted the development of semi-empirical methods for aerodynamic analysis of configurations dominated by vortex flows. One such semi-empirical method, as described by Dixon [21], was developed by Lockheed for the Air Force Flight Dynamics Directorate at Wright Laboratory and incorporated into preliminary design code called HASC. The vortex lattice method forms the foundation for the HASC code with some other vortex-based modules for prediction of forebody aerodynamics and characteristics of leading edge vortex.

As stated by Dixon, most of the major characteristics of vortex flow have been included in a preliminary design code, which approximates the resulting forces and moments on a complete aircraft. The methods include the prediction of vortex characteristics such as vortex core size, strength and position. In order to position the vortex, two empirical equations were developed that are functions of the vortex core size, the distance from the vortex origin, and the angle of attack. These equations determine the height of the vortex axis and the vortex cross-sectional area and, according to the author, are not sensitive to the type of configuration.

It is claimed by the author that the code is able to predict the leading-edge vortex transition to a turbulent vortex and its ultimate burst, taking into account both static and dynamic load effects of these two flow regimes. Also, one of the applications of the code includes the prediction of the centre frequency for a peak aerodynamic forcing function that causes tail buffet. The prediction is based on a reduced frequency of 0.5, where the length scale is based on the turbulent vortex diameter.

According to Dixon, the method assumes that vortex breakdown occurs in two stages. First, the initially laminar vortex transitions to a turbulent vortex causing some loss in lift and an aft shift in the aerodynamic centre at the wing sections affected by the turbulence. Then the vortex ultimately bursts, creating completely chaotic conditions on the wing. In this condition the wing sections affected by the vortex outside of the burst position are assumed to be completely stalled and the aerodynamic centre is considered to move to about 50% chord of the affected wing sections. It is recognised in [21] that there has not been much theoretical analysis of the bursting of a turbulent vortex and the burst is assumed to occur when the average axial velocity approaches zero. HASC also has an empirical method that causes the vortex burst to accelerate towards its origin as angle of attack increases.

It is essential to find out how the method accounts for the buffeting effect of the burst vortex. According to Dixon, the method assumes that the kinetic energy from the turbulent vortex is a major source of the forcing function or the buffet found on immersed lifting surfaces. The highest turbulent kinetic energy is supposed to exist within an annulus around the sub core of the turbulent vortex. When the vortex fully bursts, the kinetic energy is considered to be dispersed and both the associated amplitude and frequency of the forcing function approach zero. However, this assumption does not agree with the experimental results showing that the flow field of a burst vortex is a highly energetic flow with finite dominant frequency content and its buffeting effect can not be ignored.

Validation of prediction abilities of the HASC code was presented for the case of flow past a simple delta wing of an aspect ratio of one. As shown by Dixon, the semi-empirical methods, incorporated in HASC code are successful in predicting vortex transition to turbulence and its ultimate burst. As comparison with experiment showed, the prediction of the stall and post stall forces is quite accurate. The post stall moment has the right trend, but not the right values. Force and moment changes caused by the vortex transition and burst seem to be adequately estimated by the semi-empirical methods.

In general, the test and HASC code predictions showed good agreement for the centre frequency of a peak aerodynamic forcing function. The predicted fully turbulent point agreed well with the highest amplitude of the measured value of peak kinetic energy. However, due to limited description of the method, it is not clear how the underlying empirical relationships were derived and incorporated into vortex modules of the HASC code. Clarification of these issues would help to understand the advantages of the approach and reveal its limitations.

5. Conclusions and Recommendations

The aim of this work was to evaluate the feasibility of vortex-based methods for computation of LEX vortex breakdown, which defines the spectrum of unsteady buffet loads on F/A-18 empennage surfaces.

