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A Critical Assessment and Requirement for Ground Testing on Vortex Breakdown Locations Over Delta Wings

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ABSTRACT

A critical assessment has been conducted on more than sixty experimental data sets about vortex breakdown locations over 65º and 70º delta wings at different angles of attack. Test conditions, such as tunnel wall and blockage, model support interference, model geometry and its deformation under load, as well as the methodology used to define breakdown location are examined. A screening process has been conducted to help identify the relative merits of the various data sets and to extract useful, quantitative information from the contradicting database. Aerodynamic and experimental requirements to ensure high quality data are discussed. The requirements for flow quality and data accuracy is further raised.

INTRODUCTION

The tactical advantage enjoyed by more maneuverable and agile fighter aircraft has been an incentive to continually expand their flight envelope. Modern high-performance combat aircraft routinely operate at high angles of attack and high angular rates[1], conditions under which the flow field is usually dominated by strong vortices, and where loss of controllability may become a major problem. The vortical flow and, especially, the vortex breakdown in the vicinity of lifting surfaces play a critical role in causing the observed airload nonlinearities and time dependence resulting in the failure of linear or local-linear aerodynamic models[2]. Due to the lack of sufficient understanding of the flow physics, predictive capabilities have largely lagged behind operational requirements[3]. A better insight into the vortex, and particularly vortex breakdown behavior as well as aerodynamic models capable of adequately capturing them, is an essential requirement for solving the flight mechanics problems in the advanced maneuvering regime.

For these reasons, vortex behavior and vortex breakdown have been the subject of experimental investigations in wind and water tunnels for nearly five decades as well as of considerable analytical and computational studies. An important part of these investigations has been conducted to elucidate the complex vortical flow fields over slender wings at high incidence.

However, vortical experiments traditionally tended to produce qualitative rather than high quality quantitative results, as demonstrated by the fact that the experimental results were seldom satisfactorily duplicated in different facilities. Significant discrepancies, especially in the vortex breakdown location, are present in the data obtained by different investigators. Geometric variations, different test conditions, model deformations due to aerodynamic loads as well as differences in measuring techniques significantly affect the

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measured vortex breakdown position and degrade the accuracy of the results. There is also controversy on the effect of support and tunnel wall interference[4]. The discrepancies among the results cause confusion in the analysis of the relevant aerodynamics and reduce the usefulness of the data. A reliable assessment of the accuracy of the data generated in ground tests remains one of the most vexing problems to be solved in order to satisfactorily design combat aircraft and validate CFD codes due to their increasing use for that purpose. Thus an evaluation of the data sets is imperative, so that the extensive work already performed at a very high cost can be properly used in the design of new aircraft and the development of new theoretical or computational models. The objective here is to extract as much useful, quantitative information as possible from a critical examination and comparison of existing data sets of vortex breakdown locations over delta wings.

EXISTING RESULTS ON MEASURED VORTEX BREAKDOWN LOCATONS

A brief, but by no means complete, survey of published results for the primary vortex breakdown locations over delta wings with sweep angles ranging from 50º to 80º are depicted in Fig. 1 to Fig. 7. It is worthwhile mentioning that most experimental results have not been corrected for tunnel wall and support interference, model geometry, model deformation under air loads, as well as boundary-layer effects, due to the inherent difficulty of doing so. In order to facilitate further investigations, each test condition and corresponding models are listed in Table 1 with corresponding references (Ref. 5 to Ref. 34.).

Since most of the investigations were conducted on 65° and 70° delta wings and these configurations are typical and closely related to high-performance combat aircraft, this paper concentrates on these two sweepback angles. A complete survey of the vortex breakdown location data for the 65° sweep delta wing has been given by Jobe in Ref. 35.

