The Second International Vortex Flow Experiment (VFE-2) Objectives and First Results

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Abstract

This paper presents the objectives for the new International Vortex Flow Experiment (VFE-2), and its organization within an RTO Task Group is outlined. The available wind tunnel models as well as the applied experimental techniques are described briefly. Results of PSP measurements at DLR Goettingen showed a first insight into the flow mechanisms. Additional CFD results from numerical solutions of the RANS equations as calculated by EADS Munich lead to an initial understanding of the flow details and allowed a proper wind tunnel set up for the following PIV experiments at DLR Goettingen. These measurements showed the details of the flow field in the vicinity of the wing in excellent agreement with the CFD results.

Keywords: *CFD, Delta wing, Leading edges rounded, Leading edges sharp, PIV, PSP*

1.Introduction

At the beginning of the 1980’s the status of the Euler methods for the calculation of vortical flows had reached such a high standard that good experimental data were necessary to validate the various codes. This lead to the First International Vortex Flow Experiment (VFE-1) [1], which has been carried out in 1984 – 1986. On a cropped delta wing with a leading edge sweep of 65° combined with a fuselage, see **Fig. 1**, force and pressure

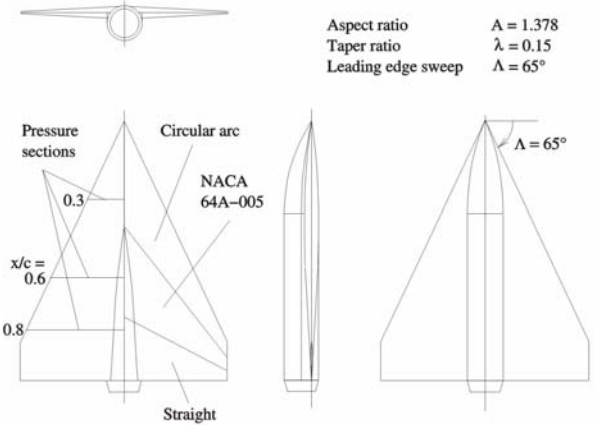

Fig. 1: Configuration of the First International Vortex Flow Experiment (VFE-1)

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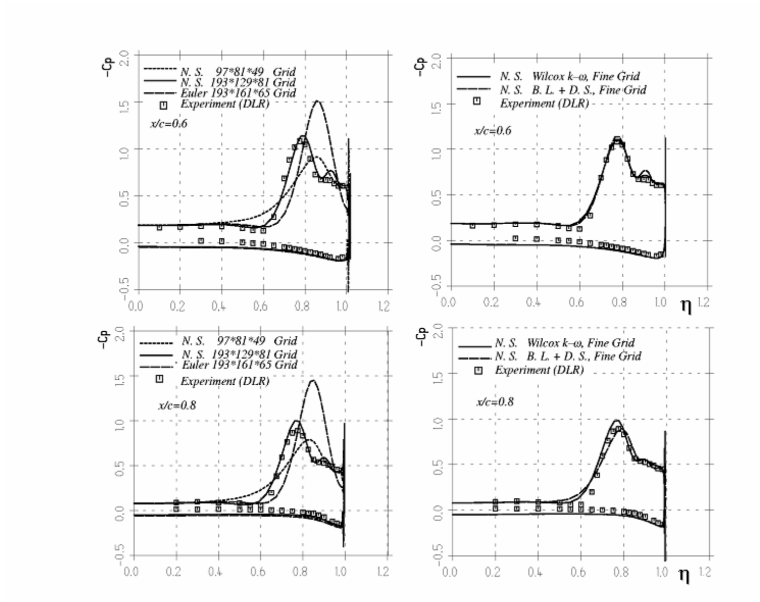

Fig. 2: Surface pressure distributions on the wing (only) of the VFE-1 configuration at M = 0.4, $R_{mac} = 3.1 \cdot 10^6$, $\alpha = 9°$. Effects of grid resolution and turbulence modelling. FLOWer code results according to W. Fritz, EADS Munich.

distribution measurements as well as flow field studies have been carried out for a certain variety of flow conditions in various wind tunnels worldwide. The results have been summarized in [2], and later the state of the art has been reviewed in [3], [4]. Even for sharp leading edges with fixed primary separation the Euler codes were not well suited to calculate the pressure distribution on a slender wing properly, see **Fig. 2**, since the secondary separation is not modelled at all.

In the last fifteen years considerable progress has been achieved in the numerical calculation of vortical flows by taking into account viscous effects through solutions of the RANS equations. This means that Reynolds number effects are now included and secondary vortices turn out. For turbulent flows in solutions of the RANS equations a turbulence model is necessary, which has to cover the attached boundary layers and the secondary

