NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

AC/323(AVT-113)TP/246

www.rto.nato.int

RTO TECHNICAL REPORT **TR-AVT-113**

Understanding and Modeling Vortical Flows to Improve the Technology Readiness Level for Military Aircraft

(Compréhension et modélisation des flux de vortex pour améliorer le niveau de maturité technologique au profit des avions militaires)

Summary Report of Task Group AVT-113.

Published October 2009

Distribution and Availability on Back Cover

NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

AC/323(AVT-113)TP/246

www.rto.nato.int

RTO TECHNICAL REPORT **TR-AVT-113**

Understanding and Modeling Vortical Flows to Improve the Technology Readiness Level for Military Aircraft

(Compréhension et modélisation des flux de vortex pour améliorer le niveau de maturité technologique au profit des avions militaires)

Summary Report of Task Group AVT-113.

The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

The content of this publication has been reproduced
directly from material supplied by RTO or the authors.

Published October 2009

Copyright © RTO/NATO 2009
All Rights Reserved

ISBN 978-92-837-0073-9

Single copies of this publication or of a part of it may be made for individual use only. The approval of the RTA Information Management Systems Branch is required for more than one copy to be made or an extract included in another publication. Requests to do so should be sent to the address on the back cover.

Table of Contents

	Page
List of Figures	**xxii**
List of Tables	**lvi**
Common Notations	**lx**
Acknowledgements	**lxiii**
Executive Summary and Synthèse	**ES-1**
Chapter 1 – Objectives and Overview	**1-1**
by J.E. Lamar and D. Hummel	
1.1 Summary	1-1
1.2 Introduction	1-1
1.3 Overview and Objectives Discussion	1-2
1.3.1 CAWAPI Facet	1-2
1.3.1.1 Overview	1-2
1.3.1.2 Objectives	1-3
1.3.2 VFE-2 Facet	1-3
1.3.2.1 Overview	1-3
1.3.2.2 Objectives	1-4
1.4 Concluding Remarks	1-5
1.5 References	1-5
Chapter 2 – Necessity and Utility of a Virtual Laboratory in AVT-113	**2-1**
by J.E. Lamar and J.M. Luckring	
2.1 Summary	2-1
2.2 Introduction	2-1
2.3 Necessity and Utility Discussion	2-2
2.3.1 CAWAPI Facet	2-2
2.3.2 VFE-2 Facet	2-6
2.3.3 Web Server Access	2-6
2.3.4 Data Types Supported by AVT-113 VL	2-6
2.4 Surprises and Adjustments	2-6
2.4.1 File Size	2-6
2.4.2 Out-Years Maintenance Cost	2-7
2.5 Collaborative CAWAPI Research Examples	2-7
2.5.1 Original Purpose	2-8
2.5.2 Structured Grid Creation	2-8
2.5.3 Large File Storage	2-9
2.6 Collaborative VFE-2 Research Examples	2-9

2.7 Concluding Remarks 2-10
2.8 References 2-10

Chapter 3 – The Cranked Arrow Wing Aerodynamics Project (CAWAP) and its Extension to the International Community as CAWAPI: Objectives and Overview **3-1**
by J.E. Lamar and C.J. Obara
3.1 Summary 3-1
3.2 Introduction 3-1
3.2.1 CAWAP History 3-1
3.2.1.1 F-16XL Airplane 3-1
3.2.1.2 HSR Program Overview 3-4
3.2.1.3 F-16XL Flight Overview / Planning for HSR 3-4
3.2.1.4 CAWAP 3-6
3.3 Data Available from CAWAP 3-8
3.3.1 Pressure Suite 3-8
3.3.2 Video Suite 3-10
3.3.3 Wind Tunnel 3-11
3.3.4 CFD Modeling 3-12
3.3.5 Database of Results 3-13
3.3.6 Sample CAWAP Comparisons 3-13
3.4 CAWAPI – Organization/Features/Presentations 3-20
3.4.1 Organization 3-20
3.4.2 Features 3-21
3.4.3 Introduction to Following Chapters 3-22
3.5 Concluding Remarks 3-29
3.6 Acknowledgements 3-30
3.7 References 3-30

Chapter 4 – F-16XL Geometry and Grids **4-1**
by O.J. Boelens, S. Görtz, S. Morton, W. Fritz, S.L. Karman Jr., T.R. Michal and J.E. Lamar
4.1 Summary 4-1
4.2 Introduction 4-1
4.3 Geometry Description 4-1
4.4 Structured Grid 4-3
4.4.1 Background 4-3
4.4.2 Grid Generation Algorithm 4-3
4.4.3 Characteristics of the Grid 4-5
4.5 Unstructured Grids 4-7
4.5.1 Baseline Unstructured Grid 4-7
4.5.2 Other Unstructured Grids 4-10
4.5.2.1 EADS-MAS 4-10
4.5.2.2 UTSimCenter 4-11
4.5.2.3 Boeing Phantom Works 4-14

4.6 Conclusions 4-15
4.7 Acknowledgments 4-16
4.8 References 4-16

Chapter 5 – Numerical Solutions for the CAWAPI Configuration on Structured Grids at NLR, The Netherlands **5-1**
by O.J. Boelens, S.P. Spekreijse, H.A. Sytsma and K.M.J. de Cock
5.1 Summary 5-1
5.2 Introduction 5-1
5.3 Grid 5-2
5.4 Flow Solver 5-2
5.4.1 General Description 5-2
5.4.2 Turbulence Model 5-3
5.4.3 Boundary Conditions 5-3
5.4.4 Details of Simulations 5-4
5.5 Comparison of the Measured and Simulated Flow Features 5-4
5.5.1 Flight Test Cases 5-4
5.5.2 Assessment of the Results 5-5
5.6 Conclusions 5-14
5.7 References 5-15

Chapter 6 – Numerical Solutions for the CAWAPI Configuration on Structured Grids at University of Glasgow/Liverpool University, United Kingdom **6-1**
by K.J. Badcock
6.1 Summary 6-1
6.2 Introduction 6-1
6.3 Formulation 6-2
6.3.1 Flow Solver 6-2
6.3.2 Test Case Description 6-3
6.4 Grids 6-5
6.4.1 Common Grid for Full Geometry 6-5
6.4.2 Wing-Only Grid 6-5
6.5 Results for Full Configuration 6-6
6.5.1 Calculation Details 6-6
6.5.2 Vortical Flow Cases 6-6
6.5.3 Transonic Case 6-12
6.6 Evaluation 6-14
6.7 Conclusions 6-16
6.8 Acknowledgements 6-17
6.9 References 6-17

Chapter 7 – Numerical Solutions for the CAWAPI Configuration on Structured Grids at NASA LaRC, United States **7-1**
by A.A. Elmiligui, K.S. Abdol-Hamid and S.J. Massey
7.1 Summary 7-1

7.2 Introduction 7-1
7.3 Computational Fluid Dynamics Simulation 7-2
7.4 Governing Equations 7-2
7.5 RANS Closure 7-3
7.5.1 Two Equation k-ε Model 7-3
7.5.2 Algebraic Reynolds Stress 7-4
7.6 Computational Domain and Boundary Conditions 7-5
7.7 Computational Results 7-6
7.8 Concluding Remarks 7-27
7.9 Acknowledgments 7-27
7.10 References 7-27

Chapter 8 – Numerical Solutions for the CAWAPI Configuration on Unstructured Grids at EADS-MAS, Germany **8-1**
by W. Fritz
8.1 Nomenclature 8-1
8.2 Introduction 8-1
8.3 Geometry 8-2
8.4 Test Cases 8-3
8.5 Grid Generation 8-4
8.5.1 General Remarks 8-4
8.5.2 Solution Based Grid Adaptation 8-4
8.6 Flow Solution 8-9
8.7 Results and Discussion 8-10
8.7.1 Flight Condition 7 8-10
8.7.2 Flight Condition 19 8-14
8.7.3 Flight Condition 25 8-15
8.7.4 Flight Condition 70 8-21
8.8 Conclusions 8-25
8.9 Acknowledgements 8-26
8.10 References 8-26

