THE INTERNATIONAL VORTEX FLOW EXPERIMENT FOR COMPUTER CODE VALIDATION

ICAS-88-0.5

by
Georg Drougge
The Aeronautical Research Institute of Sweden, FFA

Abstract

The lecture will describe how this international cooperation started and grew and which institutes took part in it. The aim of the cooperation and its scientific program, both the experimental and computational parts, will be presented and finally some few examples from the wealth of results will be presented.

I. Introduction

My colleagues in DFVLR*, NLR**, AFWAL*** and myself feel most honoured to receive the ICAS-VON-KARMAN-AWARD for International Cooperation in Aeronautics. As you will see many institutes and scientists took part in the cooperation and it is only fair that we share this honour with all of them. Apart from its scientific results, this cooperation promoted and fostered multinational contacts. This was no doubt one of Theodore von Karman's intentions when he suggested the foundation of ICAS.

The cooperation started from highly preliminary discussions in November 1982 between FFA and NLR. FFA felt the need of good experimental data for delta wings in the transonic speed range in order to validate an Euler code for delta wing vortex flow developed by Dr. Rizzi of FFA. Dr. Tijdeman and Dr. Sloof of NLR agreed to look into the possibilites to perform some tests at NLR and at a meeting at FFA in July 1983 "it was agreed to have the tests performed before the summer of 1984". This and the following meetings are reported on in Paper 1 in Appendxis 1 by A. Elsenaar, who later on was to be responsible for the NLR tests. He also describes how during the spring of 1983 more research institutes and also some aerospace industries became involved. It was around this time that an American institute, the Air Force Wright Aeronautical Laboratories was included in the coperation. A rather extensive test program was decided upon and tests were performed from the fall of 1984 until the spring of 1986 at NLR, DFVLR, FFA and TU Delft, and in October 1986 a Symposium was held in Stockholm. A list of the contents in the Proceedings from the Symposium is given in Appendix 1, where all the experimental results and the corresponding computations and analysis were published.

Before going into the Experimental Programme the participating parties will be mentioned. Figure 1 shows the organisation of the cooperation and the contributions from the different parties. It should be mentioned here that no money was exchanged between the countries or parties*, but the costs of models, wind tunnel tests, computer codes and computations is reasonably well shared between the participating parties. A few bi-lateral agreement had to be signed but the administrative processes were minimized as far as possible.

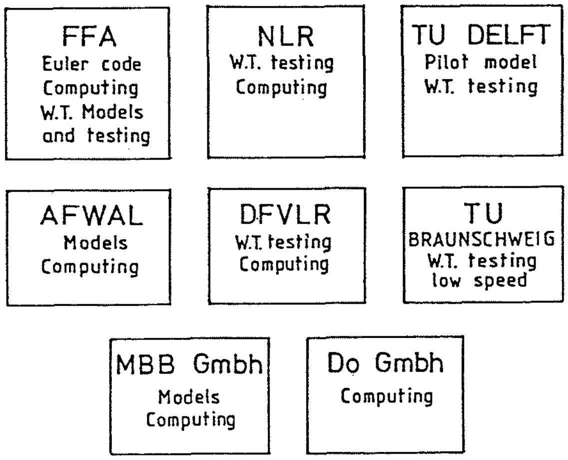

Fig. 1 Participating parties

In Appendix 2 the names, without titles, of the participants are given.

II. Experimental Programme

Model Geometry

The participants agreed early on the model geometry. The majority of the tests was carried out on a 65 deg delta wing with a constant airfoil section in streamwise direction based on the NACA 64A005 profile from 40% chord location to the trailing edge. Three different nose sections were designed, one with a round leading edge with a nose radius of 0.7% of the local chord, one with a circular arc nose section and one with a slightly drooped round leading edge section. This

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* DFVLR, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt