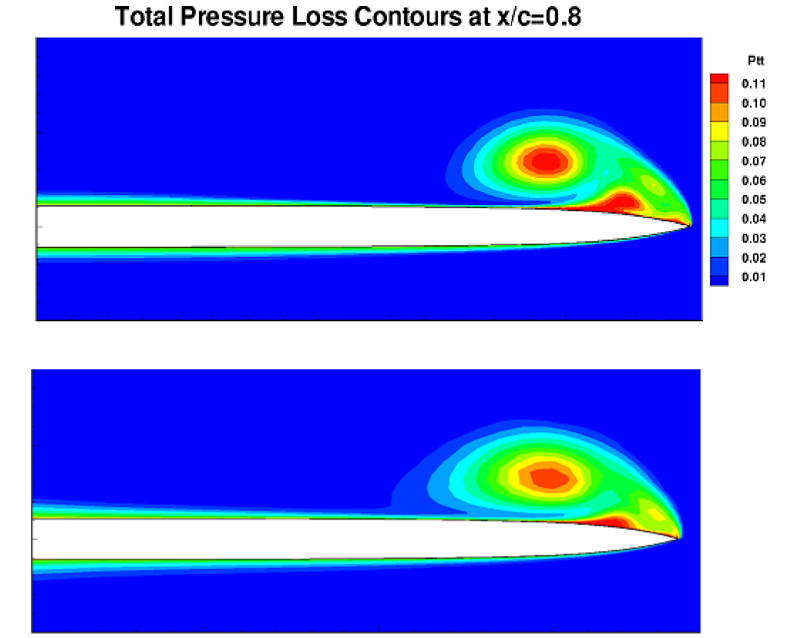

Fig. 3: Total pressure loss contours in section x/c = 0.8 on the wing of the VFE-1 configuration at M = 0.4, $R_{mac} = 3.1 \cdot 10^6$, $\alpha = 9°$. FLOWer code results using the Baldwin-Lomax (top) and the Wilcox k – ω (bottom) turbulence model according to W. Fritz, EADS Munich

vortex area properly. The pressure distribution on the upper surface of the wing is very sensitive to correct modelling of the viscous regions of the flowfield as shown in Fig. 2. If the grid resolution is fine enough reasonable pressure distributions turn out, but according to **Fig 3** large differences concerning the total pressure loss distribution are present in the flowfield for different turbulence models**.**

In order to validate the results of Navier-Stokes calculations new and more detailed experimental data are necessary, and therefore a Second International Vortex Flow Experiment (VFE-2) has been proposed [5], which will be described subsequently.

2. The Second International Vortex Flow Experiment (VFE-2)

2.1 Test configuration

The configuration for VFE-2 has been chosen in such a way that the flow regimes

i) Attached flow without vortex formation $0° \leq \alpha \leq 4°$
ii) Separated vortical flow without vortex breakdown $4° \leq \alpha \leq 20°$
iii) Separated vortical flow with vortex breakdown $20° \leq \alpha \leq 40°$
iv) Separated deadwater-type flow $40° \leq \alpha \leq 90°$

are covered properly, and this lead to a delta wing with a leading edge sweep of 65°. Concerning the thickness distribution a flat plate inner portion in combination with interchangeable leading edges was desired, and these requirements were fulfilled by the NASA configuration [6], which is shown in **Fig. 4**. Sets of one sharp and three rounded leading edges are available. The geometry of the wing as well as the shape of the sting are given by analytical expressions described in all details in [6]. Thus new wind tunnel models can be built quite easily.

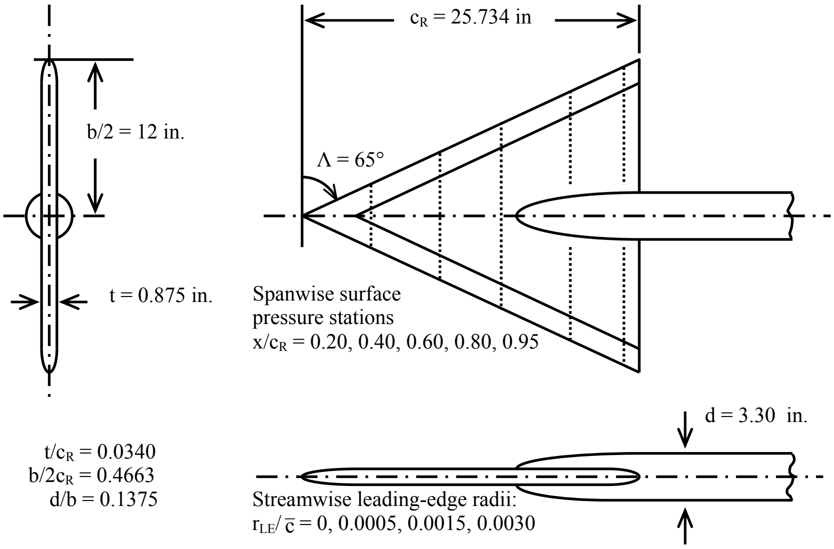

Fig. 4: VFE-2 configuration: NASA NTF delta wing A = 1.85, Λ= 65° [6]

For this configuration comprehensive measurements of lift and pitching moment as well as of pressure distributions in the sections according to Fig. 4 have already been carried out in the National Transonic Facility (NTF) at NASA, see **Fig. 5**, for a large variety of Mach numbers and Reynolds numbers [6], [7].

