Chapter 17 – THE INTERNATIONAL VORTEX FLOW EXPERIMENT 2 (VFE-2): OBJECTIVES AND OVERVIEW

by

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17.1 SUMMARY

In this chapter the objectives for the new International Vortex Flow Experiment (VFE-2) and its organization within the RTO Task Group AVT-113 are described. The available wind tunnel models and the applied experimental techniques, the program of work and its realization as well as the presentation of results within this Final Report and elsewhere are outlined.

17.2 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 codes. This lead to the First International Vortex Flow Experiment (VFE-1) [17-1], which has been carried out in 1984 – 1986: On a sharp edged cropped delta wing with a leading edge sweep of 65° combined with a fuselage, see Figure 17-1, force and pressure 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 [17-2], and later the state of the art has been reviewed in [[17-3] to [17-5]]. 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 Figure 17-2, since the secondary separation is not modelled at all.

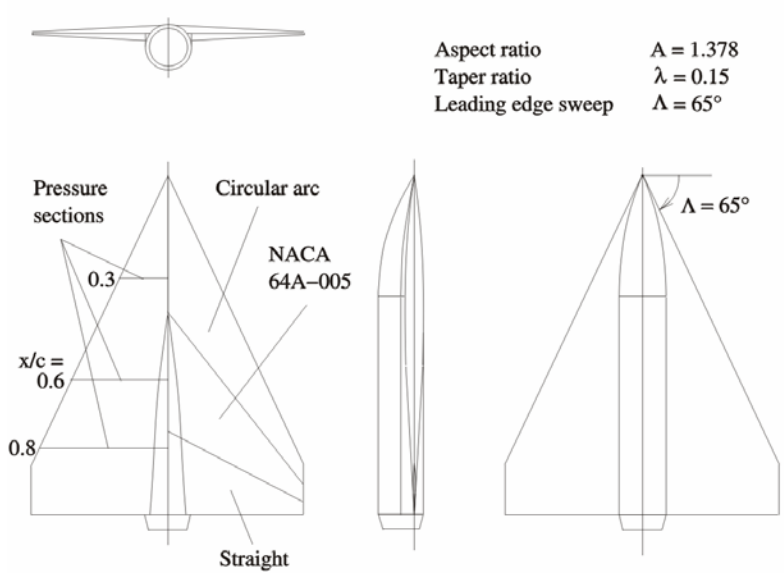

Figure 17-1: Configuration of the First International Vortex Flow Experiment (VFE-1).

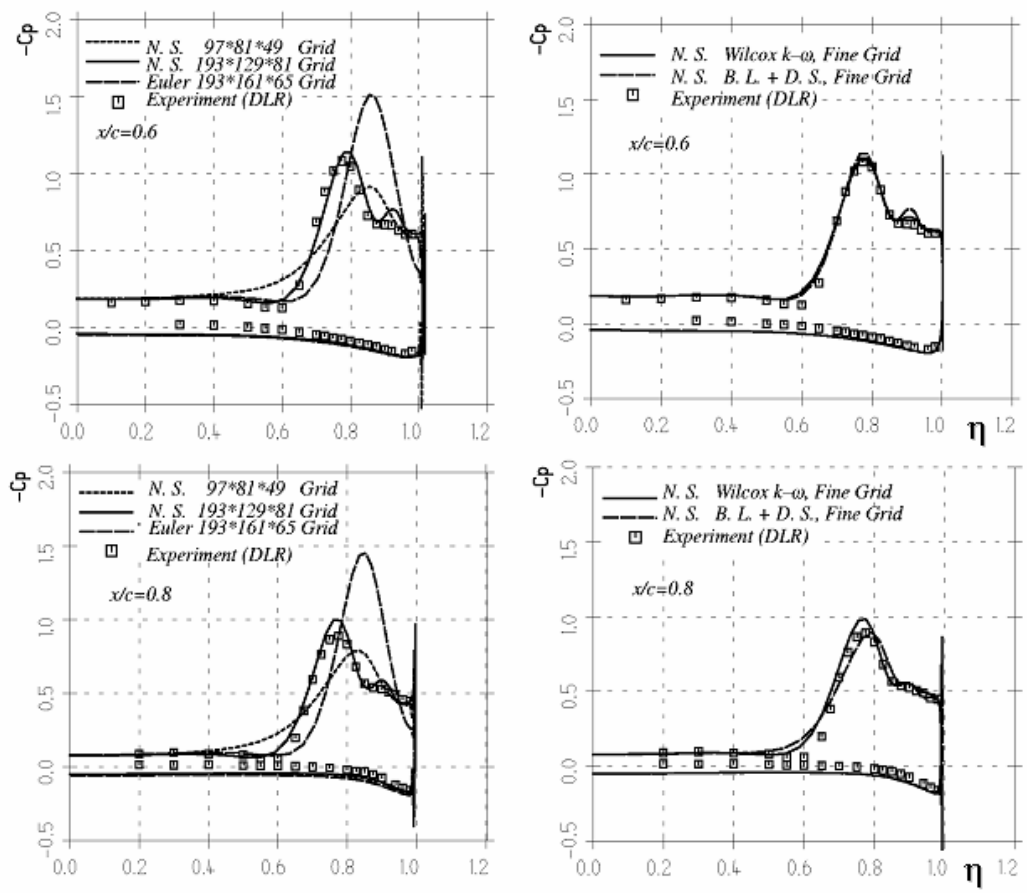

Figure 17-2: Surface Pressure Distributions on the Wing (Only) of the VFE-1 Configuration at $M = 0.4$, $R_{mac} = 3.1 \times 10^6$, $\alpha = 9°$. Comparison of solutions of the Euler and the RANS equations including effects of grid resolution and turbulence modelling. FLOWer code results according to W. Fritz, EADS Munich DEU.

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 vortex area properly. The calculated pressure distribution on the upper surface of the wing is very sensitive to correct modelling of the viscous regions of the flow field as shown in Figure 17-2. If the grid resolution is fine enough reasonable pressure distributions turn out, but according to Figure 17-3 considerable differences concerning the total pressure loss distribution are present in the flow field for different turbulence models.