Although the Euler and Navier-Stokes codes can be successfully applied to the simulation of vortex breakdown in flows over delta wings and other simple geometries, they require enormous computing resources to study more complex configurations. In fact, computation of time-accurate vortex breakdown in the flow over such complex geometry as the complete F/A-18 aircraft by using the above codes is beyond the capabilities of available supercomputers. Also, neither the Euler nor the Navier-Stokes codes can capture a sharp vorticity discontinuity without smearing it over a number of computational cells. Here, the mismatch between model-based predictions and actual behaviour is wholly attributable to numerical dissipation, which is inherent in the grid-dependent computational approaches.

A viable alternative to grid-dependent Euler and Navier-Stokes codes are the vortex-based methods which can gain economy in computation by concentrating the computational efforts in the area where the vortex breakdown occurs, taking into account a continuously developing vortex wake, which is not bound by a computational domain or grid. This is particularly important, as our ultimate aim is to predict unsteady buffet pressures on empennage surfaces which are immersed in the wake of the burst LEX vortex.

Several attempts at using vortex methods for the prediction of vortex breakdown were found in the open literature. Their advantages and shortcomings are reviewed in detail in order to evaluate their feasibility for the computation of LEX vortex burst. Based on the results, it can be concluded that vortex methods are able to predict an onset of breakdown and provide a plausible solution for its unsteady behaviour. However, none of these models is able to reproduce correctly the spatial and temporal characteristics of the unsteady wake past a burst vortex due to the simplified type of vortex elements used in the simulation. Their refinement will require the use of more comprehensive methods such as vorton or vortex particle methods. Although more computationally expensive, these methods should provide more accurate modelling of highly turbulent wakes. Despite the need for further development, vortex methods possess definite advantages over Euler codes on the grounds of the physical realism and the economy of computation as far as unsteady flows with sharp vorticity discontinuities are involved.

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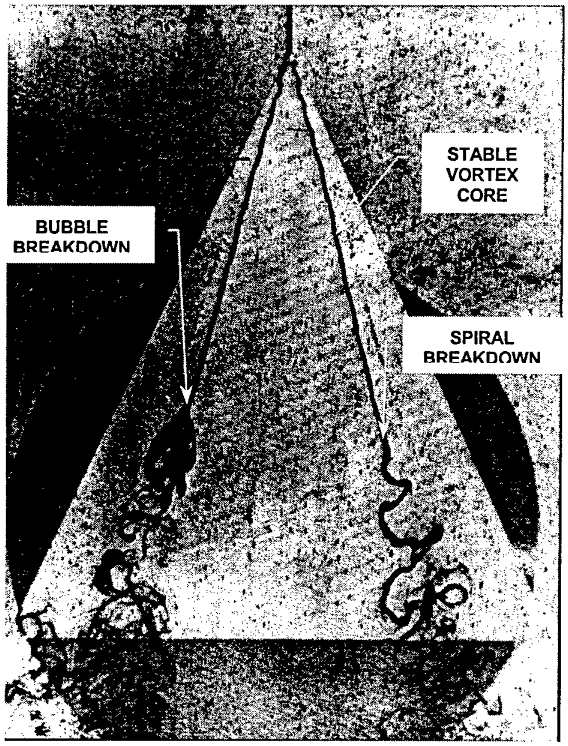

Figure 1 Vortex Breakdown over a Delta Wing (Lambourne & Bryer [4])