The preliminary comparisons shown in Fig. 4 and Fig. 5 reveal significant and unacceptable differences between different tests. The measured breakdown location for 65° delta wings at α=22.5° can be anywhere from the trailing edge (Earnshaw[8]) to 0.4 centerline chord (Lambourne & Bryer[6]). Similar scatter is found in the measurements on 70° delta wings. At $\alpha \approx 31°\sim32°$ the measured breakdown location varies from $x_{VB} \approx 0.9$ (Earnshaw & Lawford, et.al.[7]) to 0.35 (Wentz & Kohlmann[10]). Furthermore, in the case of the 70° delta wing, one data set exhibits a “knee’ reflecting a rapid, possibly discontinuous movement of the breakdown location from mid-chord to aft of the trailing edge over a minute change in angle of attack. The actual breakdown location within the large scatter as well as the possible presence of a discontinuity has a profound effect on any attempt to model breakdown behavior.

Given that vortex breakdown locations are measured at high angles of attack and/or high angular rates, where the flow tends to be more unsteady, non-linear and time dependent than at lower incidence, some scatter in the results is to be expected. Test section and support geometry, blockage and model aeroelastic deformations, all affect the results. Moreover, details of the model geometry such as thickness, leading-edge and/or trailing edge bevels, mounting arrangement, centerbody, etc. vary among the different investigations. These geometric variations also have an impact on breakdown location and degrade the consistency of results. Finally, the quality of the experimental data also depends on the criteria used to define the breakdown location, observation methodology, e.g. orientation of laser sheet normal to or along the vortex axis, seeding injection, Schlieren system set-up, measurements accuracy, etc.

However, several researchers have found that in a given investigation, the breakdown location can be very stable with high repeatability if the test conditions are well maintained. As examples, Fig. 8 depicts the standard deviations, δ, as well as maximum and minimum deviations, Δ_{max} Δ_{min}, of the breakdown location for a 75° delta wing[34]. The standard deviation δ is calculated based on 10 frames for each angles of attack. It shows that the breakdown location is stable, although a slightly increased scatter in the data can be observed when it occurs over the aft part of the model. To further confirm this behavior, a sequence of images obtained 0.2 convection times apart is depicted in Fig. 9 and Fig. 10 for α=32.1° and 35°. Lowson & Riley[27] repeated the experiments of Wentz & Kohlman[10] and Lambourne & Buyer[6] and found their data to be repeatable if the models and test conditions were accurately reproduced.

ASSESSEMENT OF EXISTING EXPERIMENTAL RESULTS

The present effort consists of assessing the effect of the aforementioned parameters on the various data sets and establishing whether such a process will lead to a better reconciliation of the different results. Clearly this process is not complete and considerable additional work is required to develop the process.

The sources of discrepancies can be classified into facility related: free-stream conditions, such as flow non-uniformity, angularity, unsteadiness and noise; wall and support interference; test conditions repeatability; etc, and simulation related: such as Reynolds and Mach numbers; model geometry; etc.

The assessment of the data sets consists of the following main steps:

1). Collate as many vortex breakdown location data as possible with the associated test conditions well described.

2). Weigh the accuracy of those data in terms of the quantitative or qualitative information about the test conditions.

3). Normalize the various data sets into "equivalent" sharp edge flat delta wings based on the well accepted assumption that x_{VB} is independent of Re for that geometry and the hypothesis, based on previous work, that Re may have a significant effect on x_{VB} in the presence of leeward bevels, rounded edges, etc. Carefully correct for estimated Re effects due to each geometric parameter.

4). In order to investigate the effect of a given geometric parameter, data sets where a minimum number of other parameters are varied are given preference. This will minimize false correlations.

Applying these steps to the results of 65° sweep delta wings, it was found that:

1). L&B's experiments[6] were conducted with t/c_r=6.3% and the blockages of 13% and 7.2% in the water and wind tunnel respectively (at α=30°). These values are several times larger than those of the other experiments. Although it is not known by how much they should be corrected, Weinberg's results[35] show that the increases of blockage and model thickness could promote (i.e., move closer to the wing apex) vortex breakdown by as much as 20% of centerline chord.