** NLR, National Aerospace Laboratory the Netherlands

*** AFWAL, Air Force Wright Aeronautical Laboratories, USA

* The work at FFA was supported by the Material Administration of the Armed Forces, Air Materiel Department (FMV-F:FL) under FFA internal project numbers AU-1441, AU-1827, AU-1959, AU-2020, and AU-2905

problem area, that is how a round leading edge and variation of Reynolds number influences the vortex start will very likely be further illuminated when the NASA Langley National Transonic Facility tests, also on a 65 deg delta wing with varying nose radius, Mach numbers and a large Re-range are carried out. The plan for these tests was described by J. Luckring in Paper 8 of Appendix 1. (It might in this connection be pointed out that for delta wings sharp leading edges or small nose radius is not a necessary condition for low supersonic drag.) It was also possible to attach a canard wing with a symmetrical circular arc profile of 5% thickness and 60 deg sweep angle. The wings were mounted on a body, mainly located on the lower side of the wing. A fourth delta wing with 55 deg sweep angle and a round leading edge was designed and tested. The 65 deg wing with the three different nose sections to be tested in the NLR HST and SST wind tunnels were designed and manufactured by AFWAL. A somewhat smaller (0.70 linear scale) but otherwise identical wing model, but only with a round leading edge to be tested in the 1m×1m Transonic Wind tunnel (TWG) of the DFVLR/ AVA, Göttingen, and in the 0.9×0.9 m transonic-supersonic Wind tunnel S4, FFA, was manufactured by MBB. The 55 deg wing, to be tested in the FFA S4 and in the TWG Wind tunnel was manufactured by FFA. A model with the same basic planform for early tests at TU Delft was also designed and manufactured for pilot testing, see Paper 3 in Appendix 1.

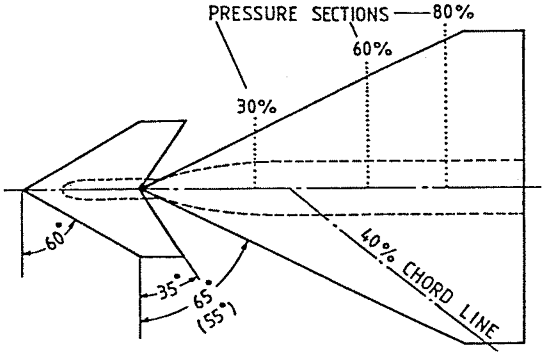

Fig. 2 Top view of the vortex flow models

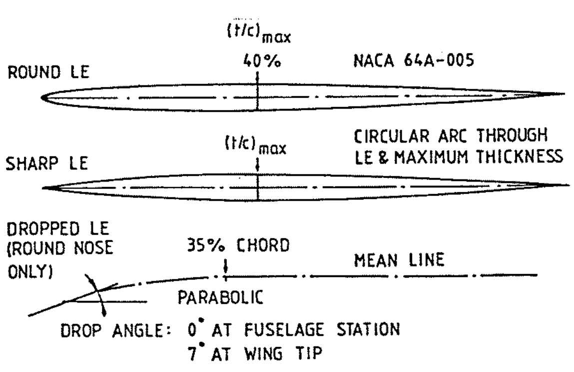

Fig. 3 Geometry of the three different airfoil sections

The final wing models are described in detail in Papers 2, 5, 6 and 7 of the Proceedings, see Appendix 1, and drawings of them are shown in Figures 2 and 3.

Figure 4 gives a clear view of the wing-body configuration. This figure is from Ref. 1 by A. Elsenaar et al.