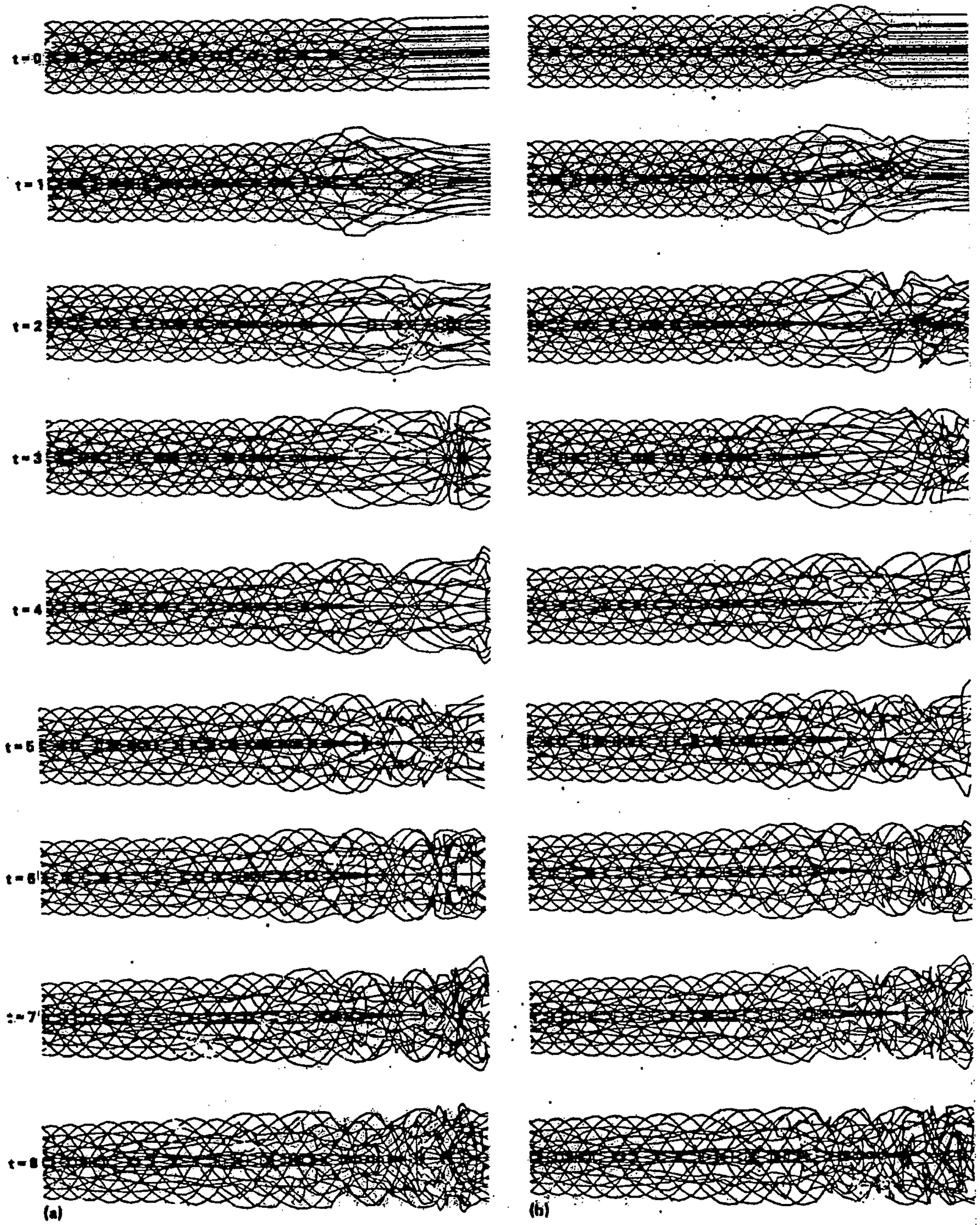

Figure 2 Evolution of vortex filaments. (a) Axisymmetric disturbance; (b) Three-dimensional disturbance (Nakamura et al. [18])