2). .Earnshaw's results[8] were obtained with a model with t/c_r=4% and symmetrical cubic curve section. According to the equation of the model surface, at the leading-edge the section half angle normal to the leading-edge is 14.2°. It is recognized that if the bevel width is comparable with the thickness of the boundary layer before separation, the bevel effect corresponds to a reduction of the effective angle of attack. If the average slope is assumed in Earnshaw's experiment, the effective angle of attack could be reduced by 3°.

3). Hanff &Huang's experiments[31,32] were conducted in two different wind tunnels using different model supports that generated comprehensive flow visualization and airload data sets. It was found that the differences between the results in the two facilities were minor and the data repeatable. In the bulk of the experiments, breakdown location was found by means of a laser sheet normal to the vortex axis and determined by a blurring of the vortex ring. This criteria is consistent with Lambourne's[37] definition for spiral vortex breakdown. Subsequent tests with a laser sheet containing the vortex axis showed this location to be approximately 10% to 15% of centerline chord aft of the kink point in the vortex axis [31](see Fig. 11 and Fig. 12). In addition, their model has a center body, as shown in Fig. 13 which has been blamed for the remaining delay (aft shift) of vortex breakdown as compared with other wing-alone data [38,39]. However, water tunnel experimental results specifically designed to elucidate center body effects conducted by Huang, Sun and Hanff[32] show that the center body effect is minor (up to 3%) as depicted in Fig. 14. It should be noted that in these experiments, there is no center body on the windward side which eliminates the so called "viscous fairing" effect suggested in Ref. 38 and Ref. 39. In summary, the average aft shift in breakdown location due to the measurement methodology is estimated to be 10% to 15% centerline chord. As discussed below, the additional delay is attributable to the leading-edge bevel.

4). Several of the models used to obtain the data sets under consideration featured beveled leading-edges. As a first approximation the bevels modify the effective angle of attack according to the kinematic equation [40]

$$\Delta\alpha=\tan\Lambda*\cos\delta$$

Kegelman and Roos[40] have investigated the effect of leading-edge shape on vortex breakdown. Based on their results it is estimated hat in their experiments the change in effective angle of attack is only 1/3 of the value predicted by the equation. Pelletier and Nelson[28] as well as Huang, Sun and Hanff[32] conducted water tunnel experiments to investigate the effect of leading-edge bevel by directly comparing the results obtained with and without bevel and found the difference to be negligible. Likewise, Wentz & Kohlmann's[41] results for a 60° delta wing with beveled and square leading edges are very similar. From the above discussion it follows that the kinematic equation cannot always be directly applied but must be modified by additional factors. The dominant one appears to be the ratio between the bevel width and the thickness of the boundary layer just before separation at the leading edge. The smaller the ratio the less effective the bevel is in reducing the angle of attack. In Wentz & Kohlmann's as well as

Pelletier's experiments the ratio is 1/15 and 1/7 of that in Hanff & Huang's experiments, explaining the negligible bevel effect in the former as compared to that in the latter which is estimated to be $\Delta\alpha_{eff} = 4.2$ deg.

The original data sets normalized into a flat plate delta wing using the above approach are shown in Fig. 15 which exhibits considerably less scatter than in Fig. 4, thus tending to support the assumptions made in the normalization process.

In the case of the 70° delta wing, in addition to a scatter similar to that for the 65° wing, there is a fundamental behavior difference in Wentz & Kohlmann's[10] results. A discontinuity in their vortex breakdown location data that is not present in the other results must be explained.