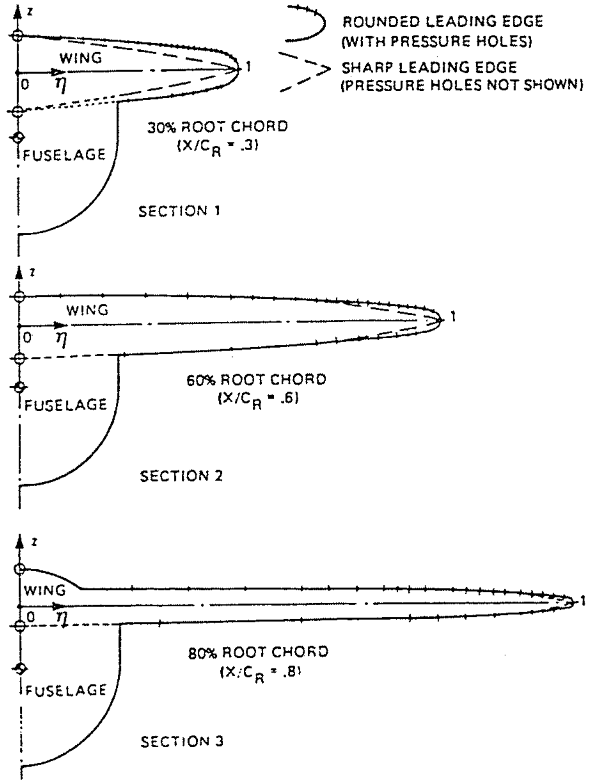

Fig. 4 Spanwise pressure sections of the 65 deg wing-body configuration

Test Programme

A fairly large test programme was agreed on and thus a very extensive data base is now available. It covers the Mach number range from M=0.4 to M=4 with angles of attack up to 25 degrees, and also variations in Reynolds number from about 2×10^6 to 13×10^6. For the higher supersonic values of M the Reynolds number was even higher. In Ref. 1, A. Elsenaar et al. give an extensive, rather detailed overview of the test programme. Some of the cases, for example M=0.85 and α=10 degrees for both round and sharp leading edges has been used as validation problems, which will be described in this lecture under Chapter III, "Some Experimental and Computed Results". It can already now be pointed out that a large part of the available data base is as yet unused both as validation cases and for aerodynamic analysis in general. So for instance there are no computations performed as regards the influence of the canard or the influence of yaw or, with some exceptions(1,3), the influence of body. The supersonic tests in the SST wind tunnel at NLR are also to a large extent not analysed. The same applies to the drooped leading edge wing. It is thus obvious that much of the well documented experimental results are awaiting further analysis.

They could be used in the first place, as was the original idea, for Euler code validations but also to explore, for instance, the limitations of potential flow calculations and for Navier-Stokes codes validation.

III. Some Experimental and Computed Results

In Paper No. 2 in Appendix 1, S.J. Boersen and A. Elsenaar, gave a fairly full description of the tests carried out in the transonic (HST) and supersonic (SST) wind tunnels of NLR on the 65 deg delta wing configurations. Some of the results and conclusions will be shown here. In Fig. 5 below, taken from their paper, examples of vortex formation at subsonic and transonic flow are given for the round leading edge wing. This vortex formation is one of the key problems, and we will come back to it later.

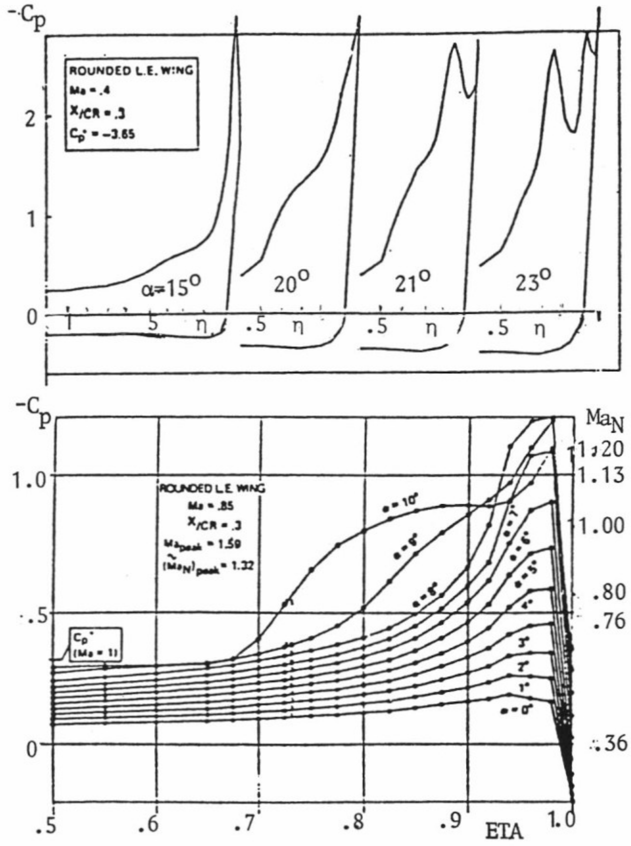

Fig. 5 Examples of vortex formation at subsonic and transonic flow for the normal leading edge

Figure 6 below shows the difference between the round and sharp leading edge wing as regards vortex formation and it is found that for the round leading edge the vortex starts downstream of the apex (the position depending on Mach number and angle of attack) whereas for the sharp leading edge the vortex forms along the whole span.