2.2 Objectives for new tests

For delta wings with sharp leading edges and fixed primary separation a large number of experimental investigations are available in the literature. Therefore within VFE-2 the case of sharp leading edges is used as reference only and the main emphasis is directed towards studies of the vortex formation on the configuration with rounded leading edges. In the first place drag data should be added to the existing balance measurements in

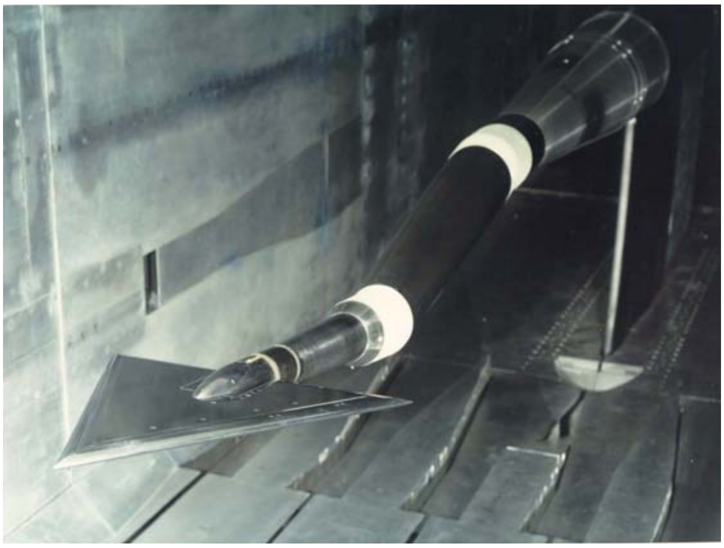

Fig. 5: NASA NTF tests on the 65° delta wing

order to provide the full three-component data set. In the second place the objectives for new experiments were

- Investigations on the laminar/turbulent transition on delta wings.
- Detailed pressure distribution measurements, especially in the region of the onset of flow separations for configurations with rounded leading edges.
- Boundary layer measurements including distributions of the components of velocity and vorticity, of turbulent energy and eddy viscosity.
- Determination of the wall shear stress and detection of the secondary and tertiary separation lines.
- Flow field measurements in the primary and secondary vortices including the distributions of the components of velocity and vorticity, of turbulent energy and eddy viscosity.
- Investigations on the vortex breakdown flow field for delta wings with sharp and rounded leading edges including the surface pressure fluctuations caused by the spiral mode of vortex breakdown.

Concerning the free stream flow conditions, i.e. Mach number and Reynolds number, only some of the new measurements will be closely related to the NTF matrix of NASA [6], whereas most of the new measurements will be carried out for incompressible flows. For this flow regime again results of NASA investigations in the Low Turbulence Pressure Tunnel (LTPT) at Langley RC on a second smaller wind tunnel model do already exist. They are unpublished up to now and their evaluation is part of the American contribution to VFE-2.

Another huge matrix of possible investigations is given by the available four leading edge shapes and by the large variety of angles of attack, which lead to various flow regimes. The new measurements will mainly concentrate on one rounded leading edge shape compared with the sharp leading edge configuration. Three angles of attack, corresponding to three different flow regimes, will be studied in detail. These are

- Onset of vortical flow, $\alpha = 13°$
    - Sharp leading edge: Separated flow
    - Medium radius leading edge: Partly attached, partly separated flow
- Separated flow without vortex breakdown, $\alpha \approx 20°$
    - Sharp leading edge
    - Medium radius leading edge
- Separated flow with vortex breakdown, $\alpha \approx 25°$
    - Sharp leading edge
    - Medium radius leading edge

From the very beginning of VFE-2 the experimental investigations have been accompanied by CFD calculations for the relatively simple delta wing configuration including the sting. The aims for these investigations were

- Validation and improvement ot the existing CFD codes by means of comparisons with the new experimental results.
- Code to code comparisons through calculations on common unstructured and structured grids.
- Assistance related to the set up, the performance and the evaluation of the new wind tunnel experiments.

2.3 Organization

The new International Vortex Flow Experiment VFE-2 is presently carried out within the framework of an RTO Task Group of the Applied Vehicle Technology (AVT) Panel

Task Group AVT-113: Understanding and Modelling Vortical Flows to Improve the
Technology Readiness Level for Military Aircraft.

Co-chairmen are Dr. John E. Lamar, NASA Langley RC, US, and Prof. Dr. Dietrich Hummel, TU Braunschweig, Germany. The Task Group consists of two facets

- **F-16XL facet (Cranked Arrow Wing Aerodynamics Project International, CAWAPI)**
  This group performs numerical calculations for the complete aircraft F-16XL and compares the results with already existing flight test data for various angles of attack and Mach numbers at full scale Reynolds numbers.
- **65° Delta Wing facet (International Vortex Flow Experiment 2, VFE-2)**
  This group performs new wind tunnel experiments in order to understand the vortical flow and uses their experimental results to validate existing CFD codes.

Between both facets a close cooperation takes place, since almost all participants of the F-16XL facet validate their CFD codes also for the more simple VFE-2 configuration. For communication among each other, within each facet a Virtual Laboratory (VL) is used, which allows to upload and download surface geometries, grids, experimental data, numerical results, etc. [8], [9].

The AVT-113 Task Group has been prepared after the AVT Symposium on “Vortex Flow and High Angle of Attack”, held in Loen, Norway, 7 – 11 May 2001, see [5], and it came into operation in spring 2003.