1). The wing thickness/length ratio in Wentz & Kohlmann's[10] experiment is only 0.007, nearly an order of magnitude less than that for the others. This situation is further exacerbated on the forward part of the model by the 7.5° bevel on the lower surface. Thus the effect of the aeroelastic deformation on vortex behavior has to be considered. The deformation under the reported test conditions[10] (q=30 psf) was estimated by the finite element method where the loading was based on the reported breakdown locations, x_{VB}, at the trailing edge (x_{VB}=1) and at 0.4 c for α•29° and 30° respectively. The calculated deflections are large and their effects can not be ignored (see Fig. 16 and Fig. 17). Specifically, at α•30° the wing has a negative camber with 1.3° deflection angle at the apex while at α•29° it exhibits a positive camber over most of wing area. In light of the above, it follows that when α decreases from 30°, initially the negative camber will result in a premature vortex breakdown. As α decreases the vortex breakdown location begins to move downstream. That movement redistributes the load such that it tends to reduce the negative camber which, in turn, makes the breakdown location move further downstream. A positive feedback is clearly present in the coupling between the deformation changes and the loading changes, leading to the reported discontinuous behavior. In fact Wentz & Kohlmann's[10] reported angular deflections, as high as 3~4 degrees at the apex section for these slender delta wings and their possible effect on breakdown location[10, 42]. Considering the above, it is reasonable to assume that Wentz & Kohlmann's[10] discontinuous vortex breakdown location for $\Lambda \geq 70°$ delta wing is anomalous due to aeroelastic effects and cannot, therefore, be deemed to be representative of the breakdown behavior over a rigid model.

2). Lemay's[16] model has a bevel angle of 23° along the leading-edge while Earnshaw's[8] model has a 14° slope at the leading-edge. Since the bevel widths are relatively larger than those in the water tunnel experiments [12, 25, 32], in the former two cases the bevel may result in a reduction of the effective angle of attack with corresponding delays in the vortex breakdown location.

The normalized data set for the 70° delta wing with sharp leading-edges and flat upper surface is depicted in Fig. 18. The data were normalized as in the previous case of the 65 sweep delta wing.

SUMMARY AND FUTURE REQUIREMENT

Results from many wind tunnel and water tunnel experiments have been examined and assessed. The scatter in the total ensemble of data is unacceptable due to flow quality limitations, interference from tunnel wall and/or support, differences in model geometric details, model aeroelastic deformations, etc. It is not readily apparent which results are adequate, either for defining the movement of the vortex breakdown over sharp leading-edges and flat upper surfaces or for validating CFD codes.

Nevertheless, the extensive experimental work already performed at high cost is extremely useful and important if a systematic screening process is performed thoroughly. This preliminary screening of the experimental results over 65° and 70° delta wings, has significantly narrowed the experimental scatter. Preparations are under way to conduct wind-tunnel tests on a 65 degree sweep wing specifically designed to elucidate the effect of bevels and a center body at higher Reynolds numbers. As attention shifts from qualitative to quantitative studies, it becomes increasingly important to set standards of flow quality and data accuracy for the measurement of vortex breakdown, and to critically assess existing data sets in light of the large variability of relevant experimental parameters. It would be worthwhile to set up a collaborative program to make the experimental results satisfy the requirement of engineering application and CFD validation.

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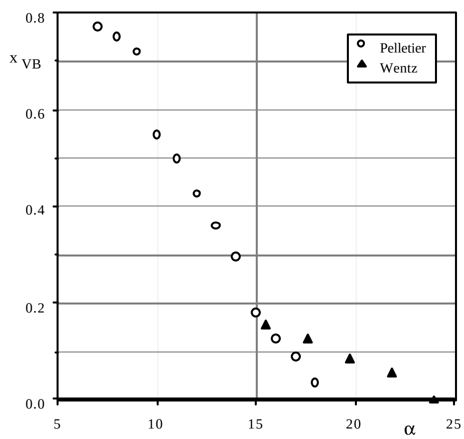