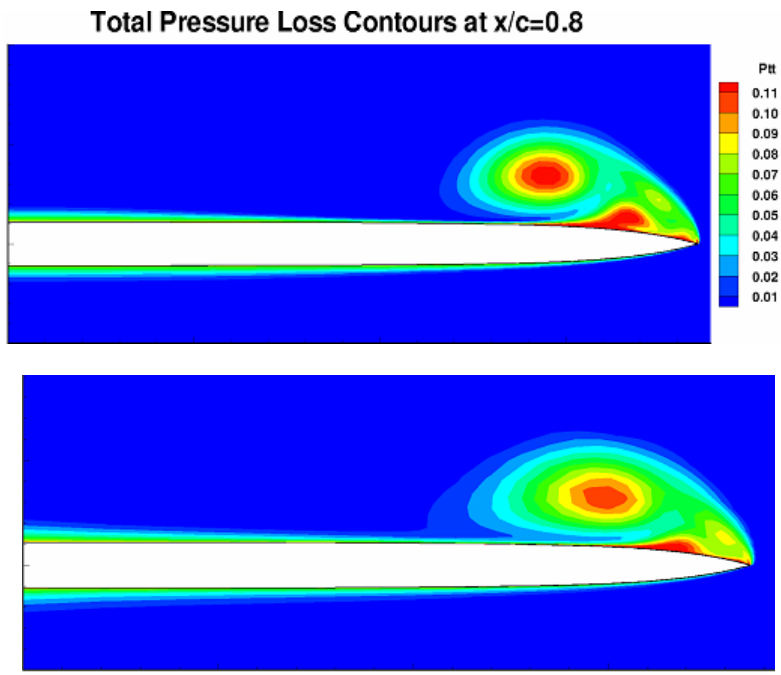

Figure 17-3: Total Pressure Loss Contours in Section x/c = 0.8 on the VFE-1 Configuration at M = 0.4, R_{mac} = 3.1 x 10^6, α = 9°. FLOWer code results using the Baldwin-Lomax (top) and the k-ω (bottom) turbulence model according to W. Fritz, EADS Munich DEU.

In order to validate the results of Navier-Stokes calculations new and more detailed experimental data are necessary, and therefore at the RTO AVT Symposium in Loen 2001 a Second International Vortex Flow Experiment (VFE-2) has been proposed [17-5], which will be described subsequently.

17.3 OBJECTIVES FOR NEW EXPERIMENTAL INVESTIGATIONS

17.3.1 Test Configuration

According to [17-5] 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 [17-6], which is shown in Figure 17-4. 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 [17-6]. Thus new wind tunnel models could be built quite easily.

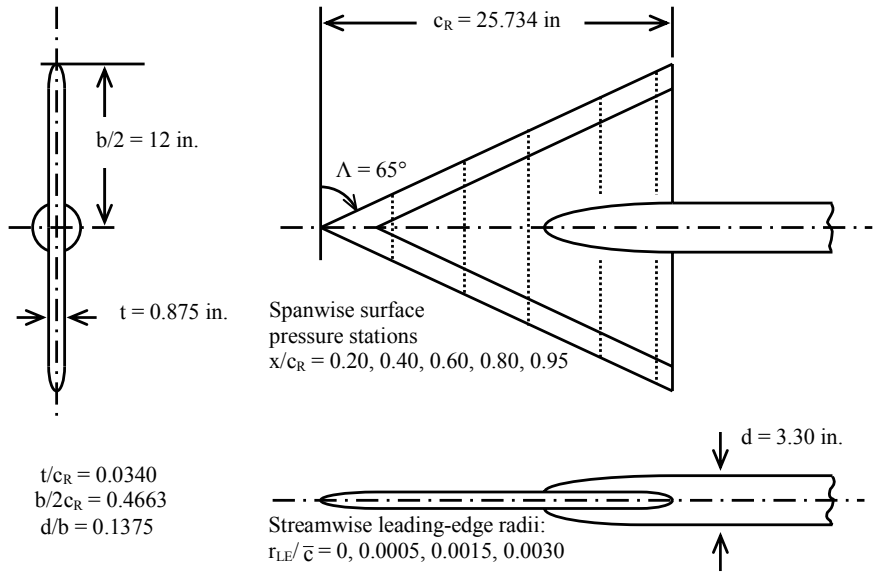

Figure 17-4: VFE-2 Configuration: NASA NTF Delta Wing A = 1.85, Λ = 65° [17-6].

For the NASA delta wing configuration comprehensive measurements of normal force and pitching moment as well as of pressure distributions in the sections according to Figure 17-4 and along the leading edges had already been carried out in the National Transonic Facility (NTF) at NASA, see Figure 17-5, for a large variety of Mach numbers and Reynolds numbers [17-6], and results of first numerical calculations have been made available at the Loen Conference [17-7].

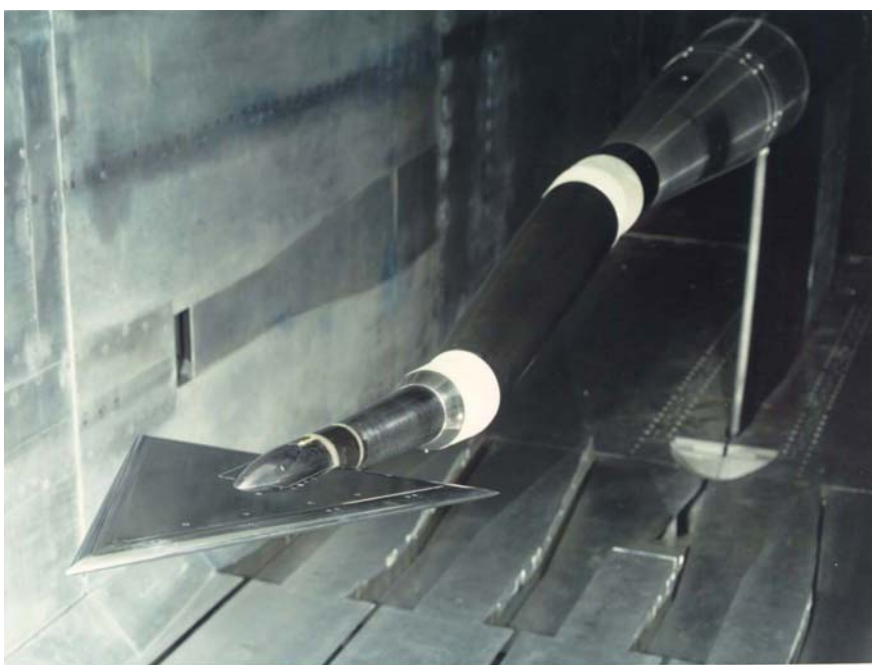

Figure 17-5: NASA NTF Tests on the 65° Delta Wing [17-6].