2.4 Program of Work

After one year of activity the program of work (POW) for AVT-113 has been fixed in spring 2004. The key issues for the VFE-2 facet may be summarized as follows:

- The NASA results for the NTF and the LTPT investigations will be made available through the Virtual Laboratory. NASA Langley RC has placed their smaller LTPT wind tunnel model at disposal for tests in other wind tunnels worldwide. A loan agreement has been signed for the transfer of the model to Germany (DLR, Goettingen), and further loan agreements, e.g. with France (ONERA, Lille, Dr. O. Rodriguez), are still open (Dr. J. Luckring).

- The NASA wind tunnel model has been transferred to Germany. A new sting for use in European wind tunnels has been produced. The model was tested in the Transonic Wind Tunnel Goettingen (TWG) in July/August 2004 (PSP measurements) and in April 2005 (PIV measurements), (Dr. R. Konrath).

- A new (second) wind tunnel model has been built at TU Munich (Germany). It will be used to perform hot-wire measurements in the boundary layers and in the vortical flow field in the low speed wind tunnels of Institute for Fluid Mechanics, TU Munich. These investigation are presently in progress, (Dr. Ch. Breitsamter).

- A third wind tunnel model has been designed and manufactured at University of Glasgow (UK). The model is aimed at new steady and unsteady balance and pressure distribution measurements as well as for PIV investigations. The measurements are presently in progress, (Prof. F. Coton).

- A fourth and a fifth wind tunnel model (with sharp and rounded leading edge respectively) have been built at ONERA in order to cover the delay in the set-up of the NASA-ONERA loan agreement. Balance measurements have already been carried out, but for the PIV studies at large angles of attack the NASA wind tunnel model is expected to become available, (Dr. O. Rodriguez).

- For the numerical calculations within VFE-2 the common grids for the sharp and the medium radius leading edge configuration are in progress
    - The structured common grids for the configuration with sharp and medium radius rounded leading edges have been provided by EADS Germany, (W. Fritz).
    - The unstructured common grids are in progress through activities at NASA Langley RC (Dr. S. Pirzadeh) with contributions by USAFA Colorado (Prof. S. Morton) and KTH Stockholm (Prof. A. Rizzi).

- Numerical calculations for the VFE-2 configuration have been carried out by
    - EADS Munich GE (W. Fritz)
    - KTH Stockholm SE (Prof. A. Rizzi et al.)
    - NLR Amsterdam NL (O. Boelens, Dr. F. J. Brandsma)
    - ONERA Lille FR (Dr. F. LeRoy)
    - University of Glasgow UK (Dr. K. Badcock et al.)
    - USAFA Colorado US (Prof. R. Cummings)
- and future contributions are expected from
    - Qinetiq UK (Dr. M. Arthur)

From the two wind tunnel entries of the American wind tunnel model in the Transonic Wind Tunnel Goettingen, Germany, as well as from the corresponding numerical calculations at EADS Munich, Germany, first results are available. They will be described subsequently.

3. First results of VFE-2

3.1 PSP results from DLR Goettingen

The first entry of the American LTPT wind tunnel model in the Transonic Wind Tunnel Goettingen, Germany, took place in August 2004. In these tests the PSP team of DLR (R. Engler, Ch. Klein, R. Konrath) performed PSI as well as PSP investigations for the configurations with sharp and with medium radius rounded leading edges. The main emphasis in theses experiments was concentrated on the vortex formation at the configuration with rounded leading edges. At moderate angles of attack the earlier NTF tests [6] had shown sectional pressure distributions with two suction peaks on each side of the configuration, and this kind of pressure distributions has never been observed for wings with sharp leading edges. The very first results of the PSP measurements have been discussed at the RTO AVT meeting in autumn 2004 in Prague, and the corresponding paper [10] summarizes the understanding of the vortex formation at that time.

The experimental pressure distribution on the VFE-2 configuration with medium radius rounded leading edges at Mach number $M = 0.4$ and Reynolds number (based on the mean aerodynamic chord) $R_{mac} = 3$ Mio. at an angle of attack $\alpha = 13°$ is shown in **Fig. 6**. On the left-hand side the pressure distributions according to the PSI measurements for the model sections with pressure tabs are shown. They coincide nicely with the earlier NTF tests [6]. In the region of attached flow near the apex of the wing high suction occurs at the leading edge. Further downstream an inner suction peak develops followed by an even higher outer suction peak, which replaces the original leading edge suction. Towards the trailing edge of the wing the outer suction peak is still maintained, whereas the inner suchtion peak reduces more and more and finally dissappears. The PSP results on the right-hand side show these features in the same way.