Chapter 9 – Numerical Solutions for the CAWAPI Configuration on Unstructured Grids at USAFA, United States **9-1**
by S. Morton, D.R. McDaniels and R.M. Cummings
9.1 Summary 9-1
9.2 Introduction 9-1
9.3 Solution Method 9-2
9.3.1 Flow Solver 9-2
9.3.2 Numerical Grid and Boundary Conditions 9-2
9.4 Results 9-4
9.4.1 Time Step Study 9-6
9.4.2 Low Speed Medium to High Alpha Flight Conditions 9-10
9.4.2.1 Flight Condition 7 9-10
9.4.2.2 Flight Condition 19 9-19

9.4.2.3 Flight Condition 46 9-20
9.4.2.4 Flight Condition 25 9-23
9.4.3 Transonic Flight Condition 70 (FC70) 9-27
9.4.4 Sideslip Flight Conditions 9-30
9.4.4.1 Flight Condition 50 9-30
9.4.4.2 Flight Condition 51 9-34
9.4.5 Improvements to the Baseline 9-37
9.4.5.1 Full Span FC46 Simulations 9-37
9.4.5.2 Turbulence Model Improvements 9-39
9.5 Concluding Remarks 9-42
9.6 References 9-42

Chapter 10 – Numerical Solutions for the CAWAPI Configuration on Unstructured Grids at KTH/FOI, Sweden – Part I **10-1**
by S. Görtz and A. Jirásek
10.1 Summary 10-1
10.2 Nomenclature 10-1
10.3 Denotation of Turbulence Models 10-1
10.4 Introduction 10-2
10.5 Flight Conditions 10-2
10.6 Aircraft Description and Geometry 10-3
10.6.1 Geometry Simplifications 10-4
10.7 Computational Method 10-4
10.7.1 Description of the Edge CFD Solver 10-4
10.7.2 Turbulence Modeling in Edge 10-5
10.7.2.1 Spalart-Allmaras Model of Turbulence (S-A) 10-5
10.7.2.2 Explicit Algebraic Reynolds Stress Model (EARSM) 10-5
10.7.2.3 Curvature Corrected Explicit Algebraic Reynolds Stress Model (EARSM + CC) 10-5
10.7.2.4 Differential Reynolds Stress Model (DRSM) 10-6
10.7.2.5 Detached-Eddy Simulation (DES) 10-6
10.7.3 Numerical Grid and Boundary Conditions 10-7
10.7.4 Convergence 10-10
10.8 Results and Discussion 10-11
10.8.1 Surface Pressure Coefficient 10-11
10.8.1.1 Flight Condition FC46 10-12
10.8.1.2 Flight Condition FC25 10-15
10.8.1.3 Flight Condition FC70 10-19
10.8.2 Skin Friction Coefficient at FC19 10-21
10.8.3 Boundary Layer Velocity Profiles at FC07 10-22
10.8.4 Adaptive Mesh Refinement at FC46 10-24
10.9 Best Practices 10-25
10.10 Conclusions 10-25
10.11 Acknowledgments 10-27
10.12 References 10-27

Chapter 11 – Numerical Solutions for the CAWAPI Configuration on Unstructured Grids at KTH/FOI, Sweden – Part II 11-1
by A. Jirásek and A. Rizzi
11.1 Summary 11-1
11.2 Introduction 11-1
11.3 Flow Solver 11-3
11.4 Calculations with Engine Boundary Conditions 11-3
11.4.1 Methodology 11-3
11.4.2 Results 11-4
11.4.2.1 Flight Condition FC46 11-4
11.4.2.2 Flight Condition FC19 11-6
11.4.2.3 Flight Condition FC07 11-7
11.4.3 Updated Values of Total Pressure in the Nozzle 11-7
11.5 Additional Results 11-8
11.6 Conclusions 11-9
11.7 Acknowledgements 11-10
11.8 References 11-10

Chapter 12 – Numerical Solutions for the CAWAPI Configuration on Unstructured Grids at Boeing-St. Louis, United States 12-1
by T.R. Michal, M. Oser, M. Mani and F.W. Roos
12.1 Summary 12-1
12.2 Introduction 12-1
12.3 CFD Toolset 12-2
12.4 Results 12-3
12.5 Summary and Conclusions 12-16
12.6 References 12-16

Chapter 13 – Numerical Solutions for the CAWAPI Configuration on Unstructured Grids at Lockheed Martin, United States 13-1
by M.B. Davis, C.L. Reed and P.J. Yagle
13.1 Summary 13-1
13.2 Introduction 13-1
13.3 Falcon v4 13-3
13.4 F-16XL Geometry and Computational Grid 13-5
13.5 Results and Discussion 13-8
13.5.1 Flight Condition 7 13-9
13.5.2 Flight Condition 19 13-15
13.5.3 Flight Condition 70 13-20
13.6 Conclusions 13-24
13.7 References 13-24

Chapter 14 – Numerical Solutions for the CAWAPI Configuration on Unstructured Grids at UT-SimCenter, United States 14-1
by S.L. Karman Jr., B. Mitchell, S. Sawyer and J. Whitt
14.1 Summary 14-1

14.2 Introduction 14-1
14.3 Unstructured Mesh Generation 14-1
14.3.1 Geometry 14-2
14.3.2 Inviscid Mesh 14-2
14.3.3 Viscous Mesh 14-4
14.4 Unstructured Flow Solver 14-6
14.4.1 Arbitrary Mach Algorithm 14-6
14.4.2 Iteration Hierarchy 14-7
14.4.3 Parallel Solver 14-7
14.4.4 Turbulence Modeling 14-7
14.5 Flight Conditions and Engine Parameters 14-7
14.6 Results 14-9
14.6.1 Adapted Mesh 14-9
14.6.2 Surface Pressure Coefficient Comparisons for All Flight Conditions 14-10
14.6.3 Selected Convergence Plots 14-30
14.6.4 Field and Surface Color Contour Plots 14-32
14.7 Concluding Remarks 14-35
14.8 References 14-36

Chapter 15 – Numerical Solutions for the CAWAPI Configuration on Unstructured Grids at NASA LaRC, United States **15-1**
by J.E. Lamar and K.S. Abdol-Hamid
15.1 Summary 15-1
15.2 Introduction 15-1
15.3 Solver Description and Application to CAWAPI 15-4
15.3.1 Description 15-4
15.3.2 Engine Modeling, Flight Conditions, and Computers Used 15-4
15.3.3 Convergence Histories 15-4
15.4 Turbulence Model Studies: Results and Discussion 15-4
15.4.1 FC46 ($M_\infty = 0.527$, $\alpha = 10.4°$, $R_n = 46.9 \times 10^6$) [Flight at $\beta < 1°$, Modeled as $\beta = 0°$] 15-4
15.4.2 FC70 ($M_\infty = 0.97$, $\alpha = 4.37°$, $R_n = 88.77 \times 10^6$) [Flight at $\beta < 1°$, Modeled as $\beta = 0°$] 15-10
15.5 Other Subsonic Comparisons 15-15
15.5.1 Symmetric: FC25 ($M_\infty = 0.242$, $\alpha = 19.84°$, $R_n = 32.22 \times 10^6$) [Flight at $\beta < 1°$, Modeled as $\beta = 0°$] 15-15
15.5.2 Asymmetric [Flight Parameter Value for $\beta \neq 0°$, Modeled] 15-18
15.5.2.1 FC50 ($M_\infty = 0.434$, $\alpha = 13.56°$, $\beta = +5.31°$, $R_n = 39.41 \times 10^6$) 15-19
15.5.2.2 FC51 ($M_\infty = 0.441$, $\alpha = 12.89°$, $\beta = -4.58°$, $R_n = 38.95 \times 10^6$) 15-22
15.5.3 Boundary Layer Comparisons 15-25
15.5.4 Skin Friction Comparisons 15-29
15.6 Conclusions 15-30
15.7 Acknowledgments 15-30
15.8 References 15-31
Appendix 15-1 15-33