17.3.2 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 it was decided to use the case of sharp leading edges within VFE-2 as reference only and to direct the main emphasis for new experiments 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 order to provide the full three-component data set. Since no investigations on the flow field around this configuration existed at all, the main general aim for VFE-2 was to provide flow field data for comparison with numerical results. 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.

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 objectives for these investigations were:

- Validation and improvement of the existing CFD codes by means of comparisons with new experimental results.
- Code to code comparisons through calculations on common unstructured and structured grids.
- Application of different turbulence models in RANS calculations and comparison with new experimental flow field data.
- Assistance related to the set up, the performance and the evaluation of the new wind tunnel experiments.
- Synergistic effects through the possibility for test runs on a simple configuration prior to expensive calculations for a complete aircraft, such as in the CAWAPI facet.

17.4 ORGANIZATION OF VFE-2

17.4.1 Formation of an RTO Task Group

At the RTO AVT-069 Symposium on “Vortex Flow and High Angle of Attack Aerodynamics” in Loen, Norway, 2001, the realization of the proposed [17-5] Second International Vortex Flow Experiment (VFE-2) has been discussed extensively by the audience. The NASA 65° delta wing configuration [17-6] had been put forward as an appropriate test configuration, and already prior to the Loen conference NASA informed the scientific community about the existence of a second smaller wind tunnel model at NASA Langley RC,

the dimensions of which were ¾ of those given in Figure 17-4 for the NTF wind tunnel model. Already at the early stage of the discussions in Loen, this second American wind tunnel model has been placed at disposal by NASA for use by the members of a forthcoming RTO Task Group in other wind tunnels worldwide. This offer was the starting point for the new VFE-2.

In the course of the RTO AVT meetings in Manchester 2001 and in Paris 2002 the establishment of a new AVT Task Group "Vortex Flow Experiment – 2" has been proposed. Another outcome of the conference in Loen 2001 was the idea to perform numerical calculations of the vortical flow around a complete military aircraft at full Reynolds numbers and to compare the results with already existing flight test data. Therefore at the same time another new AVT Task Group "F-16XL Numerical Simulations" has been discussed. Finally the RTO Applied Vehicles Technology Panel decided in Aalborg 2002 to combine the two proposals and to establish a new

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

This new Task Group acted in two facets:

1) Cranked Arrow Wing Aerodynamics Project International (CAWAPI); and
2) Second International Vortex Flow Experiment – 2 (VFE-2).

Both facets worked closely together. The numerical calculations within CAWAPI for the complete aircraft F-16XL turned out to be extremely expensive both for grid size and CPU time. On the other hand the VFE-2 configuration was relatively simple and the amount for numerical investigations was comparatively small. From this contrast resulted considerable synergistic effects within AVT-113. Prior to future expensive calculations for the full aircraft geometry, the codes and the various turbulence models could be checked using the much simpler VFE-2 configuration. Some members were active in both facets of AVT-113, and the discussions within the Task Group during its semi-annual meetings on the experiences of the members supported the anticipated synergistic effects.

The inauguration of the AVT-113 Task Group took place at the AVT Panel spring meeting in Brussels 2003. Co-chairmen became Dr. John E. Lamar, NASA Langley Research Centre, USA, (CAWAPI), and Prof. Dr. Dietrich Hummel, Technische Universität Braunschweig, DEU, (VFE-2), and Prof. Charles Hirsch, Vrije Universiteit Brussel, BEL, acted as AVT Panel Representative for the Task Group. During the inaugural meeting experimental contributions to VFE-2 were announced by NASA Langley RC (USA), DLR Goettingen and TU Munich (DEU), University of Glasgow (GBR) and ONERA Lille (FRA), and numerical contributions were planned by EADS Munich (DEU), USAFA Colorado (USA) and University of Glasgow (GBR). In the course of the investigations within VFE-2 other groups of scientists joined, and all final members of the VFE-2 facet of the AVT-113 Task Group and their affiliations are listed in Appendix 1.

17.4.2 Selection of Flow Phenomena to be Studied within VFE-2

From the proposal for the Second International Vortex Flow Experiment [17-5] as well as from the list of objectives given in Section 17.3.2 a huge number of interesting flow cases for the 65° delta wing configuration can be deduced. From the very beginning the members of the Task Group realized that not all interesting flow phenomena could be treated successfully and that a concentration concerning the topics to be investigated was necessary.

Concerning the free stream flow conditions, i.e. Mach number and Reynolds number, from the available NASA matrix [17-6] the segment for the lower Reynolds numbers is shown in Figure 17-6. Only some of the

new measurements could be closely related to the test conditions of the National Transonic Facility (NTF) at NASA Langley RC [17-6], whereas most of the **new measurements** could only be carried out **for incompressible flows**. For this flow regime unpublished results of NASA investigations in the Low Turbulence Pressure Tunnel (LTPT) at Langley RC did already exist. The corresponding free stream flow conditions are included in Figure 17-6. These experiments have been carried out by means of the second smaller wind tunnel model, the dimensions of which were ¾ of those given in Figure 17-4 for the NTF wind tunnel model. The results of these measurements remained unpublished for a long time, and their evaluation and presentation within VFE-2 is part of the NASA contribution.

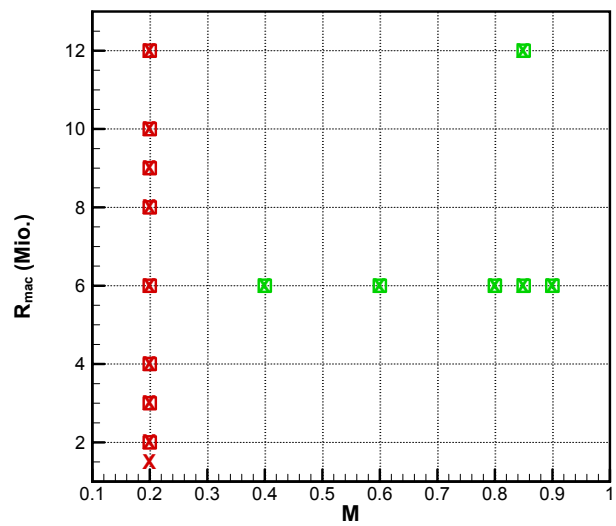

Figure 17-6: Available Test Conditions for the 65° Delta Wing Configuration at NASA Langley.