The full view of the pressure distribution on the configuration is given in the coloured figure in the centre of Fig. 6. It shows on both sides the origin of the strong outer suction peak to be located at about $x/c_R = 0.45$ and

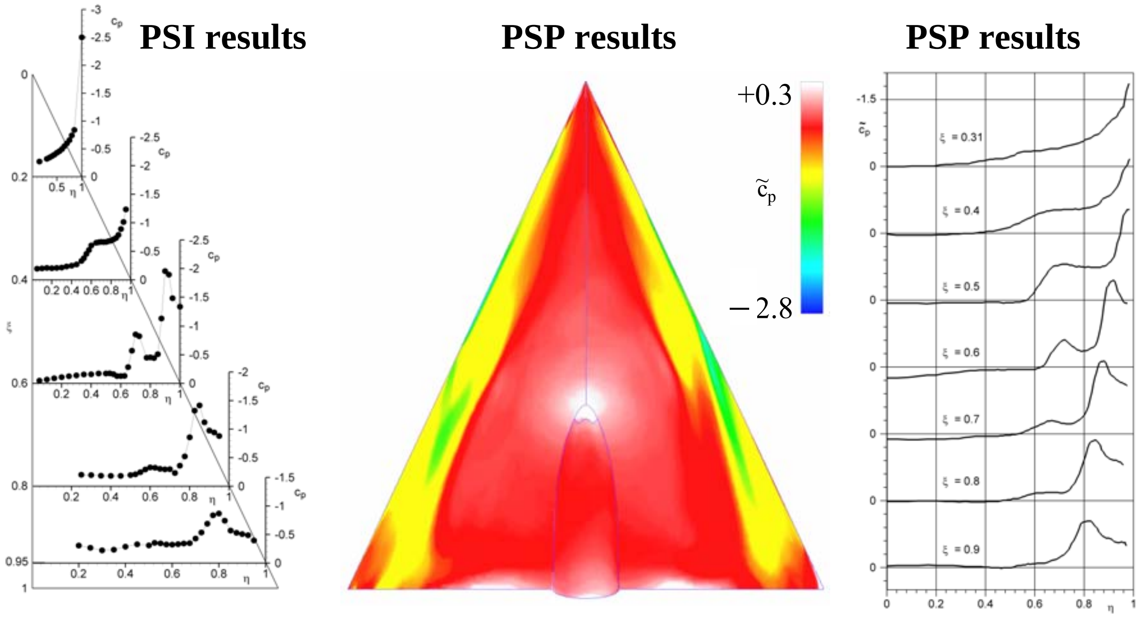

Fig. 6: Experimental pressure distribution on the VFE-2 configuration (65° delta wing, A = 1.85) with rounded leading edges (medium radius) for M = 0.4, $R_{mac} = 3 \cdot 10^6$, $\alpha = 13°$. First results from DLR Goettingen. ($\tilde{c}_p$ preliminary pressure coefficients without PSP offset correction)

undoubtedly this suction peak is related to the primary vortex of the separated flow. The inner suction peak, however, could not be understood so easily. It starts earlier than the outer suction peak and the shape of its initial pressure distributions resembled those of a separation bubble related to the transition from laminar to turbulent flow. After the formation of the primary vortex the inner suction peak reduces more and more in downstream direction. On the right-hand side it remains separate from the primary vortex, but on the left-hand side it merges into the suction area of the primary vortex. These unsymmetries are thought to be the results of imperfections of the model geometry and corresponding investigations on details of the model shape are carried out presently by DLR Goettingen.

At this stage of the investigations the inner suction peak in the pressure distribution was thought to be the outcome of boundary layer effects resulting from a 3D bubble-type laminar/turbulent transition at about x/c_R = 0.3. These effects could be sensitive to disturbances and to model imperfections. At about x/c_R = 0.5 a small inner vortex might have been formed, whose path downstream could be either separate or merged with the main primary vortex. Concerning the planned PIV experiments in the second Transonic Wind Tunnel entry in Goettingen the development of a tiny inner vortex resulting from a transitional boundary layer was expected, and concerning a numerical calculation of such a flow field there was no hope for success in the near future.

3.2 CFD results from EADS Munich

In December 2004 W. Fritz at EADS Munich started numerical calculations using the German code FLOWer.The RANS equations have been solved on a structured conical CO grid. Studies on the effects of the grid size (2 - 10 Mio nodes per half space), of the turbulence model without and with fixed transition on a conical line on the upper surface close to the leading edge have been carried out. Although considerable sensitivities with respect to these parameters do exist, remarkable results have been obtained. **Fig. 7** shows the calculated pressure distribution for the same flow conditions as given in Fig. 6 for the PSP measurements. The main features of the measured pressure distribution are predicted correctly: Following the attached flow region in the front part of the wing an inner suction peak turns out and in the rear part of the wing the strong outer vortex is indicated clearly. Towards the trailing edge the inner suction peak reduces in magnitude and it remains separate from the outer suction peak of the primary vortex.

More details of the calculated flow field may be taken from **Fig. 8**. It shows the calculated flow field with total pressure loss contours in cross-sections x/c_R = const. On both sides of the wing two vortices with the same sense