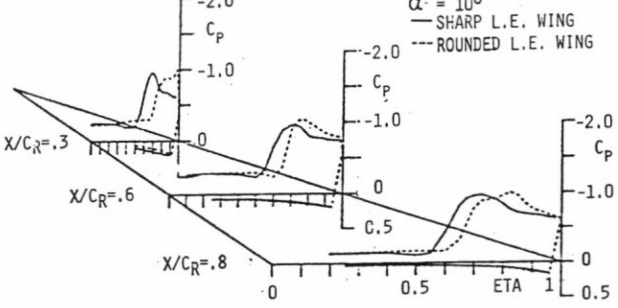

Fig. 6 Effect of leading edge shape on pressure distribution

In Fig. 7 the part span vortex formation at the round leading is clearly seen from the oil flow picture.

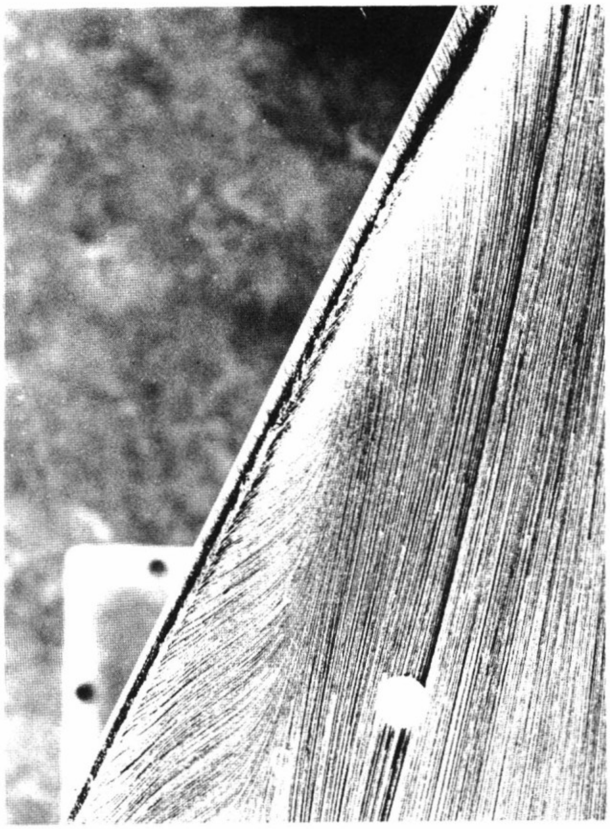

Fig. 7 Part span vortex formation

In the paper the formation of shock waves in the vortex flow field is discussed. This was also done early in the investigation by W.J. Bannick and E.M. Houtman from TU Delft (Paper No 3 in Appendix 1) and further in the paper(1) by Elsenaar et al. These shock waves play an important role for shock induced leading edge separation, see Figures 5 and 7 and also for vortex breakdown, as is sketched in Fig. 8, taken from(1). The effect of vortex breakdown on the rolling moment can be very dramatic, see again Ref. 1.

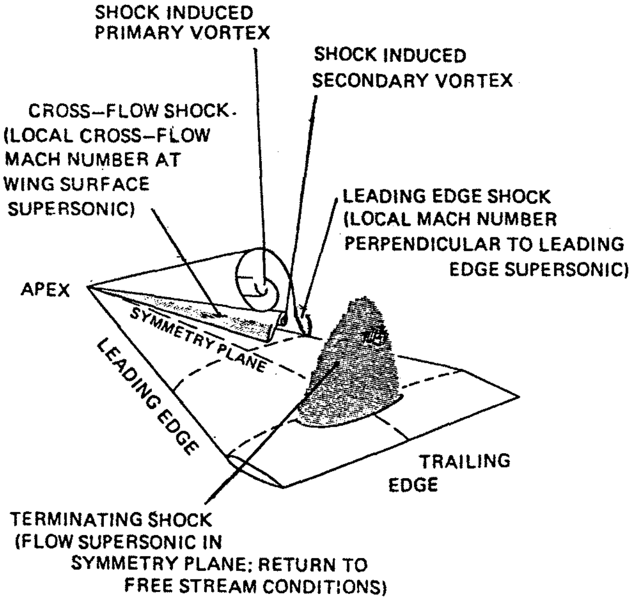

Fig. 8 Shock waves on a delta wing at transonic conditions

In Paper 14, Appendix 1, J.R. Sirbaugh from AFWAL makes an Euler code analysis using a modified Jameson Euler code.