Chapter 16 – What was Learned from Numerical Simulations of F-16XL (CAWAPI) at Flight Conditions 16-1
by A. Rizzi, A. Jirásek, K.J. Badcock, O.J. Boelens, J.E. Lamar and S. Crippa
16.1 Summary 16-1
16.1.1 Nomenclature 16-1
16.1.2 Organizations 16-1
16.2 Introduction 16-2
16.3 Overview of Codes and Comparisons 16-2
16.4 Low-Speed Flow Cases 16-4
16.4.1 Unsteady Flows at High Angle of Attack – FC25 16-4
16.4.1.1 Overview 16-4
16.4.1.2 Vortical Flow Features 16-4
16.4.1.3 C_p Comparisons along Butt Line Sections 16-6
16.4.2 Skin Friction Coefficient – FC19 16-8
16.4.2.1 Overview 16-8
16.4.2.2 Vortical Flow Features 16-8
16.4.2.3 Skin Friction Comparison 16-8
16.4.3 Velocity Profiles – FC7 16-9
16.4.3.1 Overview 16-9
16.4.3.2 Velocity Comparisons 16-9
16.4.4 Results at Sideslip Flight Conditions – FC50, FC51 16-11
16.5 Transonic Flow Case 16-12
16.5.1 Overview 16-12
16.5.2 Overall Vortical Flow Features 16-12
16.5.3 Investigating Possible Causes of Discrepancies 16-14
16.5.3.1 Activities to Eliminate Possible Numerical Effects 16-14
16.5.3.2 Activities to Eliminate Possible Flight Test Reasons 16-15
16.5.4 Highly-Adapted Meshes to Resolve Interaction of Vortex with Shock 16-16
16.5.5 Comparisons along Butt Line Sections 16-18
16.5.6 Comparisons along Flight Stations 16-21
16.5.7 FC70 Concluding Remarks and Lessons Learned 16-24
16.6 Perspectives 16-25
16.6.1 Progress Since NASA-TP 16-25
16.6.2 Technology Readiness Level Improvements 16-26
16.7 Conclusions 16-28
16.8 Acknowledgments 16-29
16.9 References 16-29
Appendix 16-1: Force and Moment Coefficient Comparisons 16-31
A1.1 Low-Speed Flow Cases 16-31
A1.1.1 FC25 – Force/Moments Comparison 16-31
A1.1.2 FC19 – Force/Moments Comparison 16-32
A1.1.3 FC7 – Force/Moments Comparison 16-32
A1.1.4 FC50 – Force/Moments Comparison 16-33
A1.1.5 FC51 – Force/Moments Comparison 16-33
A1.2 Transonic Flow 16-34
A1.2.1 FC70 – Force/Moments Comparison 16-34
Appendix 16-2: Statistical Analysis 16-35

Chapter 17 – The International Vortex Flow Experiment 2 (VFE-2): Objectives and Overview 17-1
by D. Hummel
17.1 Summary 17-1
17.2 Introduction 17-1
17.3 Objectives for New Experimental Investigations 17-3
17.3.1 Test Configuration 17-3
17.3.2 Objectives for New Tests 17-5
17.4 Organization of VFE-2 17-5
17.4.1 Formation of an RTO Task Group 17-5
17.4.2 Selection of Flow Phenomena to be Studied within VFE-2 17-6
17.4.3 Wind Tunnel Models 17-10
17.4.4 Numerical Investigations 17-10
17.4.5 Use of a Virtual Laboratory 17-11
17.4.6 Program of Work 17-11
17.5 Presentation of Results 17-13
17.6 References 17-14
Appendix 17-1: List of the Members of the VFE-2 Facet of AVT-113 17-18

Chapter 18 – Initial Experiments and Analysis of Blunt-Edge Vortex Flows 18-1
by J.M. Luckring
18.1 Summary 18-1
18.2 Nomenclature 18-1
18.3 Introduction 18-1
18.4 Basic Considerations for Slender-Wing Vortex Flows 18-2
18.5 Models and Tests 18-4
18.6 Aerodynamics of Blunt-Edged Vortex Flows 18-7
18.6.1 Contrast of Sharp and Blunt Edge Flows 18-7
18.6.2 Reynolds Number and Bluntness Effect 18-9
18.6.3 Compressibility Effects 18-13
18.6.4 Summary Effects 18-17
18.7 Concluding Remarks 18-20
18.8 References 18-21

Chapter 19 – Experimental Investigations on the VFE-2 Configuration at DLR, Germany 19-1
by R. Konrath, C. Klein, A. Schroeder and K. de Groot
19.1 Summary 19-1
19.2 Introduction 19-1
19.3 Investigations in the Transonic Wind Tunnel in Göttingen 19-3
19.3.1 Test Conditions and Measurement Setups 19-3
19.3.1.1 Wind Tunnel Facility and Model Instrumentation 19-3
19.3.1.2 Application of Pressure Sensitive Paint 19-4
19.3.1.3 Application of Particle Image Velocimetry 19-6
19.3.1.4 Vortex Identification for Flow Field Analysis 19-7

19.3.2 Results 19-8
19.3.2.1 Comparison of PSI Results Obtained in TWG by DLR and NTF by NASA 19-8
19.3.2.2 Effects of Model Coating 19-9
19.3.2.3 Onset of Primary Vortex 19-10
19.3.2.4 Occurrence of Inner Vortical Structure 19-12
19.3.2.5 Formation of an Inner and Outer Primary Vortex 19-15
19.3.2.6 Effects of Angle-of-Attack on Vortex System Above Delta Wing with Rounded Leading Edges 19-20
19.3.2.7 Effects of Reynolds Number on Vortex System Above Delta Wing with Rounded Leading Edges 19-21
19.3.2.8 Vortex Breakdown Above the Delta Wing in Transonic Flow 19-24
19.4 Investigations in the Cryogenic Wind Tunnel in Cologne 19-27
19.4.1 Test Conditions and Measurement Setups 19-27
19.4.1.1 Wind Tunnel Facility and Model Instrumentation 19-27
19.4.1.2 Application of the Temperature Sensitive Paint and Infrared Techniques 19-29
19.4.1.3 Application of Particle Image Velocimetry 19-31
19.4.2 Preliminary Results from the DNW-KKK 19-32
19.5 Conclusions 19-38
19.6 Acknowledgments 19-39
19.7 References 19-39

Chapter 20 – Experimental Investigations on the VFE-2 Configuration at ONERA, France **20-1**
by O. Rodriguez
20.1 Notations 20-1
20.2 Introduction 20-1
20.3 Experimental Set Up 20-2
20.3.1 L1 Wind Tunnel 20-2
20.3.2 Model 1 20-2
20.3.3 Models 4 and 5 20-3
20.4 Results 20-5
20.4.1 Model 1 in Solid Walls Configuration 20-5
20.4.1.1 Test Section Apparatus 20-5
20.4.1.2 Tests 20-6
20.4.1.3 Results 20-6
20.4.2 Forces Measurement in Open Jet Tunnel (Model 4 and 5) 20-11
20.4.3 Forces Measurement and PIV Velocimetry in Solid Walls (Model 4 and 5) 20-13
20.4.3.1 Forces and Static Pressures 20-13
20.4.3.2 Analysis of Axial Force Correlation with the Flow Structure 20-18
20.4.3.3 Flow Field Velocity Measurements by PIV 20-21
20.5 Conclusions 20-25
20.6 References 20-25

Chapter 21 – Experimental Investigations on the VFE-2 Configuration at TU Munich, Germany **21-1**
by A. Furman and C. Breitsamter
21.1 Nomenclature 21-1

21.2 Introduction 21-2
21.3 Experimental Set-up 21-4
21.3.1 Facility 21-4
21.3.2 Model 21-4
21.3.3 Test Cases 21-4
21.3.4 Measurement Techniques 21-5
21.4 Analysis of Results 21-6
21.4.1 Flow Topology 21-6
21.4.1.1 Flow Field 21-6
21.4.1.2 Surface Flow 21-8
21.4.2 Mean Flow Field 21-12
21.4.2.1 Pressure Distribution 21-12
21.4.2.2 Velocity Distribution 21-20
21.4.3 Turbulent Flow Field 21-25
21.4.3.1 Unsteady Surface Pressure Intensities 21-25
21.4.3.2 Unsteady Surface Pressure Spectra 21-28
21.4.3.3 Velocity Fluctuation Intensities and Reynolds Stresses 21-32
21.4.3.4 Spectral Densities of Velocity Fluctuations 21-38
21.4.3.5 Vortex Bursting and Dominant Frequency 21-43
21.4.4 Boundary Layer 21-45
21.5 Conclusions and Outlook 21-48
21.6 Acknowledgments 21-49
21.7 References 21-49