X sharp leading edges, Low Turbulence Pressure Tunnel (LTPT)
□ medium radius leading edges, Low Turbulence Pressure Tunnel (LTPT)
X sharp leading edges, National Transonic Facility (NTF)
□ medium radius leading edges, National Transonic Facility (NTF)

Since for delta wings with sharp leading edges and fixed primary separation a large number of experimental investigations are available in the literature, the Task Group decided on its meeting in Warsaw 2003 to use the case of sharp leading edges within VFE-2 as reference only and to direct the main emphasis for new experiments towards studies of the vortex formation on the configuration with **rounded leading edges**. The available NASA data [17-6] showed for the configurations with rounded leading edges spanwise pressure distributions with two separate suction peaks on the upper surface of the wing, see Figure 17-7, which have never been observed for sharp edged delta wings. Therefore the Task Group decided to study the onset of separated flow for rounded leading edges in more details, and for this purpose the medium radius leading edge configuration (= 0.0015) has been selected.

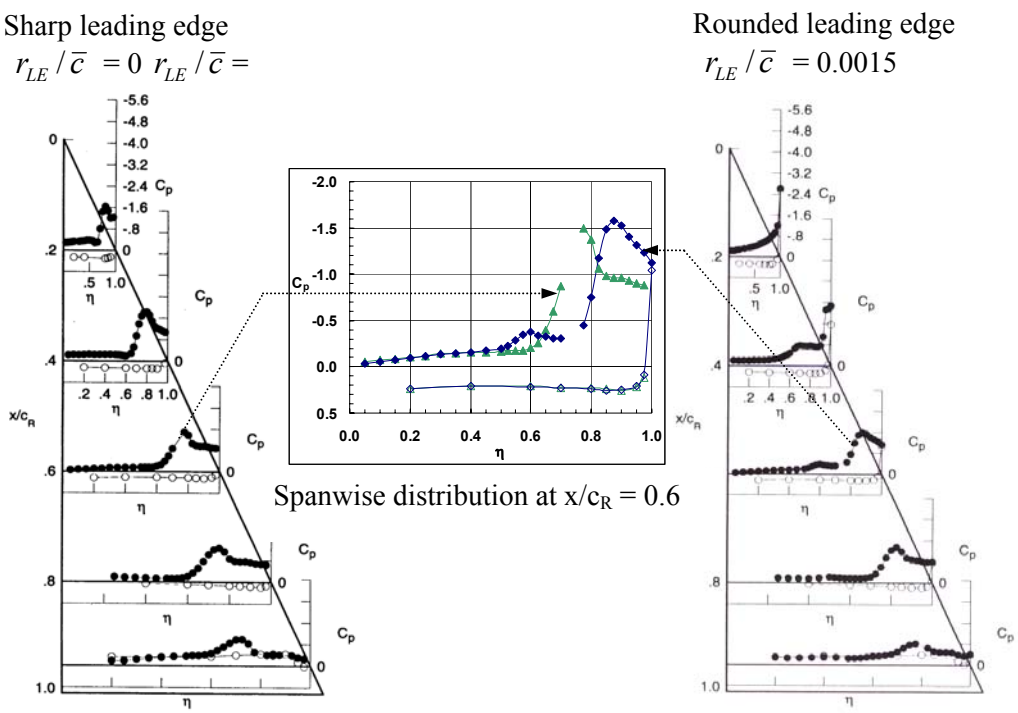

Figure 17-7: Effect of Leading Edge Bluntness on the Pressure Distribution of the 65° Delta Wing Configuration (A = 1.85) at M = 0.4, R_{mac} = 6 x 10^6, α = 13° [17-6].

A huge matrix of possible investigations is given by the large variety of angles of attack, which lead to various flow regimes. The new measurements mainly concentrated on one rounded leading edge shape in comparison with the sharp leading edge configuration and according to the decision of the Task Group in Warsaw 2003 **three angles of attack**, corresponding to three different flow regimes, have been studied in detail. These are:

- Onset of vortical flow, α = 13°
  - Sharp leading edges: Separated flow
  - Medium radius leading edges: Partly attached, partly separated flow
- Separated flow without vortex breakdown, α = 18°
  - Sharp leading edges
  - Medium radius leading edges
- Separated flow with vortex breakdown, α = 23°
  - Sharp leading edges
  - Medium radius leading edges.

For the chosen flow conditions pressure distribution measurements as well as normal force and pitching moment data were already available from NASA for wide ranges of Mach number and Reynolds number [17-6]. The new experiments should complete these measurements by adding **drag data**.

However, the main emphasis for the new experiments was to obtain **flow field data**, mainly by PIV and hot-wire techniques (HWA).

On delta wings the formation of the boundary layers underneath the vortex system is very important for the vortex formation [17-8], [17-9], but the **status of the boundary layers** is poorly known. More detailed knowledge on this subject would be very useful either for the validation of related prediction methods or for the adaptation of the results of numerical calculations to the experimental status. Therefore attempts have been made to determine the laminar and the turbulent regions on the upper surface of the wing.

At large angles of attack **vortex breakdown** takes place in the primary vortices. Today it is common understanding that the flow past slender delta wings at large angles of attack becomes unsteady even for fixed wings. This means in other words that for large angles of attack and steady boundary conditions only unsteady solutions of the governing equations do exist. The spiral-type vortex breakdown is well predicted by numerical solutions of the Navier-Stokes equations [17-10], [17-11], see Figure 17-8. The instantaneous vortex axis spirals in space against the sense of rotation of the primary vortex and this spiral turns around with respect to time in the sense of rotation of the primary vortex, and in the center of the spiralling motion a region of reversed flow is present. Correspondingly all quantities of the flow field show oscillations. Therefore, in the new experiments **unsteady pressure distribution measurements** have been carried out in order to provide data on the oscillations including the governing frequencies for comparison with numerical results.