Figure 9 is taken from Sirbaughs paper and shows as an example the surprisingly good agreement between computations and experiments for the global force coefficients in spite of the partly poor agreement for the surface pressures. The vortex breakdown is also quite well predicted. The same conclusion can also be reached from other later investigations such as in Ref. 2, where S.M. Hitzel and B. Wagner compare the NLR-HST experiment with Euler calculations including very fine mesh. With the finest mesh the agreement with experimental surface pressure distribution, however, is also fairly good. Of cource no secondary separation is found from the Euler code computations. One concludes that a viscous model is needed. This problem, the use of Navier-Stokes equations, is referred to later, but talking of viscous models, the interesting work in applying boundary layer computations by de Bruin and H. Hoeijmakers in Paper 10 in Appendix 1 should be mentioned.

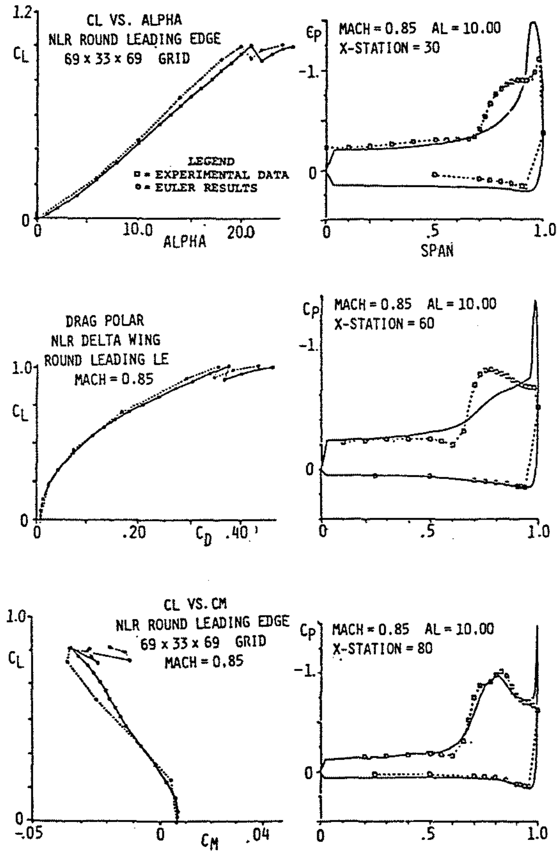

Fig 9 C_L-α curve. Drag polar, C_L-C_M curve and spanwise pressure distributions ($\alpha=10^{\circ}$) for round leading edge delta wing, M=0.85.

An important part of the experimental investigation has been the exploration of the vortex flow field above the wing. This has been carried out both in the FFA S4 Wind Tunnel and the DFVLR/AVA TWG. Detailed descriptions of the measuring technique can be found in Papers 6 and 7 of Appendix 1. At FFA a seven hole pressure probe was used to get the velocity vector field in the vortex and at TWG an LDA technique was used. As mentioned earlier both the 65 and 55 degree delta wings vortex flow field was explored and models were exchanged between the two institutes in order to check the two techniques. This turned out to be a valuable cooperation. In Fig. 10, from Ref. 1, two sets of test are compared and an impressive agreement was found. These results were very valuable for validating the Euler codes results in the vortex flow field. The Euler results show a vortex location which is somewhat more outboard compared to the experiments, which is due to the viscous secondary separation. In Fig. 11 from Ref. 4 the measured flow field, from Paper 7, Appendix 1, is compared with both Euler code and, FFA laminar Navier-Stokes code computations. The tests were performed at a rather low Reynolds number so at least part of the wing flow is probably laminar.

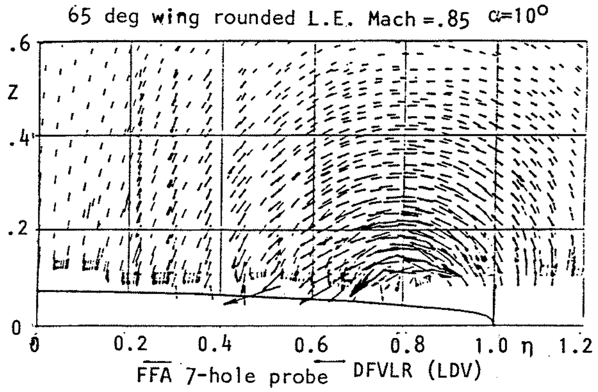

Fig. 10 Comparison of FFA (7-hole probe) and DFVLR (LDV) flow field measurements-cross flow velocities at $X/C_R=0.8$