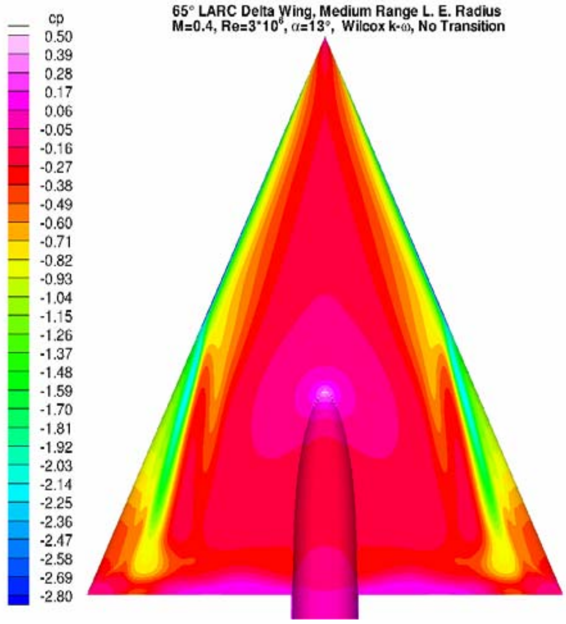

Fig. 7: Numerical pressure distribution on the VFE-2 configuration (65° delta wing, A = 1.85) with rounded leading edges (medium radius) for M = 0.4, $R_{mac} = 3 \cdot 10^6$, $\alpha = 13°$. First results from EADS Munich by means of the FLOWER code and the k-ω turbulence model

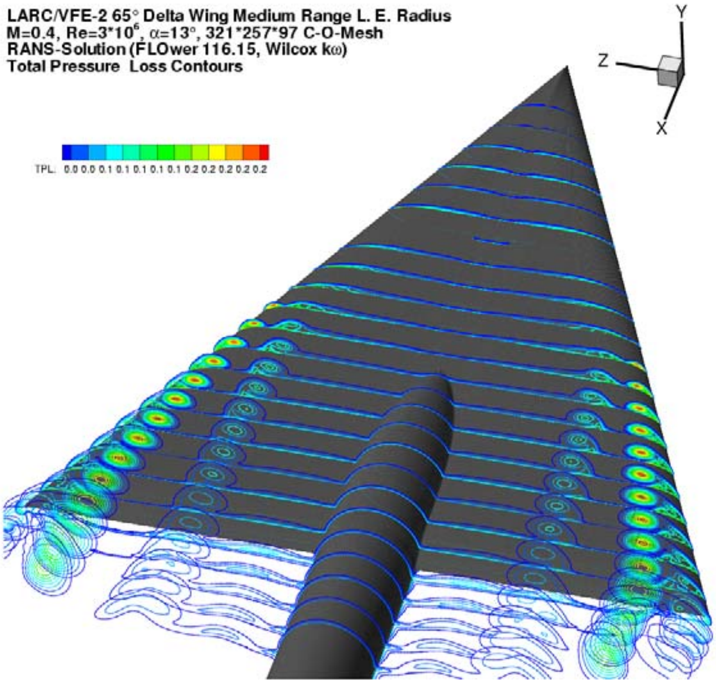

Fig. 8: Total pressure loss contours in the calculated flow field around the VFE-2 configuration (65° delta wing, A = 1.85) with rounded leading edges (medium radius) for M = 0.4, $R_{mac} = 3 \cdot 10^6$, $\alpha = 13°$. First results from EADS Munich by means of the FLOWer code and the k-ω turbulence model

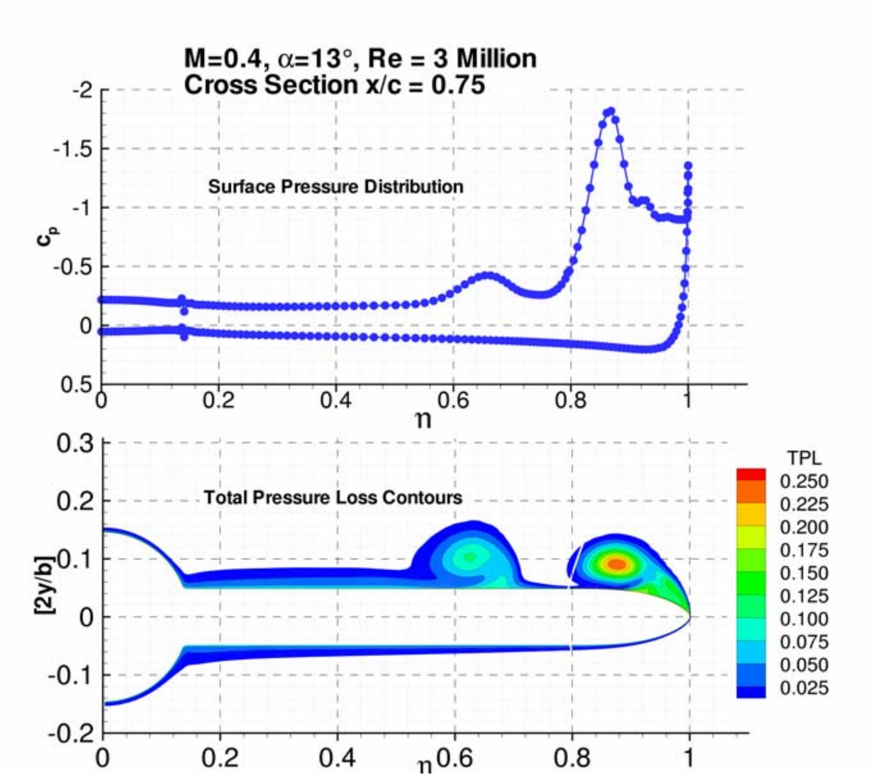

Fig. 9: Numerical pressure distribution and vortex pattern, described by total pressure loss contours, in the cross section at $x/c_R = 0.75$ for the the VFE-2 configuration (65 ° delta wing, A = 1.85) with rounded leading edges (medium radius) for M = 0.4, $R_{mac} = 3 \cdot 10^6$, $\alpha = 13°$. First results from EADS Munich by means of the FLOWER code and the k-ω turbulence model