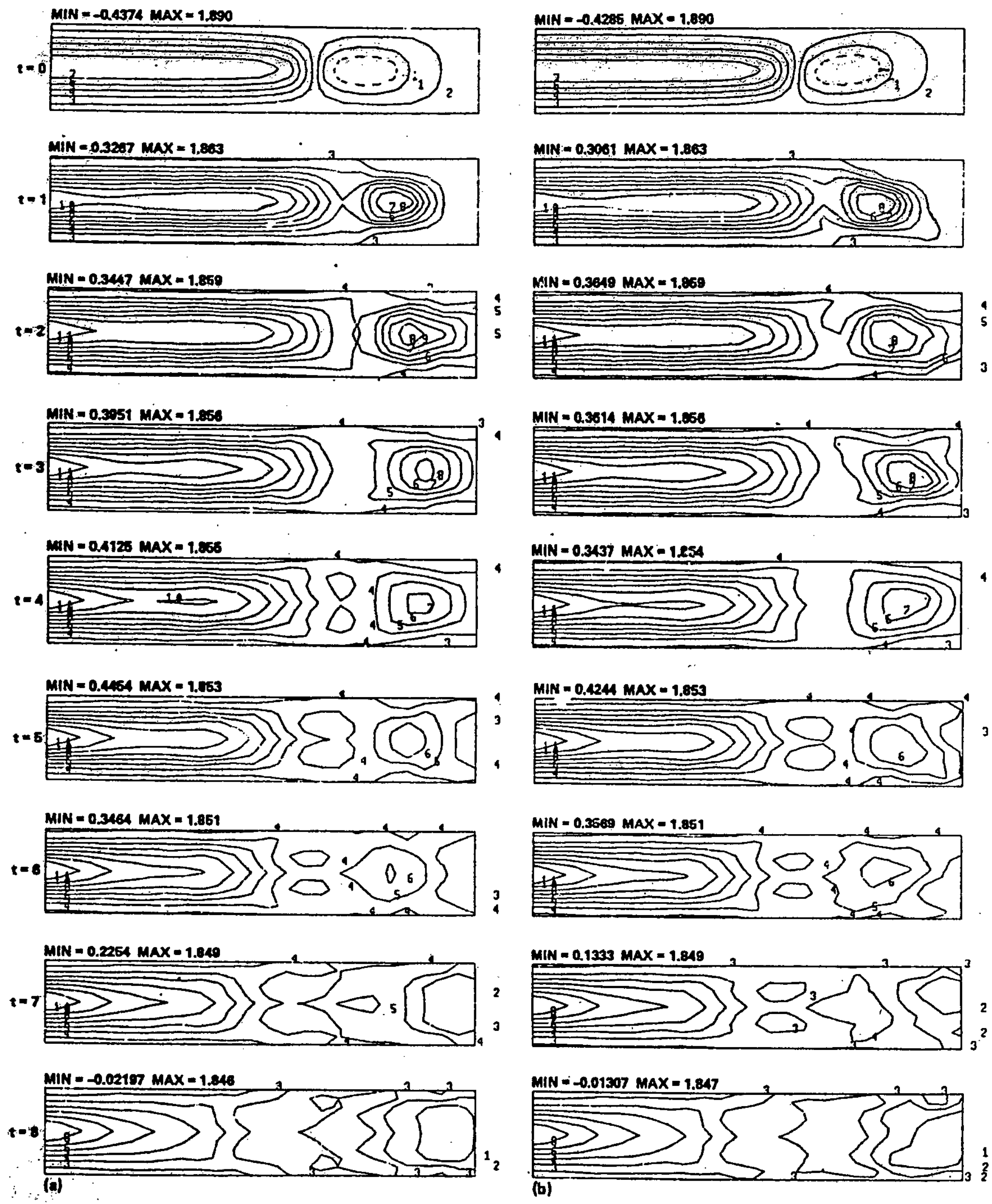

Figure 3 Axial velocity contours. (a) Axisymmetric disturbance; (b) Three-dimensional disturbance (Nakamura et al. [18])