Chapter 22 – Experimental Investigations on the VFE-2 Configuration at Glasgow University, United Kingdom **22-1**
by F.N. Coton, S.B. Mat and R.A.McD. Galbraith
22.1 Introduction 22-1
22.2 Experimental Set Up and Wind Tunnel Testing 22-1
22.2.1 Wind Tunnel Model 22-1
22.2.2 Test Set-up 22-2
22.2.3 Wind Tunnel Testing 22-5
22.3 The Delta Wing Flowfield 22-5
22.3.1 Sharp Leading Edge 22-5
22.3.2 Rounded Leading Edge 22-6
22.4 Results 22-7
22.4.1 Flow Visualization Results 22-7
22.4.1.1 Sharp Leading Edge Wing 22-8
22.4.1.2 Medium Radius Leading Edge Wing 22-9
22.4.1.3 Influence of Reynolds Number on Rounded Leading Edge Flow 22-11
22.4.1.4 Further Insight into Leading Edge Rounding 22-12
22.4.2 Forces and Moments 22-13
22.4.2.1 Steady Forces and Moments 22-13
22.5 Conclusions 22-16
22.6 References 22-16

Chapter 23 – Experimental Investigations on the VFE-2 Configuration at TUBITAK-SAGE, Turkey 23-1
by S. Kurun
23.1 Summary 23-1
23.2 Nomenclature 23-1
23.3 Introduction 23-1
23.4 Experimental Set Up and Wind Tunnel Testing 23-2
23.4.1 Wind Tunnel 23-2
23.4.2 Wind Tunnel Model 23-3
23.4.3 Test Set-up 23-4
23.4.4 Wind Tunnel Testing 23-6
23.5 Results 23-7
23.5.1 Oil Flow Visualization Results 23-7
23.5.2 Force-Moment Measurement Results 23-10
23.6 Conclusions 23-15
23.7 Acknowledgments 23-16
23.8 References 23-16

Chapter 24 – What was Learned from the New VFE-2 Experiments 24-1
by J.M. Luckring and D. Hummel
24.1 Summary 24-1
24.2 Nomenclature 24-1
24.3 Introduction 24-1
24.4 Normal/Axial Forces and Pitching Moment Characteristics for Sharp and Rounded Leading Edges 24-3
24.5 Onset of Vortical Flow on the VFE-2 Configuration with Rounded Leading Edge 24-5
24.5.1 Principal Flow Structure at $\alpha = 13°$ 24-5
24.5.2 Variation of the Angle of Attack 24-8
24.5.3 Variation of Reynolds Number 24-10
24.5.4 Variation of Mach Number 24-13
24.5.5 Status of the Boundary Layers at $\alpha = 13°$ 24-14
24.6 Fully Developed Vortical Flow Without Vortex Breakdown 24-16
24.7 Fully Developed Vortical Flow With Vortex Breakdown 24-21
24.8 Concluding Remarks 24-24
24.9 Acknowledgments 24-25
24.10 References 24-25

Chapter 25 – Numerical Solutions for the VFE-2 Configuration on Structured Grids at EADS-MAS, Germany 25-1
by W. Fritz
25.1 Nomenclature 25-1
25.2 Organizations 25-1
25.3 Introduction 25-2
25.4 Geometry and Computational Grids 25-3

25.5 Flow Solver 25-4
25.6 Results and Discussion 25-5
25.6.1 Effect of Leading Edge Bluntness 25-5
25.6.2 Effect of Reynolds Number and Transition 25-6
25.6.3 Test Case 4.5, M = 0.4, Re = 3 x 10^6, α = 13° 25-10
25.6.4 Test Case 14, M = 0.4, Re = 6 x 10^6, α = 18° 25-17
25.7 Conclusions 25-19
25.8 Acknowledgements 25-20
25.9 References 25-20

Chapter 26 – Numerical Solutions for the VFE-2 Configuration on Structured Grids at ONERA, France **26-1**
by J.-F. LeRoy and J. Riou
26.1 Introduction 26-1
26.2 Nomenclature 26-1
26.3 Steady Approach 26-1
26.3.1 Computational Grids 26-2
26.3.2 Computational Method 26-2
26.3.3 Aerodynamic Conditions 26-3
26.3.4 Sharp Leading Edge Results 26-3
26.3.5 Medium Leading Edge Results 26-9
26.4 Unsteady Approach 26-14
26.4.1 Computational Method 26-14
26.4.2 Study of the Instantaneous Flow 26-15
26.4.3 Study of the Time-Averaged Flow 26-16
26.4.4 Spectral Analysis 26-20
26.5 Conclusions 26-22
26.6 References 26-22

Chapter 27 – Numerical Solutions for the VFE-2 Configuration on Structured Grids at NLR, The Netherlands **27-1**
by O.J. Boelens
27.1 Introduction 27-1
27.2 Grid 27-2
27.3 Flow Solver 27-3
27.4 Results 27-3
27.4.1 Sharp Leading Edge Delta Wing 27-3
27.4.2 Large Radius Leading Edge Delta Wing 27-3
27.5 Concluding Remarks 27-3
27.6 References 27-4
Appendix 27-1: Sharp Leading Edge Delta Wing 27-5
Appendix 27-2: Large Radius Leading Edge Delta Wing 27-11

Chapter 28 – Numerical Solutions for the VFE-2 Configuration on Unstructured Grids **28-1**
by E. Gurdamar, Y. Ortakaya, S. Kaya and B. Korkem
28.1 Computational Details 28-2
28.1.1 Flow Solver 28-2
28.1.2 Numerical Grid and Boundary Conditions 28-2
28.2 Test Cases 28-4
28.3 Results and Discussion 28-5
28.3.1 Flow Solver (xFLOWg) Evaluation 28-5
28.3.2 Comparison with Experimental Results 28-11
28.3.3 Some Factors Influencing the Vortical Flow Field 28-14
28.3.3.1 Influence of Mach Number 28-14
28.3.3.2 Influence of Leading Edge Bluntness 28-17
28.3.3.3 Influence of Angle of Attack 28-21
28.4 Conclusions 28-25
28.5 References 28-25

Chapter 29 – Shock Effects on Delta Wing Vortex Breakdown **29-1**
by L.A. Schiavetta, O.J. Boelens, S. Crippa, R.M. Cummings, W. Fritz and K.J. Badcock
Abstract 29-1
29.1 Introduction 29-1
29.2 Experiments 29-2
29.3 CFD Study 29-3
29.3.1 Subsonic Results 29-4
29.3.2 Transonic Results 29-5
29.3.3 Location of Shock Waves in Glasgow Solution 29-6
29.3.4 Sensitivity Study 29-8
29.3.4.1 Effect of Grid Refinement 29-8
29.3.4.2 Effect of Turbulence Model 29-9
29.3.4.3 Comparison of Structured Grid Results 29-10
29.3.4.4 Influence of Time Accuracy 29-11
29.4 Evaluation 29-11
29.4.1 Shock-Vortex Interaction – Analysis Framework 29-11
29.4.2 Quantitative Assessment 29-13
29.4.3 Validation of the Axial Flow Predictions 29-17
29.4.4 Shock Behaviour in Unsteady Solutions 29-19
29.4.5 Motion of Vortex Breakdown Location 29-21
29.5 Conclusions 29-23
29.6 Acknowledgements 29-23
29.7 References 29-23

Chapter 30 – Numerical Solutions for the VFE-2 Configuration on Unstructured Grids at KTH, Sweden **30-1**
by S. Crippa
30.1 Introduction 30-1