of rotation are present. The outer primary vortex starts at about mid chord and it is accompanied by a secondary vortex. The inner vortex obviously starts earlier from a boundary layer separation. Surprisingly at the onset of the outer primary vortex the inner vortex has reached already a considerable size. More downstream the whole vorticity is shed into the strong outer primary vortex. On the other hand the inner vortex is no longer fed with vorticity. Therefore its strength reduces more and more due to viscous effects. This means that after the formation of the outer primary vortex the inner vortex decays.

In order to demonstrate the size of the innner vortex in relation to the outer vortex, the flow field in the cross-section at $x/c_R = 0.75$ is analyzed in **Fig. 9**. The total pressure loss contours show the upper and lower surface boundary layers as well as two vortices of about the same size and with the same sense of rotation. The outer primary vortex is the stronger one as indicated by the higher total pressure losses there. The outer primary vortex is accompanied by a secondary vortex, and the shape of the total pressure loss contours of the inner vortex leads to the conclusion that this is also the case for the inner vortex. The surface pressure distribution shows the signatures of both vortices as well as the additional suction caused by the secondary vortex underneath the outer primary vortex.

3.3 PIV results from DLR Goettingen

The results of the numerical calculations became available in March 2005 just in good time prior to the second entry of the American LTPT model in the Transonic Wind Tunnel Goettingen. The technical equipment for the envisaged PIV investigations could be chosen in order to measure a well developped inner vortex rather than a tiny boundary layer structure. The PIV measurements by the PIV team of DLR (J. Kompenhans, R. Konrath, A. Schroeder) took place in April 2005 in the Transonic Wind Tunnel Goettingen.

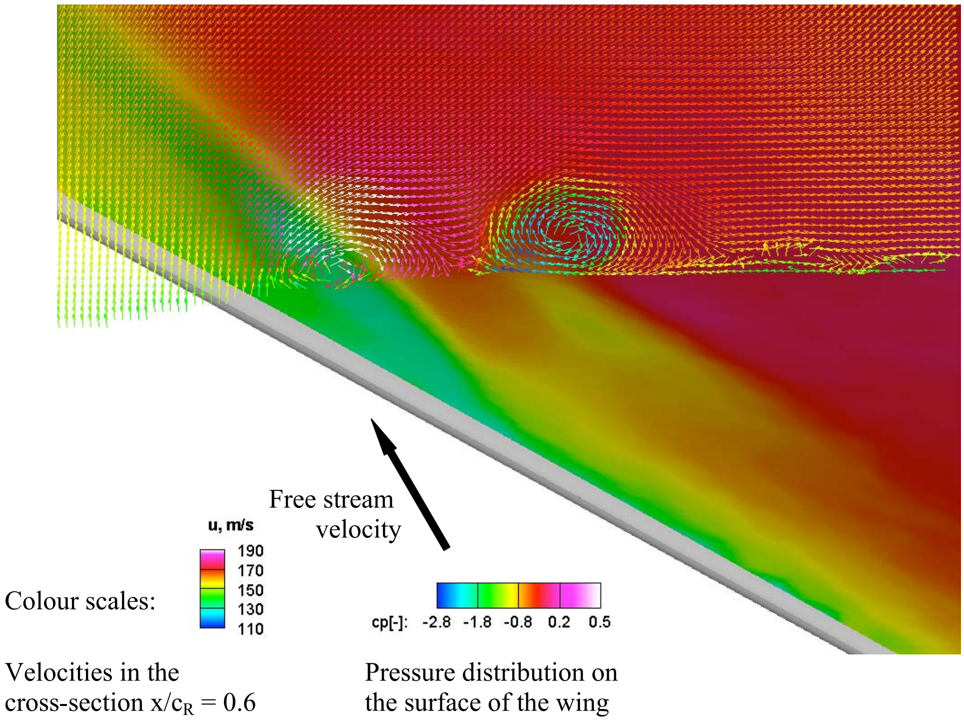

Fig. 10: Measured velocity distribution in the flow field around the VFE-2 configuration (65° delta wing, A = 1.85) with rounded leading edges (medium radius) for $M = 0.4$, $R_{mac} = 3 \cdot 10^6$, $\alpha = 13°$. Preliminary PIV results and comparison with PSP results from DLR Goettingen

The 3D investigations have been carried out using two light sheets perpendicular to each other and each of them inclined against the model centre line at an angle of 45°. **Fig. 10** shows the result for the cross-sectional plane at $x/c_R = 0.6$ for the same free stream conditions as in Figs. 6 to 9. The view in Fig. 10 is directed downstream indicated by the free stream velocity vector. The surface pressure dictribution from the PSP investigations, see Fig. 6, is displayed in colours for the right half of the wing. The outer suction peak underneath the primary vortex is marked by the green area and the one underneath the inner vortex can be identified by a yellow band. Due to the position of the light source in the wind tunnel there exists a certain region in the vicinity of the leading edge, which was not illuminated, and therefore no velocity measurements are available for this region. The two vortices with the same sense of rotation are clearly indicated in the section at $x/c_R = 0.6$. In the section under consideration the size of both vortices is about the same as predicted by the CFD results. More downstream the outer vortex becomes the stronger one, whereas the inner vortex decays.