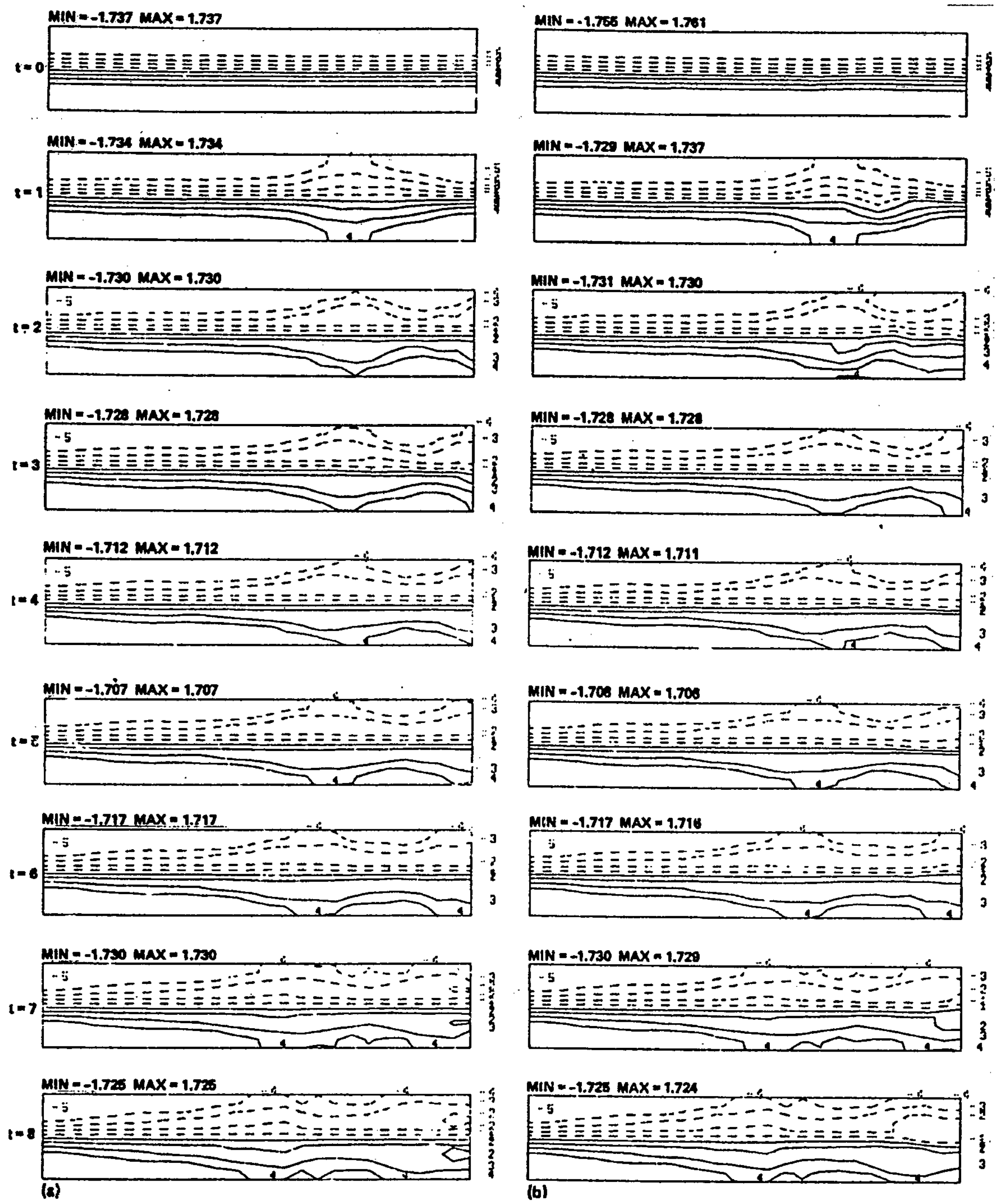

Figure 4 Tangential velocity contours. (a) Axisymmetric disturbance; (b) Three-dimensional disturbance (Nakamura et al. [18])

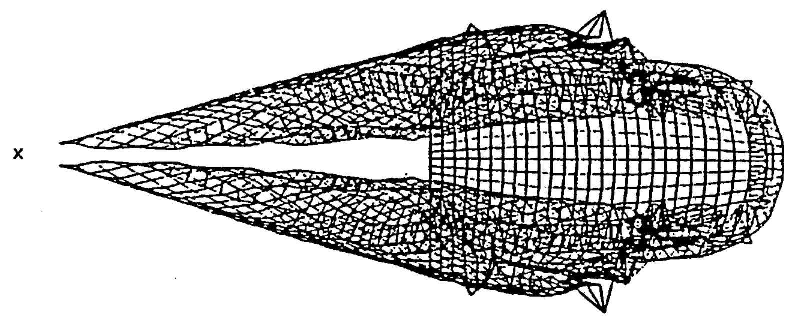

Figure 5 Wake mesh at 20.5 degrees angle of attack (Lorey [20]).