Fig. 1 Vortex breakdown location on 50° delta wing

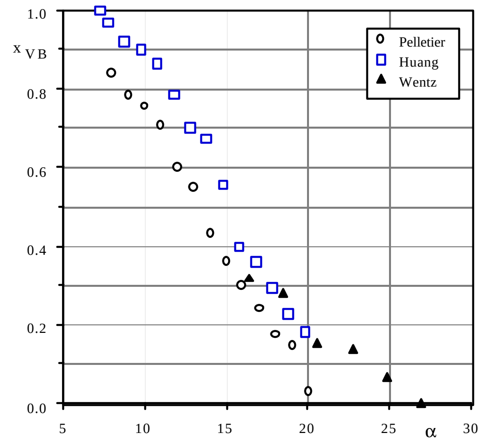


Fig. 2 Vortex breakdown location on 55° delta wing

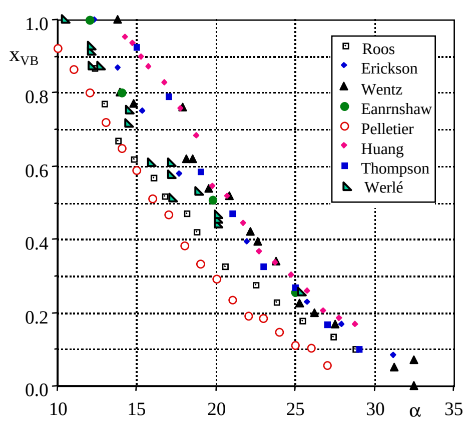


Fig. 3 Vortex breakdown location on 60° delta wing

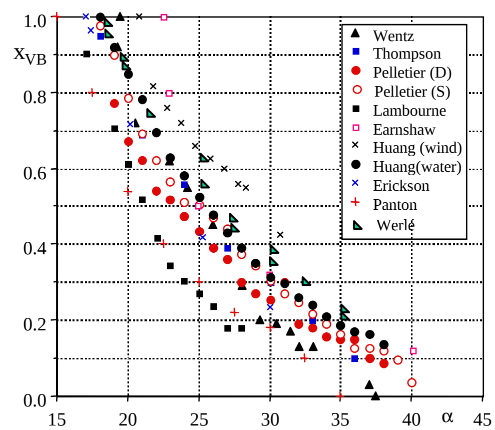


Fig. 4 Vortex breakdown location on 65° delta wing

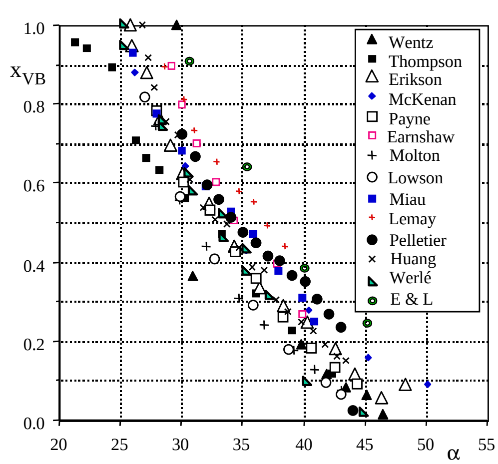


Fig. 5 Vortex breakdown location on 70° delta wing

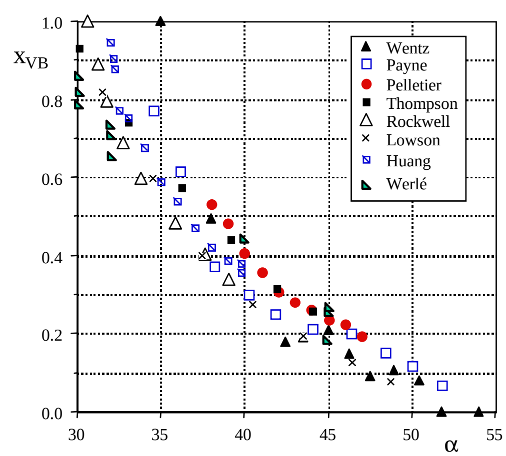