4. Cooperation between Experiments and CFD in VFE-2

From the very beginning of the Second International Vortex Flow Experiment (VFE-2) experimental and CFD teams worked closely together. Up to now this cooperation was extremely useful in order to analyse the vortex formation for the VFE-2 configuration with rounded leading edges at a small angle of attack as demonstrated in the previous section 3. The combination of both ways of investigating flows led to a synthesis and to a proper understanding of the flow phenomena.

Concerning the vortex formation on the configuration with rounded leading edges new problems have been identified in pursuance of the new results, and the corresponding questions should be answered within VFE-2. One of those is related to the onset of the vortex formation. Obviously the initial flow separation causes the inner vortex. Is this vortex an inner primary vortex? More downstream a second flow separation takes place close to the rounded leading edge, and this leads to the strong outer vortex, which is normally denoted as the (outer) primary vortex. The occurrence of two vortices on each side having the same sense of rotation is a new phenomenon for delta wings known only for wings with rounded leading edges. The inner vortex is first supplied with vorticity from the boundary layer, but soon this feeding switches to the outer vortex. Its strength increases downstream more and more, whereas the inner vortex decays. These phenomena should be studied in more detail. Experimental investigations could be performed using again the PSP and PIV techniques, but in the first place numerical studies of the flow behaviour in this region should be carried out in order to get a certain idea about the details to be expected. Calculations of this kind are in progress.

In the numerical calculations of the flow field the RANS equations have been solved using different turbulence models. In the CFD results according to Figs. 7 - 9 the flow on the whole upper surface has been assumed to be turbulent. For this kind of approach some differences concerning the position of the onset of the flow separations can be recognized from a detailed comparison of Figs. 6 and 7. Another result of these calculations, however, is the fact that the onset of the vortex formation in a CFD solution can be triggered by prescribing laminar/turbulent transition along conical lines close to the leading edge on the upper surface of the wing. This means that a good correlation between CFD and experiments can only be achieved if the transition line in the flow around the leading edge is well predicted in the calculations as compared with experiments or if transition is prescribed in the calculations in the correct position known from measurements.

These results from CFD solutions lead to new demands for future experiments. Even for sharp edged delta wings the location of the laminar/turbulent transition line is substantially unknown. On the upper surface of a slender sharp edged delta wing laminar/turbulent transition leads to a kink in the secondary separation line as described in [10], [11]. Thus only one single point of the transition line is known but the general slope of this line on the wing surface is missing and transition in the flow past rounded leading edges has not yet been studied in detail. Since this lack of information is known since a long time, the determination of the laminar/turbulent transition line has been placed in the program of the new Vortex Flow Experiment [5] and it is mentioned in the list of objectives in section 2.2. According to the situation described so far, measurements of the laminar/turbulent transition are now an urgent need for VFE-2. In order to solve this problem experiments using the wind tunnel model of TU Munich are planned: This model is capable to be tested under cryogenic conditions and measurements in the Cryogenic Wind Tunnel (KKK) of DLR Cologne, Germany, using the Temperature Sensitive Paint (TSP) technique for the detection of the laminar/turbulent transition are envisaged. Preliminary tests for this wind tunnel entry are already in progress.

5. Conclusions

For the new International Vortex Flow Experiment (VFE-2) the objectives, the organization within an RTO Task Group, the available wind tunnel models and the applied experimental techniques have been described. From the very beginning the measurements have been accompanied by numerical solutions of the RANS equations using various turbulence models.

The vortex formation has been studied for a 65° delta wing with medium radius rounded leading edges at Mach number $M = 0.4$, Reynolds number $R_{mac} = 3 \cdot 10^6$ and angle of attack $\alpha = 13°$. First results were shown from

- PSP measurements at DLR Goettingen, Germany
- CFD solutions from FLOWer code calculations at EADS Munich, Germany
- PIV measurements at DLR Goettingen, Germany.

The combination of experiments and CFD lead to the understanding that on this configuration for the given flow conditions a system of two vortices with the same sense of rotation is formed on each side of the wing. As long as these vortices are fed with vorticity they increase downstream in size and strength.Upon the existence of the outer vortex the feeding with vorticity switches from the inner to the outer vortex. The latter increases downstream, whereas the inner one decays.

For future studies within VFE-2 the approach with a combination of CFD and experiments will be continued. The onset of the vortical flow will be studied by CFD solutions followed by measurements. The knowledge of the location of the laminar/turbulent transition line is now an important input for numerical calculations, and therefore new experiments on this subject will be carried out.

6. Acknowledgements

The results presented in this paper will be published in detail by the VFE-2 teams in the Final Scientific Report of the RTO AVT Task Group 113 and elsewhere. The author is indebted to R. Engler, Ch. Klein, J. Kompenhans, R. Konrath and A. Schroeder (DLR Goettingen) and W. Fritz (EADS Munich) for the possibility to use them for this first overview.

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