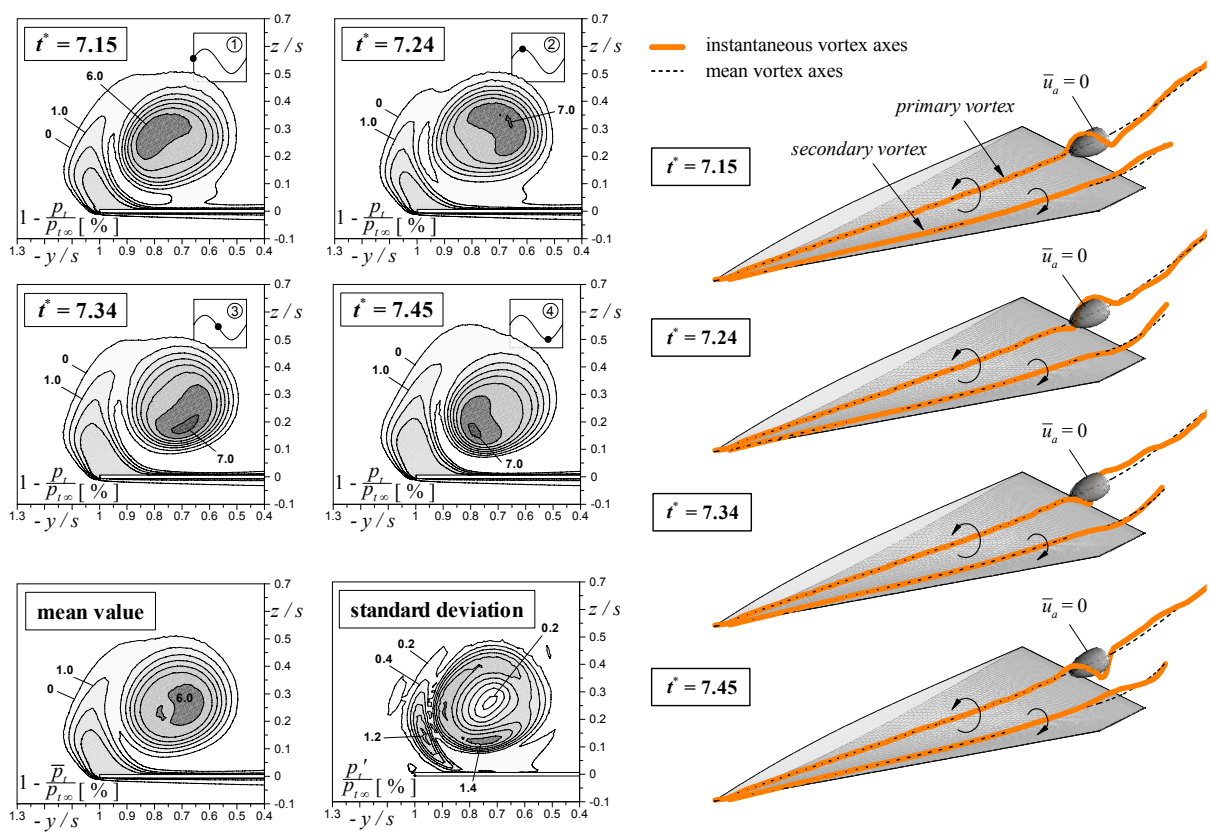

Figure 17-8: Numerical Simulation of Vortex Breakdown for the VFE-1 Configuration at M = 0.2, R = 1.55 x 10^6, α = 21°. Navier-Stokes solutions with k-ω turbulence model: Total pressure losses at x/c_R = 0.95 and vortex axes for different time steps [17-11].

17.4.3 Wind Tunnel Models

The wind tunnel models used within VFE-2 are listed in Table 17-1. As a reference the original NASA NTF wind tunnel model is included as Nr. 0. The smaller NASA LTPT wind tunnel model Nr. 1 has been made available by NASA Langley RC for use by the facet members. This model was shipped to Europe and tested by means of PSP and PIV at DLR (DEU) in the Transonic Wind Tunnel Goettingen (TWG of Deutsch-Niederlaendischer Windkanal, DNW) as well as by means of balance measurements and PIV at ONERA Lille (FRA). A new wind tunnel model Nr. 2 was built at TU Munich (DEU) in order to perform surface oil flow investigations, pressure distribution measurements as well as flow field surveys by means of the PIV and the hot-wire (HWA) techniques. The same wind tunnel model has also been tested by DLR in their Cryogenic Wind Tunnel KKK at Cologne (DEU). Additional PIV tests have been carried out there, and the TSP and infrared (IR) techniques have been applied for the detection of the laminar/turbulent transition. Another wind tunnel model Nr. 3 has been built and tested through unsteady balance, pressure distribution and flow field studies at University of Glasgow (GBR). Two other new wind tunnel models Nr. 4 and 5 have been built by ONERA Lille (FRA) in order to carry out balance measurements and flow visualization tests, and these two models were shipped to Turkey in order to perform balance measurements and to investigate the laminar/turbulent transition at TUBITAK-SAGE, Ankara (TUR).

Table 17-1: Wind Tunnel Models Used in VFE-2 [Notations for Leading Edge Shapes: (S) Sharp edged, (RS) Rounded: Small Radius, (RM) Rounded: Medium Radius, (RL) Rounded: Large Radius]

Model Nr.	Span [m]	Root Chord [m]	Leading Edge	Tested At	Owner
0	0.610	0.653	S, RS, RM, RL	NASA, NTF	NASA Langley RC
1	0.457	0.490	S, RS, RM, RL	NASA, LTPT DLR, TWG ONERA	NASA Langley RC
2	0.933	0.980	S, RM	TU Munich DLR, KKK	TU Munich
3	0.987	1.059	S, RM	Uni. Glasgow	Uni. Glasgow
4	0.457	0.490	S	ONERA TUBITAK-SAGE	ONERA Lille
5	0.457	0.490	RM	ONERA TUBITAK-SAGE	ONERA Lille

17.4.4 Numerical Investigations

At the very beginning of VFE-2 the results of numerical investigations at NASA Langley RC by means of an adapted unstructured grid were available [17-7].

New calculations within AVT-113 for the VFE-2 configuration have been carried out firstly on structured grids and secondly on unstructured grids. In the solutions of the RANS equations a large variety of existing

turbulence models has been applied. For (medium radius) rounded leading edges the flow field at lower angles of attack with two vortices on each side of the configuration has been considered for $\alpha = 13°$. The ordinary vortex formation with one vortex on each side of the configuration (accompanied by a secondary vortex) has also been studied numerically at $\alpha = 18°$ for sharp and rounded leading edges, and for very high angles of attack the unsteady behaviour of the vortical flow (vortex breakdown) has also been treated at $\alpha = 23°$.