Fig. 6 Vortex breakdown location on 75° delta wing

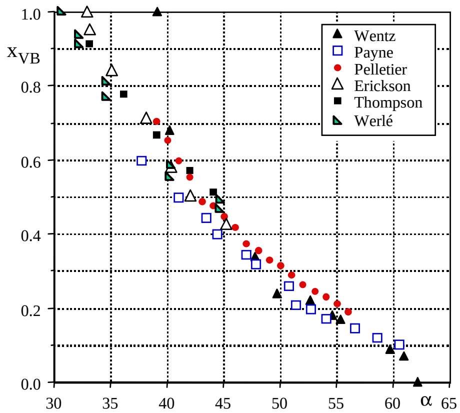


Fig. 7 Vortex breakdown location on 80° delta wing

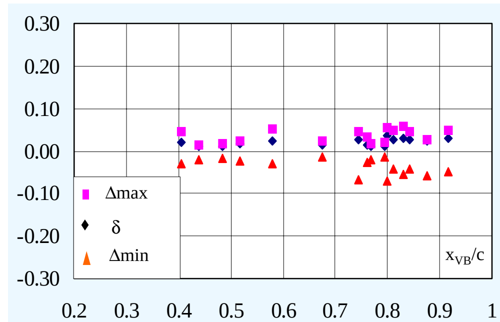


Fig. 8 Standard and maximum deviations of measured vortex breakdown location

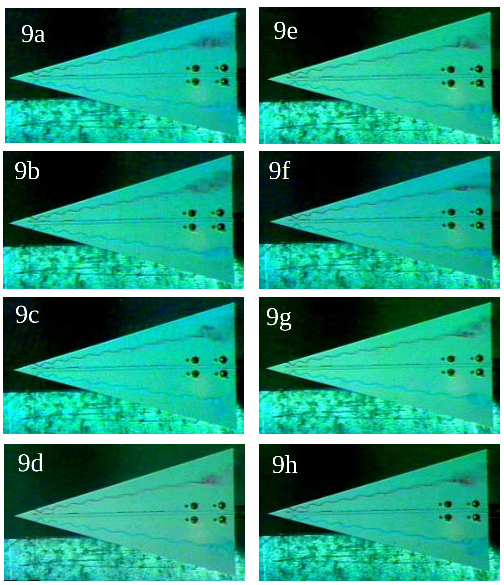


Fig. 9 Series of vortex breakdown images (α=32.1°)

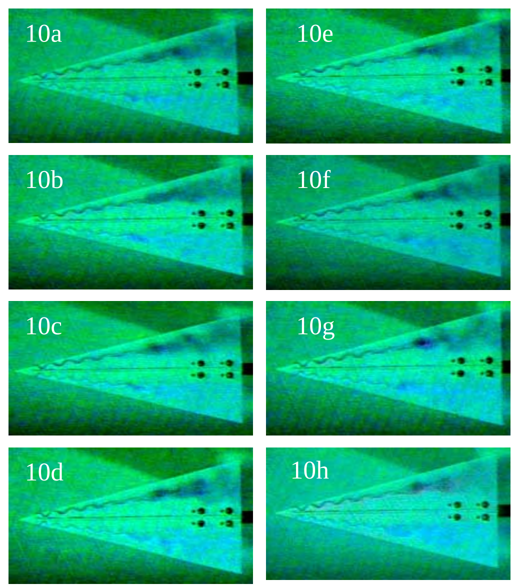
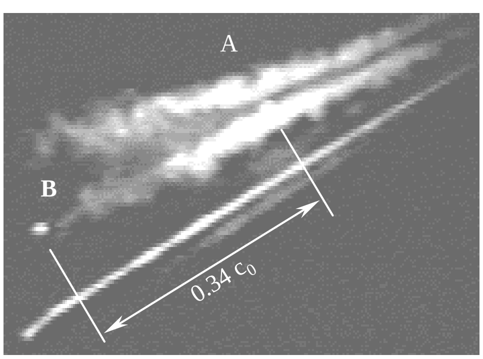
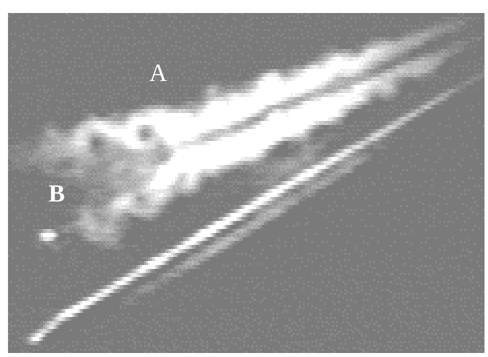