30.2 Model Description 30-1
30.3 Computational Method 30-1
30.3.1 Solver 30-1
30.3.2 Numerical Model and Boundary Conditions 30-2
30.4 Subsonic Cases 30-3
30.4.1 Test Cases 30-3
30.4.1.1 Mid to High Incidence 30-3
30.4.1.2 Low Incidence 30-4
30.4.2 Numerical Grids 30-4
30.4.2.1 Low Reynolds Number Cases 30-5
30.4.2.2 High Reynolds Number Cases 30-7
30.4.2.3 Inviscid Case 30-7
30.4.3 Results and Discussion 30-8
30.4.3.1 Separation Onset Analysis 30-8
30.4.3.2 Flow Topological Analysis 30-17
30.5 Transonic Cases 30-26
30.5.1 Introduction 30-27
30.5.2 Test Case 30-27
30.5.3 Numerical Grids 30-27
30.5.4 Comparison of Numerical Grids 30-29
30.5.5 Results 30-30
30.5.5.1 Sting Installation 30-31
30.5.5.2 Sideslip 30-33
30.6 References 30-34

Chapter 31 – Numerical Solutions for the VFE-2 Configuration on Unstructured Grids at DLR, Germany **31-1**
by A. Schütte and H. Lüdeke
31.1 Introduction 31-1
31.2 Numerical Approach 31-2
31.2.1 CFD Solver TAU 31-2
31.3 Experimental Data 31-3
31.3.1 Flow Topology 31-4
31.4 Numerical Results 31-7
31.4.1 Computational Grid 31-7
31.4.2 Wilcox k-ω Calculations 31-8
31.4.3 Spalart-Allmaras Calculations 31-11
31.4.4 Sensitivities 31-14
31.4.5 Flow Physics 31-15
31.5 Conclusions 31-20
31.6 References 31-20

Chapter 32 – Numerical Solutions for the VFE-2 Configuration on Unstructured Grids at USAFA, United States **32-1**
by R.M. Cummings and A. Schütte
32.1 Nomenclature 32-1

32.2 Introduction 32-2
32.3 Numerical Approach 32-3
32.3.1 CFD Solver Cobalt 32-3
32.3.2 Turbulence Models 32-3
32.3.2.1 Spalart-Allmaras Turbulence Model (SA) 32-3
32.3.2.2 Spalart-Allmaras Turbulence Model with Rotation Correction (SARC) 32-5
32.3.2.3 Detached-Eddy Simulation (DES) 32-5
32.3.2.4 Delayed Detached-Eddy Simulation (DDES) 32-6
32.4 Experimental Data 32-6
32.5 Numerical Results and Discussion 32-9
32.5.1 Rounded Leading Edge Flowfield 32-9
32.5.2 RANS Simulations 32-9
32.5.3 DES and DDES Simulations 32-20
32.5.4 Discussion of Flow Topology 32-26
32.6 Conclusions 32-28
32.7 Acknowledgements 32-29
32.8 References 32-29

Chapter 33 – Semi-Empirical Prediction of Vortex Onset on the VFE-2 Configurations **33-1**
by R.K. Nangia
Abstract 33-1
33.1 Nomenclature 33-1
33.2 Introduction and Background 33-2
33.3 Prediction Approach 33-8
33.3.1 General Approach 33-9
33.3.2 Analysis of Sectional LE Thrust (Based on Carlson's Work) 33-12
33.3.2.1 Mach and Reynolds Number Effects on C_{plim} or K_T 33-15
33.3.2.2 Aerofoil Geometry Effects on C_{plim} and K_T 33-19
33.3.3 LE Thrust Considerations for Swept 3-D Wings 33-21
33.3.3.1 C_{plim} on 3-D Wings 33-23
33.3.3.2 Modelling Delay in Flow Separation Onset Due to Model Thickness 33-23
33.3.4 Summarising the Process for Determining the Position of the Onset of Vortical Flow 33-24
33.3.5 Remarks 33-24
33.4 Comparisons with VFE-2 Experiments 33-25
33.4.1 Modelling Detail from NASA LaRC Work Programme on 65° Delta 33-25
33.4.2 Results from Luckring's Papers on Vortex Flow Onset 33-25
33.4.3 Results and Comparisons 33-26
33.5 Concluding Remarks 33-32
33.6 Acknowledgements 33-33
33.7 References 33-33

Chapter 34 – Lessons Learned from the Numerical Investigations on the VFE-2 Configuration **34-1**
by W. Fritz and R.M. Cummings
34.1 Nomenclature 34-1

34.2 Introduction 34-2
34.3 Goals for the VFE-2 Numerical Solutions 34-5
34.4 Rounded Leading Edge Flow Topology 34-5
34.5 Computer Codes and Turbulence Models 34-7
34.6 Results and Discussions 34-8
34.6.1 Case 4.5: MRLE, M = 0.40, α = 13°, Re = 3 x 10^6 34-8
34.6.2 Case 5: MRLE, M = 0.40, α = 13°, Re = 6 x 10^6 34-13
34.6.3 Case 14: MRLE, M = 0.40, α = 18°, Re = 6 x 10^6 34-17
34.6.4 Case 15: SLE, M = 0.40, α = 18°, Re = 6 x 10^6 34-20
34.6.5 Case 24: SLE, M = 0.40, α = 23°, Re = 6 x 10^6 34-22
34.6.6 Case 27: SLE, M = 0.85, α = 23°, Re = 6 x 10^6 34-25
34.7 Conclusions and Recommendations 34-31
34.8 Acknowledgements 34-32
34.9 References 34-32
Appendix 34-1 34-34

Chapter 35 – Final Results of the International Vortex Flow Experiment – Resumé and Outlook **35-1**
by D. Hummel
35.1 Summary 35-1
35.2 Introduction 35-1
35.3 Fully Separated Flow Without Vortex Breakdown 35-2
35.3.1 Overall Forces and Moments 35-2
35.3.2 Pressure Distributions 35-3
35.3.3 Viscous Flow Details 35-6
35.3.3.1 Flow Field Measurements 35-6
35.3.3.2 Laminar/Turbulent Transition 35-9
35.4 Fully Separated Flow With Vortex Breakdown 35-11
35.4.1 Subsonic Flow Investigations 35-12
35.4.1.1 Surface Pressure Fluctuations 35-12
35.4.1.2 Unsteady Flow Field 35-13
35.4.1.3 Time-Averaged Surface Pressure Distributions 35-14
35.4.2 Transonic Flow Investigations 35-16
35.4.2.1 Experimental Results 35-16
35.4.2.2 Numerical Results 35-16
35.5 Partly Separated Vortical Flow 35-18
35.5.1 Overall Forces and Moments 35-19
35.5.2 Pressure Distributions 35-20
35.5.3 Effects of Angle of Attack 35-23
35.5.4 Effects of Reynolds Number 35-24
35.5.5 Effects of Mach Number 35-25
35.5.6 Understanding of the Flow Physics 35-26
35.6 Conclusions and Outlook 35-29
35.7 References 35-31

Chapter 36 – Summary of the Synergistic Effects Obtained by the Present Study of Vortical Flows **36-1**
by J.E. Lamar and D. Hummel
36.1 Summary 36-1
36.2 Introduction 36-1
36.3 Synergy 36-1
36.3.1 Experimental and Computational Data 36-1
36.3.2 Virtual Laboratory Usage 36-2
36.3.3 Dissemination of Results 36-2
36.3.3.1 Conferences 36-2
36.3.3.2 Journal Articles 36-2
36.3.4 Career Development 36-3
36.4 Concluding Remarks 36-3
36.5 References 36-3

Chapter 37 – Conclusions and Recommendations **37-1**
by J.E. Lamar and D. Hummel
37.1 Summary 37-1
37.2 Introduction 37-1
37.3 Conclusions 37-1
37.3.1 CAWAPI Facet 37-1
37.3.2 VFE-2 Facet 37-2
37.4 Recommendations 37-2
37.4.1 CAWAPI Facet 37-2
37.4.2 VFE-2 Facet 37-2
37.5 References 37-3

Appendix 1 – List of the Members of the Task Group AVT-113 **A1-1**

Appendix 2 – CAWAP Experimental Data – NASA/TP-2001-210629/ Supplement **A2-1**
by J.E. Lamar
A2.1 Summary A2-1
A2.2 Introduction A2-1
A2.3 Conclusions A2-1