Finally a semi empirical/numerical method to predict the onset of vortical flow over the upper surface of a delta wing with rounded leading edges with different radii has been developed.

17.4.5 Use of a Virtual Laboratory

Within the Task Group AVT-113 a Virtual Laboratory has been developed by NASA Langley RC, which enabled the members of the working group to upload and download computer programs, configuration geometries and grids as well as experimental and numerical results [[17-12], [17-13]]. This Virtual Laboratory enabled and facilitated collaborative research within the Task Group. It has been used in the first place by the F-16XL-1 related facet "Cranked Arrow Wing Aerodynamics International" (CAWAPI) of AVT-113. The corresponding communication among the members of the delta wing related facet "Vortex Flow Experiment 2" (VFE-2) has been developed after this, and therefore the communication within VFE-2 took place on a large extend on an individual basis.

17.4.6 Program of Work

At the inauguration of the Task Group AVT-113 in spring 2003 in Brussels, the facet VFE-2 has been formed and new experiments have been envisaged. The detailed program for these tests has been discussed at the autumn meeting 2003 in Warsaw, and the final Program of Work (POW) has been fixed at the spring meeting 2004 in Williamsburg. According to the original objectives for new tests (described in Section 17.3.2) and the selection of flow phenomena to be studied within VFE-2 (described in Section 17.4.2) the official POW contained:

- 3-component balance measurements.
- Surface pressure distribution measurements.
- 3D boundary layer investigations including the transition laminar/turbulent.
- Flow field measurements within the vortices.
- Investigations on the unsteady vortical flow at higher angles of attack (vortex breakdown) including surface pressure fluctuations.
- Numerical investigations on structured and unstructured grids and comparison with the new test results.

These new experiments and the related numerical investigations were aimed at the understanding of the vortex formation on the wing with rounded leading edges and the case with sharp leading edges would be used as reference only.

The realization of this program depended on the availability of wind tunnel testing time and CFD capacities. The steps to fulfil the POW will be described subsequently.

Progress in 2004. As the basis for VFE-2 the results of the NTF tests on the 65° delta wing with different leading edge shapes at various Reynolds- and Mach numbers, see [17-14] to [17-16], have been summarized by NASA Langley (USA) at the ICAS 2004 Congress in Yokohama [17-17].

The loan agreement between NASA (USA) and DLR (DEU) had already been signed in December 2003. The American wind tunnel model Nr. 1 was shipped to Europe in March 2004. DLR Goettingen performed PSP measurements in a first entry in the Transonic Windtunnel Goettingen (TWG) of Deutsch-Niederlaendischer Windkanal (DNW) in July and August 2004. Preliminary results have been discussed by the Task Group at their autumn meeting 2004 in Prague and presented in October 2004 at the RTO Symposium AVT-111 [17-9]. For the wing with rounded leading edges at an angle of attack of 13° two vortices on each side of the configuration were clearly indicated. At that time the inner vortex was regarded to represent the remains of a 3D bubble-type laminar/turbulent transition in the front part of the configuration. Concerning the forthcoming PIV investigations a tiny inner vortex resulting from a transitional boundary layer was expected.

Progress in 2005. Starting already in December 2004 first numerical calculations of the flow field have been carried out at EADS Munich (DEU) by means of the German FLOWer code on a structured grid, and pressure distributions with two suction peaks on each side of the configuration turned out in excellent agreement with the PSP measurements. Looking into the details of the numerical solution an inner vortex of about the size of the outer vortex turned out, but downstream of the onset of the outer vortex, the inner vortex decays, since it is no longer fed with vorticity. Using these numerical results the set-up for the forthcoming PIV investigations could be adjusted properly and the second entry of DLR in the TWG with stereo-PIV investigations took place in April 2005. Again the shape of the two vortices turned out as predicted in the calculations. Preliminary results of this cooperation between CFD and experiments have been discussed by the Task Group at their spring meeting 2005 in Budapest and presented at Cranfield University in September 2005 [17-15].

In 2005 further wind tunnel models came into operation: Model Nr. 2 at TU Munich (DEU) had been completed, and pressure distribution and flow visualization tests have been carried out there. Since the loan agreement between NASA (USA) and ONERA (FRA) was delayed, ONERA Lille built two new wind tunnel models Nr. 4 and 5 with sharp and rounded leading edges and performed balance and exploratory PIV tests. After the first successful calculations of the flow, a common structured grid was provided by EADS Munich (DEU) and a common unstructured grid by USAFA Colorado (USA). In addition also individual structured meshes were used by the participants, and calculations were underway at University of Glasgow (GBR), NLR Amsterdam (NLD) and EADS Munich (DEU). Calculations on unstructured grids have been started on individual meshes at KTH Stockholm (SWE) and DLR Braunschweig (DEU) as reported to the Task Group at the autumn meeting 2005 in Granada.

Progress in 2006. After full evaluation the PSP and PIV results from DLR Goettingen have been presented at various conferences, [17-19] to [17-23], and these results were mentioned as an outstanding experimental achievement for 2006 [17-24]. The NASA wind tunnel model Nr. 1 has been transferred from DLR Goettingen (DEU) to ONERA Lille (FRA), and new balance measurements have been carried out there. At TU Munich unsteady pressure distribution measurements have been performed on wind tunnel model Nr. 2 for angles of attack at which vortex breakdown takes place over the wing. Preliminary results were presented to the Task Group at the spring meeting 2006 in Amsterdam, and first results were published later this year [17-25], [17-26]. New experiments have been carried out in November/December 2006 on wind tunnel model Nr. 2 of TU Munich in the KKK cryogenic wind tunnel of DLR in Cologne (DEU) for additional PIV investigations and in order to investigate the laminar/turbulent transition by means of IR and TSP techniques. The two wind tunnel models Nr. 4 and 5 have been transferred from ONERA Lille (FRA) to TUBITAK-SAGE Ankara (TUR), and balance measurements as well as tests on transition laminar/turbulent have been carried out there.