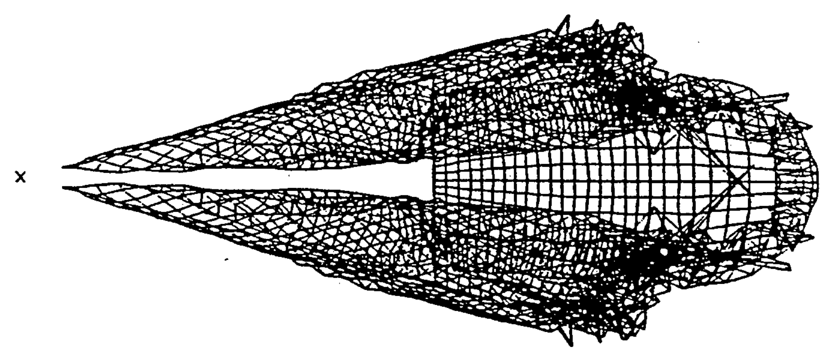

Figure 6 Wake mesh at 30 degrees angle of attack (Lorey [20]).

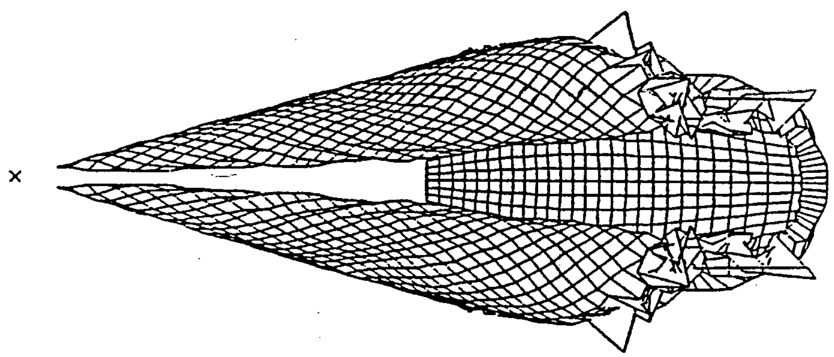

Figure 7 Hidden line view of the wake mesh at 20.5 degrees angle of attack (Lorey [20]).

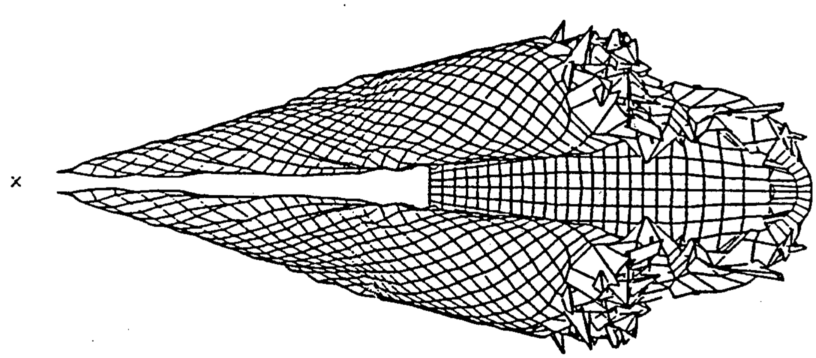

Figure 8 Hidden line view of the wake mesh at 30 degrees angle of attack (Lorey [20]).