Appendix 3.1 – Experimental Results from NASA Langley **A3.1-1**
by J.M. Luckring
A3.1.1 Summary A3.1-1
A3.1.2 Pressure Measurements A3.1-1
A3.1.3 Force Measurements A3.1-3
A3.1.4 References A3.1-3

Appendix 3.2 – Experimental Results from DLR Göttingen **A3.2-1**
by R. Konrath
A3.2.1 Surface Pressure Distributions A3.2-1
A3.2.2 Flow Velocity Vector Fields A3.2-1

Appendix 3.3 – Experimental Results from TU Munich **A3.3-1**
by A. Furman and C. Breitsamter

Appendix 3.4 – Experimental Results from ONERA **A3.4-1**
by O. Rodriguez
A3.4.1 Structure of the Data A3.4-1
A3.4.1.1 General Configuration and Test Conditions A3.4-1
A3.4.1.2 Specific Test Conditions A3.4-1

Appendix 3.5 – Experimental Results from University of Glasgow **A3.5-1**
by F.N. Coton, S.B. Mat and R.A.McD. Galbraith
A3.5.1 Flow Visualisation Data A3.5-2
A3.5.1.1 Angle of Attack, $\alpha = 13.3°$ A3.5-2
A3.5.1.2 Angle of Attack, $\alpha = 18.5°$ A3.5-5
A3.5.1.3 Angle of Attack, $\alpha = 23°$ A3.5-8
A3.5.2 Steady Force and Moment Coefficients for VFE-2 Wing Configurations A3.5-11
A3.5.2.1 Medium Radius Wing A3.5-11
A3.5.2.2 Sharp Edged Wing A3.5-11
A3.5.3 Unsteady Force and Moment Coefficients A3.5-11

Appendix 3.6 – Structured Grids from EADS-MAS, Germany **A3.6-1**
by W. Fritz
A3.6.1 Geometry A3.6-1
A3.6.2 Computational Grid A3.6-2
A3.6.3 Availability of the Grids A3.6-5
A3.6.4 Some EADS Results Using the Grids A3.6-8

Appendix 3.7 – Unstructured Grid Geometry and Description **A3.7-1**
by A. Schütte
A3.7.1 Geometry A3.7-1
A3.7.2 DLR TAU-Code and Cobalt Grid Generation Description A3.7-2

List of Figures

Figure		Page
CHAPTER 1		
Figure 1-1	The F-16XL Aircraft in Flight with Tuft and Video Targets on the Left Wing	1-1
Figure 1-2	The 65° Delta Wing-Sting Combination in the NASA NTF	1-2
CHAPTER 2		
Figure 2-1	Primitive AVT-113 Solution: Original Process	2-3
Figure 2-2	Components Needed to Create a Virtual Laboratory Solution for AVT-113, Plan 2003/2004	2-4
Figure 2-3	Replacement of Primitive Solution with Virtual Laboratory: Improved Process	2-5
Figure 2-4	Planned Upgrade Virtual Laboratory for AVT-113 to Satisfy Reduced Annual Cost, 2005	2-5
Figure 2-5	Necessitated Upgrade to Virtual Laboratory to Satisfy Loss of Mass Storage System, 2005	2-7
Figure 2-6	Virtual Laboratory Process as Envisioned for CAWAPI Facet	2-8
Figure 2-7	Virtual Laboratory Including VFE-2 Facet Capability	2-9
CHAPTER 3		
Figure 3-1	F-16XL-1 Aircraft with Missiles, Tufts, Modified Flow-Visualization Paint Scheme, and Video Targets at NASA Dryden Flight Research Center	3-3
Figure 3-2	Three-View Drawing of F-16XL-1 Airplane	3-3
Figure 3-3	High-Speed Civil Transport Concept	3-4
Figure 3-4	F-16XL-1 Research Aircraft Modifications	3-5
Figure 3-5	Schematic of Ground to Flight Correlation for Assessing the Impact of Aerodynamic and Operational Concepts on Noise Profiles	3-5
Figure 3-6	General Layout of Pressure and Hot-Film Instrumentation Suite on the F-16XL-1 Aircraft	3-8
Figure 3-7	Details of Complete-Pressure-Instrumentation Suite and Layout on the Airplane	3-9
Figure 3-8	General Arrangement of Rake and Modified Preston Tube Relative Locations on F-16XL-1 Left Wing; Pressure Instruments Oriented for $M_\infty = 0.29$, $\alpha = 13°$ and $R_n = 46.1 \times 10^6$	3-10
Figure 3-9	Locations of the Video Suite on the F-16XL-1 Airplane	3-11
Figure 3-10	CFD Block Structure Layout for F-16XL-1	3-12
Figure 3-11	CFD (CFL3D) and Measured C_p at FC46 ($M_\infty = 0.527$, $\alpha = 10.4°$, $R_n = 46.9 \times 10^6$)	3-14
Figure 3-12	Flight Tuft Data from Three Cameras on F-16XL-1 Airplane and CFD Solution at FC46 ($M_\infty = 0.527$, $\alpha = 10.4°$, $R_n = 46.9 \times 10^6$)	3-17
Figure 3-13	Predicted and Measured Velocity Profiles for Boundary-Layer Rakes on F-16XL-1 Airplane for FC7 ($M_\infty = 0.304$, $\alpha = 11.89°$, $\beta_{nom} = 0°$, h = 5000 ft, $R_n = 44.4 \times 10^6$)	3-19

Figure 3-14 Predicted and Measured c_f on F-16XL-1 Airplane at FS 330 for FC19/FC7 (M_{avg} = 0.33, α_{avg} = 11.9°, β_{nom} = 0°, $R_{n,avg}$ = 45.6 x 10^6) 3-20
Figure 3-15 Abstraction of the Surface Geometry and Projected Abstraction for the F-16XL Half-Span Model from Boelens, et al. 3-22
Figure 3-16 Surface Streamlines with Interpretation for FC7 with ENSOLV Solver 3-23
Figure 3-17 Upper and Lower Surface C_p Results for FC7 with PMB Solver 3-24
Figure 3-18 Turbulence Modeling Effect on C_p for FC46 with PAB3D Solver 3-24
Figure 3-19 Turbulence Modeling Effect on C_p for FC19 with Edge Solver 3-25
Figure 3-20 Turbulence Modeling Effect on C_p for FC46 with USM3D Solver 3-25
Figure 3-21 Solution Adaptive Grid Effect for FC46 with TAU Solver 3-26
Figure 3-22 Time Accurate Solution for FC19 with Cobalt Solver 3-26
Figure 3-23 Time Dependent Solution for FC7 with BCFD Solver 3-27
Figure 3-24 Mach 1 Iso-Surface Colored by Total Pressure at FC70 with Falcon v4 Solver 3-27
Figure 3-25 Pressure-Colored Streamlines and x-Vorticity Component for FC50 with TENASI Solver 3-28

CHAPTER 4

Figure 4-1 CAD Geometry Representation of the F-16XL Aircraft 4-2
Figure 4-2 Abstraction of the Surface Geometry (a) and Projected Abstraction (b) for the F-16XL Half-Span Model 4-4
Figure 4-3 Topology on the Geometry, the Symmetry Plane and the Far-Field Boundaries 4-5
Figure 4-4 Upper Surface Grid for the Structured Grid 4-6
Figure 4-5 Grid Planes Showing the Grid Density Off the Aircraft Surface in a Plane Approximately Normal to the Flow Direction (FS is constant) (a) and in a Plane Approximately Parallel to the Flow Direction (BL is constant) (b) 4-7
Figure 4-6 Levels of y^+ on the Upper Surface for Flight Condition 19 (TNT k-ω Turbulence Model with Correction for Vortical Flows) 4-7
Figure 4-7 Surface Grid of the Hybrid Baseline Unstructured Grid for the F-16XL-1 Half-Span Model (160,226 Faces) 4-8
Figure 4-8 Levels of y^+ on the Upper Surface for the Hybrid Baseline Unstructured Grid for Flight Condition 19 (EARSM) 4-8
Figure 4-9 Symmetry Plane of the Hybrid Baseline Unstructured Grid Showing the Meshed Inlet Duct and Nozzle 4-9
Figure 4-10 Wrinkly Cutting Plane at FS496 Showing the Grid Density Off the Aircraft Surface Close to the Trailing Edge of the Wing 4-9
Figure 4-11 Initial EADS-MAS Surface Grid and Final Adapted Grid for Flight Condition 25 (α = 19.84°, M = 0.242) 4-11
Figure 4-12 Leading Edge Mesh Showing the Converted Structured Mesh Domain Next to an Unstructured Mesh Domain 4-12
Figure 4-13 Symmetry Plane Mesh 4-12
Figure 4-14 Crinkle Cut of Mesh Near the Symmetry Plane at the Inlet 4-13
Figure 4-15 Magnified Views of Symmetry Plane Mesh at the Upper Inlet Lip and the Lower Inlet Lip 4-13