Fig. 10 Series of vortex breakdown images (α=35°)



11a slow dissipation process



11b fast dissipation process

Fig. 11 Different spiral breakdown appearances (Λ=65°, α=26°)

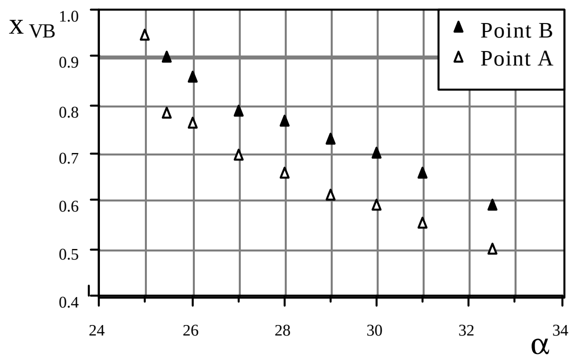


Fig. 12 Time averaged vortex breakdown location (Λ=65°)

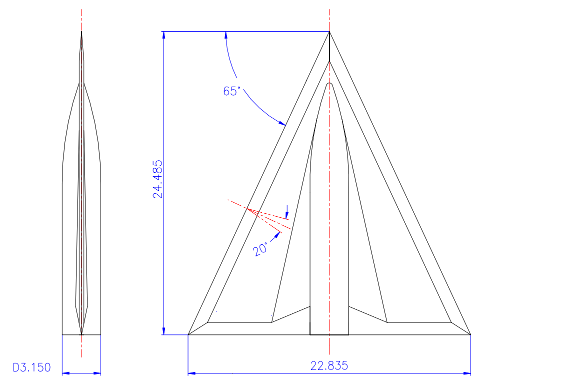


Fig. 13 65° delta wing model in H&H's test

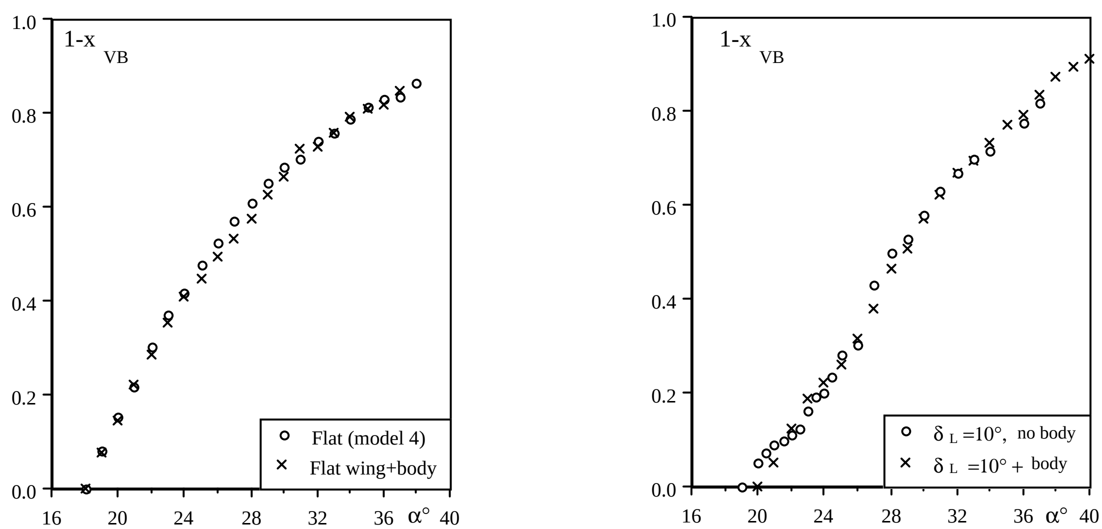


Fig. 14 Center body effect on vortex breakdown in Huang's water tunnel experiment
(no centerbody on windward side)