New structured CFD solutions have been carried out by ONERA Lille (FRA), and at U. Glasgow (GBR) the formation of shock waves in the flow field has been studied in detail. Comparisons of the results of three

CFD-codes calculated on structured grids for the sharp-edged configuration provided by University of Glasgow (GBR), NLR Amsterdam (NDL) and EADS Munich (DEU) were presented at an AIAA conference [17-27]. Numerical calculations on unstructured grids were started at USAFA Colorado (USA), KTH Stockholm (SWE) and DLR Braunschweig (DEU). First results of such calculations within AVT-113 for the rounded leading edge case have been obtained at KTH Stockholm (SWE) and were presented at an AIAA Conference [17-28] and at the ICAS Congress 2006 [17-29] and comprehensive discussions within the Task Group took place at the autumn meeting 2006 in Vilnius. The semi-empirical method for the prediction of flow separations on the VFE-2 configuration with rounded leading edges developed by Nangia (GBR) as a consultant to AVT-113 has been reviewed in 2006.

Progress in 2007. The experiments at TU Munich (DEU) on their wind tunnel model Nr. 2 continued with PIV and HWA investigations, and further results have been published [17-30]. In autumn 2007 additional boundary layer HWA measurements have been carried out. At DLR the evaluations of the TSP and IR investigations in the KKK cryogenic wind tunnel have been started. The new PIV results led to an extension of the existing data base towards higher Reynolds numbers at low Mach numbers. The measurements on wind tunnel model Nr. 3 at Uni. Glasgow (GBR) have been carried out in the second half of 2007. The test results obtained for the two wind tunnel models Nr. 4 and 5 at ONERA Lille (FRA) and at TUBITAK-SAGE Ankara (TUR) have been evaluated and compared with those from NASA. Comprehensive discussions on this subject took place within the Task Group at the spring meeting 2007 in Florence and at the autumn meeting 2007 in Athens.

Towards the end of the working period of VFE-2 the activities on the numerical side increased very much. Based on the available experimental data a set of flow cases for comparisons of experiments and numerics has been proposed. Calculations have been carried out for α = 13°, 18° and 23°on structured grids by EADS Munich (DEU), ONERA Lille (FRA) and TUSAS Ankara (TUR) and on unstructured grids by USAFA Colorado (USA), KTH Stockholm (SWE) [17-31] and DLR Braunschweig (DEU). The principal objective for these calculations was the comparison of the various results with the experimental data. Due to the lack of experimental information on the formation of the inner vortex in the apex region of the wing and on the interaction at the onset of the outer primary vortex, however, the numerical results from EADS Munich (DEU), KTH Stockholm (SWE), USAFA Colorado (USA) and DLR Braunschweig (DEU) have also been used to analyse the flow physics in these regions of the wing, and comprehensive discussions within the Task Group on this aspect took place at the autumn meeting 2007 in Athens. At Uni. Glasgow/Liverpool (GBR) the formation of shock waves in the flow field has been studied intensively on the basis of calculations on structured grids. This lead to a PhD-thesis [17-32], and later also results from calculations on unstructured grids have been taken into consideration in comparisons with experimental data [17-33], [17-34]. The semi-empirical method for the prediction of flow separations on the VFE-2 configuration with rounded leading edges developed by Nangia (GBR) has been settled and the final version has been accepted. At mid 2007 the status of VFE-2 has been summarized [17-35].

In addition to these detailed activities another objective for the VFE-2 facet of AVT-113 in 2007 was the preparation of 15 papers of VFE-2 members as well as an “Open Panel Discussion” to be presented in two special sessions at the 46th AIAA Aerospace Sciences Conference (Reno 2008), see [17-36] to [17-50].

17.5 PRESENTATION OF RESULTS

The Second International Vortex Flow Experiment (VFE-2) has been proposed in [17-5] and its basis were the already existing experimental investigations from the NTF at NASA Langley RC [17-6], which were later summarized in [17-14] to [17-17].

At the very beginning of VFE-2 in 2003 new experimental contributions were announced and later realized by NASA Langley RC USA (Chapter 18), DLR Goettingen DEU (Chapter 19), ONERA Lille FRA (Chapter 20), TU Munich DEU (Chapter 21), Univ. of Glasgow GBR (Chapter 22), and later also by TUBITAK-SAGE Ankara TUR (Chapter 23). The lessons learned from the new experiments will be discussed in a separate article (Chapter 24).

Within VFE-2 the first solution on a structured grid was provided by EADS Munich DEU (Chapter 25) and later other solutions on structured grids were added by ONERA Lille FRA (Chapter 26), NLR Amsterdam NLD (Chapter 27) and TUSAS Ankara TUR (Chapter 28), and studies on the vortex formation at transonic flow conditions have been initiated at the Universities of Glasgow and Liverpool GBR (Chapter 29).

A first numerical solution for the VFE-2 configuration on an unstructured grid was already available at the very beginning of VFE-2 by NASA Langley RC [17-7]. New solutions on unstructured grids for the VFE-2 configuration are due to KTH Stockholm SWE (Chapter 30), DLR Braunschweig DEU (Chapter 31) and USAFA Colorado USA (Chapter 32). In addition a semi-empirical prediction method for the vortex formation on delta wings with rounded leading edges is presented (Chapter 33). The experience from calculations on structured and unstructured grids is summarized in a separate article (Chapter 34), and the results of the whole VFE-2 are discussed in a concluding section (Chapter 35). All members of the VFE-2 facet of AVT-113 and their affiliations are listed in Appendix 17-1.

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Appendix 17-1: List of the Members of the VFE-2 Facet of AVT-113

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		Numerical	Experimental
Lamar, Dr. John E. NASA Langley Research Center Mail Stop 499 Hampton, VA 23681-2199 USA	john.e.lamar@nasa.gov	Co-chairman	
Hummel, Prof. Dr.–Ing. Dietrich Institut für Strömungsmechanik TU Braunschweig Bienroder Weg 3 D-38106 Braunschweig Germany	d.hummel@tu-bs.de	Co-chairman	
Hirsch, Prof. Charles VrijeUniversiteit Brussel Pleinlaan, 2 1050 Brussels Belgium	charles.hirsch@numeca.be	Panel Mentor	
Arthur, Dr. Malcolm Terence Aerodynamics Integration Dept. QinetiQ, Cody, Ively Road Farnborough, Hampshire GU14 0LX United Kingdom	mtarthur@qinetiq.com	Structured Grid Transition	
Badcock, Prof. Dr. Ken J. Department of Engineering The University of Liverpool Brownlow Hill, Liverpool L69 3GH United Kingdom	k.j.badcock@liverpool.ac.uk	Structured Grid	
Bin Mat, Mr. Shabudin The University of Glasgow Dept. of Aerospace Engineering Glasgow G12 8QQ United Kingdom	smat@eng.gla.ac.uk		Model Nr. 3 Forces, Oilfl. Pressures by PSI, Kulites PIV
Boelens, Mr. Okko J. Aerospace Vehicles Division Dept. of Flight Physics and Loads National Aerosp. Laboratory NLR 2 Anthony Fokkerweg 1059 BM Amsterdam The Netherlands	boelens@nlr.nl	Structured Grid	