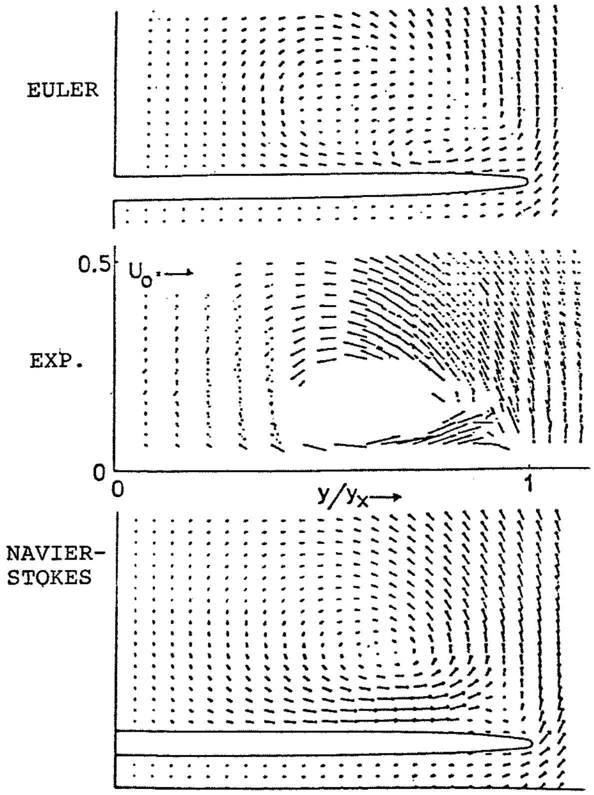

Fig. 11 The velocity vector in the spanwise plane x/c=0.80 as found from the Navier-Stokes and Euler computations and from laser measurements α=20 deg.

From the same paper, Ref 4, Fig. 12 is extracted. The improvement in agreement at α=20° by using the Navier-Stokes code instead of the Euler code is striking. In the same investigation the case for α=2° is also computed with the Navier-Stokes code, and in Fig. 13 the velocity vectors in a plane normal to the leading edge are shown. The interesting case of a reattaching laminar bubble appears, which for higher angles of attack will very likely turn into a separated vortex sheet. The pressure distribution curve shows the attachment line, the pressure minimum, a sign of separation, which of course cannot be found in the Euler code distribution, and finally reattachment.

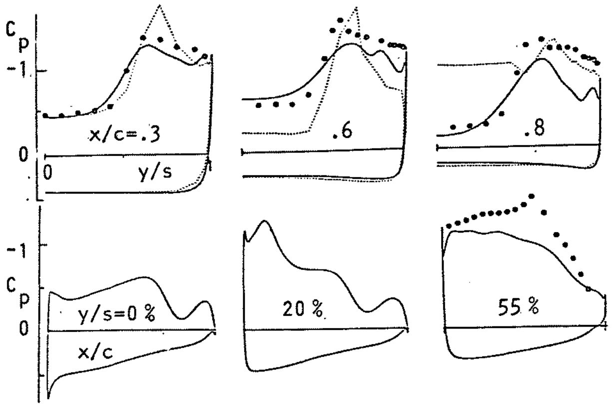

Fig. 12 Spanwise and chordwise plots comfparing Navier-Stokes and Euler solutions with experiments for α=20 deg.

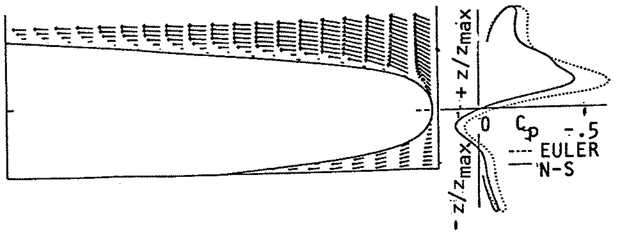

Fig. 13 Velocity vectors in the plane normal to the leading edge at x/c)0.7 and the distributions of C_p versus z/z_{max} of the Navier-Stokes and Euler solutions for α=2 deg