Figure 4-16 Magnified View of Axial Cut Through Tip Missile Fins and Wing 4-14

Figure 4-17 Comparison of Surface Meshes Near the Wing Leading Edge: (a) Hybrid Baseline Unstructured Grid; (b) Boeing Grid 4-15

CHAPTER 5

Figure 5-1 Iso-Surface (Level Equals 250 Hz) of Vorticity Magnitude for Flight Condition 7 (α = 11.89°, M = 0.304 and Re = 44.40 x 10^6) 5-6

Figure 5-2 Surface Pressure Coefficient for Flight Condition 25 (α = 19.84°, M = 0.242 and Re = 32.22 x 10^6) along Butt Lines: (a) BL55; (b) BL80; (c) BL 95; (d) BL153.5 and (e) BL184.5; and Fuselage Stations: (f) FS300; (g) FS375; and (h) FS450 5-7

Figure 5-3 Surface Pressure Coefficient for Flight Condition 7 (α = 11.89°, M = 0.304 and Re = 44.40 x 10^6) and Flight Condition 19 (α = 11.85°, M = 0.360 and Re = 46.80 x 10^6) along Butt Lines: (a) BL55; (b) BL80; (c) BL 95; (d) BL153.5; and (e) BL184.5; and Fuselage Stations: (f) FS300; (g) FS375; and (h) FS450 5-8

Figure 5-4 Boundary Layer Profiles for Flight Condition 7 (α = 11.89°, M = 0.304 and Re = 44.40 x 10^6) 5-10

Figure 5-5 Local Skin Friction Coefficient for Flight Condition 19 (α = 11.85°, M = 0.360 and Re = 46.80 x 10^6) at FS300 and FS330 5-11

Figure 5-6 Surface Streamlines Superimposed on the Negative of the Tuft Image for (a) Flight Condition 7 (α = 11.89°, M = 0.304 and Re = 44.40 x 10^6), Flight 145, Run 16b, Video (yr, 1996), 078:14:03:44 (Day:hr:min:sec) and (b) Flight Condition 25 (α = 19.84°, M = 0.242 and Re = 32.22 x 10^6), Flight 144, Run 16b, Video (yr, 1996), 074:10:04:03 (Day:hr:min:sec) 5-12

Figure 5-7 Surface Streamline Pattern for Flight Condition 7 (α = 11.89°, M = 0.304 and Re = 44.40 x 10^6): (a) Surface Streamlines with Non-Dimensional Vorticity Magnitude on a Cross-Sectional Plane at FS407.5; (b) Overview of the Surface Streamline Pattern; (c) Detail of the Surface Streamline Pattern on the Part of the Wing Inboard of the Crank; and (d) Detail of the Surface Streamline Pattern on the Part of the Wing Outboard of the Crank 5-13

CHAPTER 6

Figure 6-1 Geometry and Leading Edge Details 6-3

Figure 6-2 Measurement Locations Used for Comparisons 6-4

Figure 6-3 View of the Surface Mesh for the Full and Wing Only Configurations 6-5

Figure 6-4 Surface Pressure Coefficients 6-7

Figure 6-5 Comparison of Computations with Flight Measurements for FC07 6-8

Figure 6-6 Comparison of Computations with Flight Measurements for FC46 6-9

Figure 6-7 Comparison of Computations with Flight Measurements for FC25 6-10

Figure 6-8 Comparison of Boundary Layer Profiles with Flight Measurements for FC07 6-11

Figure 6-9 Surface C_p for FC70 6-12

Figure 6-10 Comparison of Computations with Flight Measurements for FC70 6-13

Figure 6-11 Comparison of Computations with Flight Measurements for FC07 6-15

Figure 6-12 Evaluation of Full and Wing Solutions for FC07 6-16

CHAPTER 7

Figure 7-1	Missiles, Tufts, Modified Flow-Visualization Paint Scheme, and Video Targets on Airplane at Dryden Flight Research Center	7-5
Figure 7-2	Computational Grid on Wing-Fuselage	7-6
Figure 7-3	Convergence History for FC 7 ($M = 0.304$, $\alpha = 11.89°$, $R_n = 44.4 \times 10^6$)	7-8
Figure 7-4	Computed and Measured Flight C_p at FC 46 ($M = 0.527$, $\alpha = 10.4°$, $R_n = 46.9 \times 10^6$)	7-9
Figure 7-5	Upper Surface Pressure Distribution with Streamlines FC 46 ($M = 0.527$, $\alpha = 10.4°$, $R_n = 46.9 \times 10^6$)	7-12
Figure 7-6	Surface with Vortex Core Location for FC 46 ($M = 0.527$, $\alpha = 10.4°$, $R_n = 46.9 \times 10^6$)	7-13
Figure 7-7	C_p Contours with Vortex Core Representation FC 46 ($M = 0.527$, $\alpha = 10.4°$, $R_n = 46.9 \times 10^6$)	7-14
Figure 7-8	Velocity Profiles for Boundary Layer Rakes on F-16XL for FC 7 ($M_\infty = 0.304$, $\alpha = 11.89°$, $R_n = 44.4 \times 10^6$)	7-15
Figure 7-9	Upper Surface Pressure Distribution for FC 7 ($M_\infty = 0.304$, $\alpha = 11.89°$, $R_n = 44.4 \times 10^6$)	7-16
Figure 7-10	Skin Friction on F-16XL Aircraft at FS 330 for FC 19 ($M_\infty = 0.36$, $\alpha = 11.85°$, $R_n = 46.8 \times 10^6$)	7-17
Figure 7-11	Upper Surface Pressure Distribution for FC 19 ($M_\infty = 0.36$, $\alpha = 11.85°$, $R_n = 46.8 \times 10^6$)	7-18
Figure 7-12	Upper Surface Pressure Distribution for FC 50 ($M = 0.434$, $\alpha = 13.56°$, $\beta = +5.31$, $R_n = 39.4 \times 10^6$)	7-19
Figure 7-13	Upper Surface Pressure Distribution for FC 51 ($M = 0.441$, $\alpha = 12.89°$, $\beta = -4.58$, $R_n = 38.9 \times 10^6$)	7-20
Figure 7-14	Comparison between PAB3D and USM3D C_p for FC 50 ($M = 0.434$, $\alpha = 13.56°$, $\beta = +5.31$, $R_n = 39.4 \times 10^6$)	7-21
Figure 7-15	Computed and Measured Flight C_p at FC 70 ($M = 0.97$, $\alpha = 4.37°$, $R_n = 88.77 \times 10^6$)	7-24