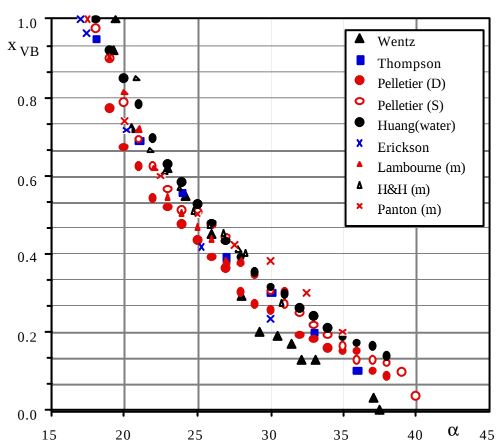


Fig. 15 Normalized results for 65° delta wings

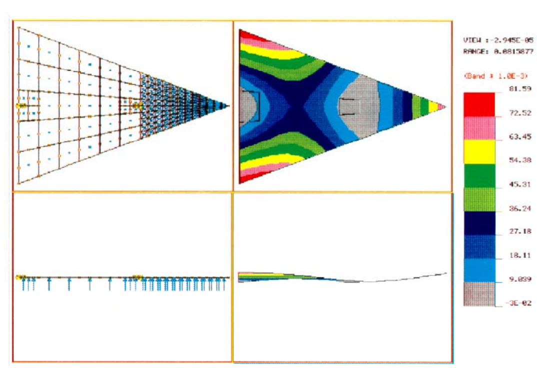


Fig. 16 Deformations estimated at α=30° and x_{VB}=0.4

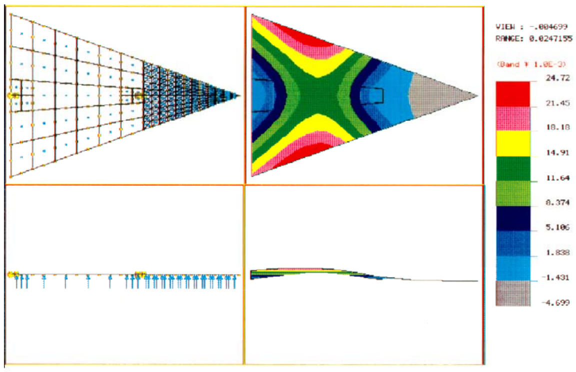


Fig. 17 Deformations estimated at α=29° and x_{VB}=1

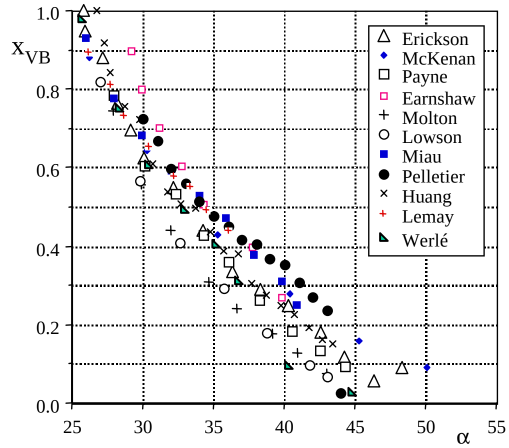


Fig. 18   Normalized results for 70° delta

Paper: 17
Author: Dr. Jobe

Question by Lt. Col. Pantelatos: Have you produced any error model after the assessment of all the experimental data that you gathered, in order to use this model in a controls engineering prediction method?

Answer: Not yet, but that is an excellent suggestion.

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