To the symposium in Stockholm were also invited representatives from some national research organisatives who did not take part in the cooperative effort. From this time, October 1986, the results were open and free to be published and the Proceedings were the first sign of this. On this occasion representatives from ONERA, RAE and NASA Langley were present. As mentioned earlier James Luckring from NASA Langley RC gave a very interesting presentation of "Selected Vortex-Lift Research at NASA Langley Research Center". An overview of the Symposium was given by Jeremy H.B. Smith, RAE, whose deep insight and vast experience of the subject made him most appropriate to do so. Has main conclusions, however, which came as no surprise to many of the participants was that the agreement between Euler code calculations and experiments in many cases, for the round leading edge, was not too good as regards the surface pressure distributions. This points no doubt towards the necessity for using a viscous flow model, that is the Navier-Stokes equations. However, the Euler code computations give quite good results for the global forces as pointed out by J. Sirbaugh, AFWAL, which might be of interest for engineering purposes at least. This was also stressed by the MBB and SAAB-SCANIA representatives.

After the Stocholm meeting the results from this cooperations have been used and analyzed at many meetings. So, for instance, at an IUTAM Symposium "Fundamental Aspects of Vortex Motion", 31 August to 4 September 1987 in Tokyo, Japan, "Detailed measurements in the transonic vortical flow over a delta wing" were reported and analyzed by H. Hornung, DFVLR, Göttingen and A. Elsenaar, NLR, Amsterdam, see Ref. 5.

At the IUTAM Symposium Transonicum III in May 24-27, 1988 at DFVLR-AVA, Göttingen there was a session on "Vortical Flows" in which much of the results from the "International Vortex Flow Experiment" were reported and discussed, see among others Ref. 2, 4, and 6. In a AIAA Paper(7) 88-2518 "Wing Vortex-Flows Up Into Vortex-Breakdown. A Numerical Simulation", S.M. Hitzel of Dornier, discusses the vortex breakdown, shock waves under transonic conditions and also the effect of mesh sizes and topologies, and in a paper(8) at the AGARD Lisbon Symposium, M.A. Schmatz et al. treat some problems which have bearing on the Vortex Flow 65 degree delta wing. The same applies to another paper(9) at the same symposium by B. Wagner et al.

Concluding remarks

The main aim of this international cooperation, that is validation of Euler codes from experiments turned out to be more difficult to reach than perhaps was expected. Much more further research concerning the numerical problems such as the relation between vorticity generation and discretisation and related questions is needed.

As regards the cooperation itself this must be said to have been quite successful and, to come back to Jeremy Smith's overview at the Stockholm Symposium, the momentum generated from the results of the cooperation is certainly not lost and also a valuable data base is available.

Acknowledgements

For very valuable advice and discussions when I prepared this ICAS VON KARMAN LECTURE I am most grateful to Bram Elsenaar and Hans Hornung.

To Eva Eriksson who made those figures I could not steal directly from the published papers and last but not least to Inez Engström who did all the typing and much of the editing I want to convey my sincere thanks.

References

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2 Hitzel, S.M., and Wagner, B., Dornier GmbH: "Computations relating to the Vortex Flow Experiment". IUTAM Symposium Transsonicum III, May 24-29, 1988, DFVLR-AVA, Göttingen

3 Berglind, T., Drougge, G., and Eliasson, P. FFA: "The influence of the leading edge geometry on the wave drag for a 65° delta wing at low supersonic speed and small angles of attack". FFA Report 141, 1988.

4 Rizzi, A., Drougge, G., FFA, and Müller, B., DFVLR-AVA: "Navier-Stokes and Euler solutions for vortex flow over a delta wing". IUTAM Symposium Transsonicum III, Göttingen, May 24-27, 1988.

5 Hornung, H., DFVLR, and Elsenaar, A., NLR: "Detailed measurements in the transonic vortical flow over a delta wing". IUTAM Symposium, Tokyo, Aug 1987.

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7 Hitzel, S.M., Dornier GmbH: "Wing Vortex-Flow Up Into Vortex-Breakdown". AIAA 88-2518, 1988.

8 Schmatz, M.A., Brenneis, A., and Eberle, A., MBB: "Verification of an Implicit Relaxation Method for Steady and Unsteady Viscous and Inviscid Flow Problems". AGARD FDP. Symposium on Validation of Computational Fluid Dynamics, 2-5 May 1988, , Lisbon, Portugal.