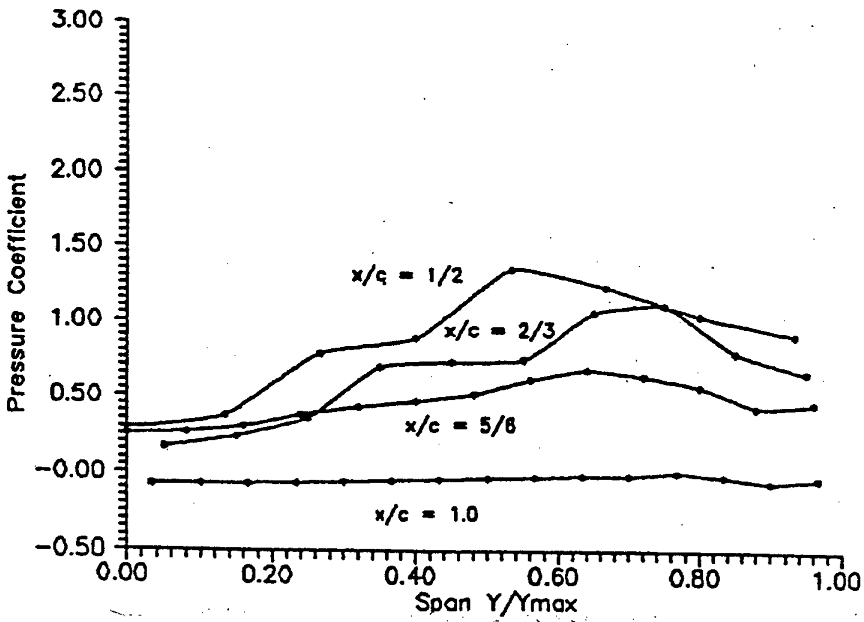

Figure 9 Pressure distribution over the wing at 20.5 degrees angle of attack (Lorey [20]).

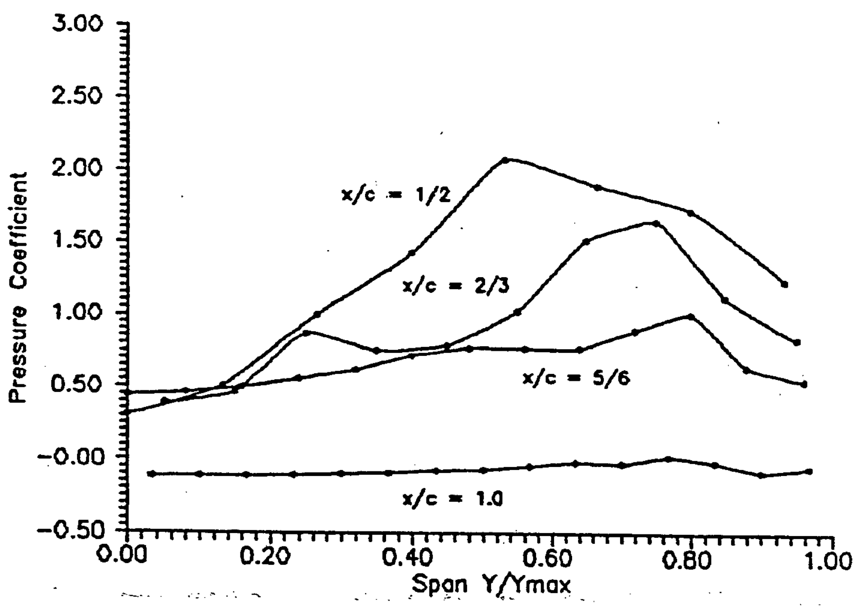

Figure 10 Pressure distribution over the wing at 30 degrees angle of attack (Lorey [20]).

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Oleg Levinski

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19. ABSTRACT

The aim of this work is to identify current developments in the field of vortex breakdown modelling in order to initiate the development of a numerical model for the simulation of F/A-18 empennage buffet. Some attempts at using vortex models for prediction of vortex breakdown were found in the open literature. Their advantages and shortcomings are discussed, allowing the evaluation of their feasibility for the computation of LEX vortex burst. It was concluded that vortex methods are able to simulate an onset of breakdown in simple vortical flows. However, their predictive abilities require further improvement to provide accurate modelling of the temporal and spatial characteristics of the unsteady pressure field past a burst LEX vortex.