Name and Full Postal Address	Email Address	Contribution to VFE-2	
		Numerical	Experimental
Breitsamter, Dr.-Ing. Christian Lehrstuhl für Aerodynamik Technische Universität München Boltzmannstr. 15 D-85748 Garching Germany	christian.breitsamter@ aer.mw.tum.de		Model Nr. 2 Oilflow patt. Pressures by PSI, Kulites PIV, HWA
Coton, Prof. Frank N. The University of Glasgow Dept. of Aerospace Engineering Glasgow G12 8QQ United Kingdom	f.coton@aero.gla.ac.uk		Model Nr. 3 Forces, Oilflow Pressures by PSI, Kulites PIV
Crippa, Mr. Simone Royal Inst. of Technology (KTH) Aeron. and Vehicle Engineering Division of Aerodynamics Teknikringen 8 SE-10044 Stockholm Sweden	crippa@kth.se	Unstructured Grid	
Cummings, Prof. Russell M. US Air Force Academy Department of Aeronautics 2354 Fairchild Drive, Suite 6H27 Colorado Springs, CO 80840-6222 USA	russ.cummings@usafa.edu	Unstructured Grid	
Fritz, Mr. Willy Senior Development Engineer EADS – Military Air Systems Rechliner Straße D-85077 Manching Germany	willy.fritz@eads.com	Structured Grid	
Furman, Andrej Lehrstuhl für Aerodynamik Technische Universität München Boltzmannstr. 15 D-85748 Garching Germany	andrej.furman@ aer.mw.tum.de		Model Nr. 2 Oilflow patt. Pressures by PSI, Kulites PIV, HWA
Galbraith, Prof. Roderick The University of Glasgow Dept. of Aerospace Engineering Glasgow G12 8QQ United Kingdom	roddy@aero.gla.ac.uk		Model Nr. 3 Forces, Oilfl. Pressures by PSI, Kulites PIV

Name and Full Postal Address	Email Address	Contribution to VFE-2	
		Numerical	Experimental
Groot, Dr. Klaus de Institut für Aerodynamik und Strömungstechnik DLR Braunschweig Lilienthalplatz 7 D-38108 Braunschweig Germany	klaus.degroot@dlr.de		Model Nr. 2 IR (KKK)
Gürdamar, Emre Turkish Aircraft Industries TUSAS Ziyabey Cad.3 sok.No:16 06520 Balgat, Ankara Turkey	egurdamar@tai.com.tr	Structured Grid	
Kaya, Serpil Turkish Aircraft Industries TUSAS Ziyabey Cad.3 sok.No:16 06520 Balgat, Ankara Turkey	serkaya@tai.com.tr	Structured Grid	
Klein, Dr. Christian Institut für Aerodynamik und Strömungstechnik DLR Göttingen Bunsenstr. 10 D-37073 Göttingen Germany	christian.klein@dlr.de		Model Nr. 1 PSP (TWG) Model Nr. 2 TSP (KKK)
Konrath, Dr. Robert Institut für Aerodynamik und Strömungstechnik DLR Göttingen Bunsenstr. 10 D-37073 Göttingen Germany	robert.konrath@dlr.de		Model Nr. 1 PSI, PSP, PIV (TWG) Model Nr. 2 PIV, TSP, IR (KKK)
Korkem, Mr. Bulent Turkish Aircraft Industries TUSAS Ziyabey Cad.3 sok.No:16 06520 Balgat, Ankara Turkey	bkorkem@tai.com.tr	Structured Grid	
Kurun, Mr. Suleyman Aerodynamic Division TUBITAK-SAGE, P.K. 16 06261 Mamak, Ankara Turkey	skurun@sage.tubitak.gov.tr		Models Nr. 4 and 5 Forces, Transition

Name and Full Postal Address	Email Address	Contribution to VFE-2	
		Numerical	Experimental
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Luckring, Dr. James M. NASA Langley Research Centre Mail Stop 499 Hampton, VA 23681-2199 USA	james.m.luckring@nasa.gov		Model Nr. 1 Balance Measurements Pressures PSI
Luedeke, Dr. Heinrich DLR Braunschweig Lilienthalplatz 7 D-38108 Braunschweig Germany	heinrich.luedeke@dlr.de	Unstructured Grid	
Nangia, Dr. Raj K. Nangia Aero Associates Maggs House 78 Queen's Road Clifton, Bristol BS8 1QX United Kingdom	nangia@blueyonder.co.uk	Invited Consultant	
		Prediction of vortex formation for blunt edged delta wings	
Ortakaya, Yüksel Turkish Aircraft Industries TUSAS Ziyabey Cad.3 sok.No:16 06520 Balgat, Ankara Turkey	yortakaya@tai.com.tr	Structured Grid	
Rizzi, Prof. Dr. Arthur Royal Inst. of Technology (KTH) Aeron. and Vehicle Engineering Division of Aerodynamics Teknikringen 8 SE-10044 Stockholm Sweden	rizzi@kth.se	Unstructured Grid	
Rodriguez, Dr. Ovide ONERA – Centre de Lille 5, Boulevard Painleve F-59045 Lille France	ovide.rodriguez@onera.fr		Models Nr.1, 4 and 5 Balance Pressures PSI PIV

Name and Full Postal Address	Email Address	Contribution to VFE-2	
		Numerical	Experimental
Schiavetta, Ms. Lucy The University of Glasgow Dept. of Aerospace Engineering Glasgow G12 8QQ United Kingdom	lschiave@aero.gla.ac.uk	Structured Grid	
Schröder, Dr. Andreas Institut für Aerodynamik und Strömungstechnik DLR Göttingen Bunsenstr. 10 D-37073 Göttingen Germany	andreas.schroeder@dlr.de		Model Nr. 1 PIV (TWG) Model Nr. 2 PIV (KKK)
Schütte, Dipl.-Ing. Andreas DLR Braunschweig Lilienthalplatz 7 D-38108 Braunschweig Germany	Andreas.Schuette@dlr.de	Unstructured Grid	