9 Wagner, B., Hitzel, S.M., DORNIER GmbH, Schmatz, M.A., Schwarz, W., MBB-UF, and Hilgenstock, A., Scherr, S., DFVLR: "Status of CFD Validation on the Vortex Flow Experiment". AGARD FDP. Symposium on Validation of Computational Fluid Dynamics, 2-5 May 1988, Lisbon, Portugal.

APPENDIX 1

Table of contents from the Proceedings of the Symposium on International Vortex Flow Experiment on Euler Code Validation, October 1-3, 1986, Stockholm, Sweden

Paper
No.

1 How it All Started: The International Vortex Flow Experiment on Euler Code Validation in Retrospect -
A. ELSENAAR

2 Tests on the AFWAL 65° Delta Wing at NLR: A Study of Vortex Flow Development between Mach=.4 and 4 -
S.J. BOERSEN and A. ELSENAAR

3 Experiments on the Transonic Flow over a Delta Wing at High Angles of Attack -
W.J. BANNINK and E.M. HOUTMAN

4 Vortex Interference Effects on Close-Coupled Canard Configurations in Incompressible Flow -
D. HUMMEL and H.-CHR. OELXER

5 Force and Pressure Measurements Including Surface Flow Visualizations on a Cropped Delta Wing -
K. HARTMANN

6 Test on a 55° and 65° Delta wing -
L. HJELMBERG

7 Flow Field Study on a 65° Delta wing -
K.A. BÜTEFISCH, D. PALLEK and J. REICHMUTH

8 Selected Vortex-Lift Research at NASA Langley Research Center -
J.M. LUCKRING

9 The Mechanism of Vorticity Creation in Euler Solutions for Lifting Wings -
E.H. HIRSCHEL and A. RIZZI

10 Computation of the Three-Dimensional Boundary Layer Transition and Deparation on a 65 Deg Swept Delta Wing at 20 Deg Angle of Attack -
A.C. De BRUIN and H.W.M. HOEIJMAKERS

11 Numerical Solution of Flow Fields Around Delta Wings Using Euler Equation Method, Part I: The Validation of the Euler Code -
A. KUMAR and A. DAS

12 Numerical Solution of Flow Fields Around Delta Wings Using Euler Equation Method, Part II: Analysis of the Results and Comparison with Experiments -
A. DAS and A. KUMAR

13 On the Swelling and Break Down of Rolled Up Vortex Sheets in Inviscid Flows Around Slender Delta Wings -
A. DAS

14 Euler Analysis of the AFWAL 65° Delta Wing -
J.R. SIRBAUGH

15 A Note on the Influence of the Leading Edge Geometry of the Three Euler Wings at Small Angles of Attack -
G. DROUGGE

16 Navier-Stokes Simulation of Laminar Flow over the 65 Deg Round Leading Edge Delta Wing at $M_\infty=0.85$ and $\alpha=10$ Deg -
B. MÜLLER and A. RIZZI

17 Euler-Simulation of the Vortex-Flow-Experiment. A Critical Consideration -
S.M. HITZEL, B. WAGNER and S. LEICHER

18 Euler-Simulation of Shed Vortex Flows over the 65 Deg Delta Wings -
A. RIZZI, G. DROUGGE and C.J. PURCELL

19 Some Aspects on the Use of Euler Codes in Vortex Flow Computations -
B. ARLINGER and L. ELMELAND

20 Overwiev of the Symposium -
J.H.B. SMITH

APPENDIX 2

List of participants:

AFWAL
K. Richey
T. Buter
J.R. Sirbaugh

T U BRAUNSCHWEIG
D. Hummel
H.Chr. Oelker

T U Delft
W.J. Bannink
E.M Houtman
J. Möller
P. Bakker

DFVLR (Göttingen)
H. Hornung
K. Hartman
K.A. Bütefish
D. Pallek
K.H. Sauerland
K. Pszolla
J. Reichmuth

DFVLR (Braunschweig)
A. Das
A. Kumar

FFA
G. Drougge
G. Eriksson
L. Hjelmberg
A. Rizzi
H. Sörensén

DORNIER GmbH
B. Wagner
S.M. Hitzel
S. Leicher

NLR
A. Elsenaar
S.J. Boersen
R. Hirdes
A.C.de Bruin
H.W.M Hoeijmakers
P.L. Amerom

MBB GmbH
P. Sacher
E.H. Hirschel
W. Staudacher