CHAPTER 8

Figure 8-1	Surface Geometry of the F-16XL Aircraft Used in the CFD-Simulations	8-3
Figure 8-2	Surface Grid Adaptation for FC 25 ($M_\infty = 0.242$, $\alpha = 19.84°$, $Re = 32.22 \times 10^6$)	8-5
Figure 8-3	Field Grid Adaptation for FC 25 ($M_\infty = 0.242$, $\alpha = 19.84°$, $Re = 32.22 \times 10^6$)	8-7
Figure 8-4	Manually and Solution Adapted Grid for FC 25 ($M_\infty = 0.242$, $\alpha = 19.84°$, $Re = 32.22 \times 10^6$)	8-8
Figure 8-5	Convergence of Surface Pressure Distribution during the Grid Adaptation for FC 25, ($M_\infty = 0.242$, $\alpha = 19.84°$, $Re = 32.22 \times 10^6$)	8-9
Figure 8-6	Surface Grids and Surface Pressure Contours for FC 7 ($M_\infty = 0.304$, $\alpha = 11.89°$, $Re = 44.4 \times 10^6$)	8-10
Figure 8-7	Effect of Turbulence Model on Surface Pressure Distribution at FC 7	8-11
Figure 8-8	Surface Pressure Distributions at Wing Sections y = constant for FC 7 ($M_\infty = 0.304$, $\alpha = 11.89°$, $Re = 44.4 \times 10^6$)	8-12
Figure 8-9	Surface Pressure Distributions at Cross-Sections x = constant for FC 7 ($M_\infty = 0.304$, $\alpha = 11.89°$, $Re = 44.4 \times 10^6$)	8-13

Figure 8-10	Comparison of Boundary Layer Profiles with Flight Measurements for FC 7 (M_∞ = 0.304, α = 11.89°, Re = 44.4 x 10^6, Solution Adapted Grid)	8-14
Figure 8-11	Comparison of Predicted and Measured c_f for FC 19 (M_∞ = 0.36, α = 11.85°, Re = 46.8 x 10^6)	8-15
Figure 8-12	Surface Pressure Contours for FC 25 (M_∞ = 0.242, α = 19.84°, Re = 32.22 x 10^6)	8-16
Figure 8-13	Computed and Measured Surface Pressure Distribution at FC 25 (M_∞ = 0.242, α = 19.84°, Re = 32.22 x 10^6)	8-17
Figure 8-14	Total Pressure Loss Contours at FC 25 (M_∞ = 0.242, α = 19.84°, Re = 32.22 x 10^6)	8-20
Figure 8-15	Surface Skin Friction Lines and Total Pressure Loss Contours at FC 25 (M_∞ = 0.242, α = 19.84°, Re = 32.22 x 10^6)	8-21
Figure 8-16	Grids for FC 70 (M_∞ = 0.97, α = 4.37°, Re = 88.77 x 10^6)	8-22
Figure 8-17	Computed Surface Pressure Contours in Different Grids at FC 70 (M_∞ = 0.97, α = 4.37°, Re = 88.77 x 10^6)	8-23
Figure 8-18	Computed and Measured Surface Pressure Distributions at FC 70 (M_∞ = 0.97, α = 4.37°, Re = 88.77 x 10^6)	8-24
Figure 8-19	y^+ Distribution at Wing Upper Surface for FC 70 (M_∞ = 0.97, α = 4.37°, Re = 88.77 x 10^6)	8-25

CHAPTER 9

Figure 9-1	F-16XL-1 Half-Span Model Surface Grid (160,266 Faces)	9-3
Figure 9-2	Symmetry Plane of the F-16XL-1 Baseline Unstructured Grid	9-3
Figure 9-3	Crinkle Cut Plane through the Grid at FS496	9-4
Figure 9-4	Spectrum of Unsteady Flow Phenomena	9-6
Figure 9-5	PSD of Normal Force Variation with Time at Various Time Steps	9-7
Figure 9-6	(a) Iso-Surfaces of X-Vorticity and Velocity Cutting Planes; (b) Velocity Cutting Planes and Pressure Tap Locations	9-8
Figure 9-7	Power Spectral Density Results for Pressure Tap #1	9-9
Figure 9-8	Wave Number Variation with Time Step for Pressure Tap #1	9-10
Figure 9-9	Flight Condition 7: (a) Iso-Surfaces of Vorticity Magnitude Colored by Pressure at an Instant in Time; (b) Time Averaged Surface Pressure Coefficient Distribution, C_p	9-11
Figure 9-10	Close Up View of the Vortical Flowfield above the F-16XL-1 at Flight Condition 7; Iso-Surfaces of Vorticity Magnitude Colored by Pressure at an Instant in Time	9-12
Figure 9-11	Comparison of an Instantaneous Solution to a Solution Time-Averaged after 2000 Time Steps: (a) Iso-Surfaces of Vorticity Magnitude Colored by Pressure; (b) Surface Pressure Coefficient Distribution, C_p	9-13
Figure 9-12	Comparison of an Instantaneous SARCDES Solution to a SARC RANS Solution; Iso-Surfaces of Vorticity Magnitude Colored by Pressure	9-13
Figure 9-13	Flight Condition 7; Cross-Planes of Vorticity in the x-Coordinate Direction	9-14
Figure 9-14	Flight Condition 7; Surface C_p along Various F-16XL Butt Line Stations (BL) for Flight Test, Computed Mean, and Computed Max and Min Value for a Series of Time Accurate Solutions	9-16
Figure 9-15	Flight Condition 7; Surface C_p along Various F-16XL Fuselage Stations (FS) for Flight Test, Computed Mean, and Computed Max and Min Values	9-17

Figure 9-16	Boundary Layer Rake Velocities Scaled by Rake-Edge Velocity for Rakes 3, 4, 5, and 7 at Flight Condition 7	9-18
Figure 9-17	Flight Condition 19: (a) Iso-Surfaces of Vorticity Magnitude Colored by Pressure; (b) Surface Pressure Coefficient Distribution, C_p	9-19
Figure 9-18	Local Skin Friction Coefficient along Fuselage Station 330	9-20
Figure 9-19	Flight Condition 46: (a) Iso-Surfaces of Vorticity Magnitude Colored by Pressure; (b) Surface Pressure Coefficient Distribution, C_p	9-21
Figure 9-20	Flight Condition 46: Surface C_p along Various F-16XL Butt Line Stations (BL) for Flight Test, Computed Mean, and Computed Max and Min Value for a Series of Time Accurate Solutions	9-22
Figure 9-21	Flight Condition 25: (a) Iso-Surfaces of Vorticity Magnitude Colored by Pressure; (b) Surface Pressure Coefficient Distribution, C_p	9-23
Figure 9-22	Close Up View of the Vortical Flowfield above the F-16XL-1 at Flight Condition 25; Iso-Surfaces of Vorticity Magnitude Colored by Pressure	9-24
Figure 9-23	Flight Condition 25: Surface C_p along Various F-16XL Butt Line Stations (BL) for Flight Test, Computed Mean, and Computed Max and Min Value for a Series of Time Accurate Solutions	9-25
Figure 9-24	Flight Condition 25: Surface C_p along Various F-16XL Fuselage Stations (FS) for Flight Test, Computed Mean, and Computed Max and Min Values	9-26
Figure 9-25	Flight Condition 70: (a) Iso-Surfaces of Vorticity Magnitude Colored by Pressure; (b) Surface Pressure Coefficient Distribution, C_p	9-27
Figure 9-26	Flight Condition 70: Surface C_p along Various F-16XL Butt Line Stations (BL) for Flight Test, Computed Mean, and Computed Max and Min Value for a Series of Time Accurate Solutions	9-28
Figure 9-27	Flight Condition 70: Surface C_p along Various F-16XL Fuselage Stations (FS) for Flight Test, Computed Mean, and Computed Max and Min Values	9-29
Figure 9-28	Flight Condition 50: (a) Iso-Surfaces of Vorticity Magnitude Colored by Pressure; (b) Surface Pressure Coefficient Distribution, C_p	9-30
Figure 9-29	Flight Condition 50: Surface C_p along Various F-16XL Butt Line Stations (BL) for Flight Test, Computed Mean, and Computed Max and Min Value for a Series of Time Accurate Solutions	9-32
Figure 9-30	Flight Condition 50: Surface C_p along Various F-16XL Fuselage Stations (FS) for Flight Test, Computed Mean, and Computed Max and Min Values	9-33
Figure 9-31	Flight Condition 51: (a) Iso-Surfaces of Vorticity Magnitude Colored by Pressure; (b) Surface Pressure Coefficient Distribution, C_p	9-34
Figure 9-32	Flight Condition 51: Surface C_p along Various F-16XL Butt Line Stations (BL) for Flight Test, Computed Mean, and Computed Max and Min Value for a Series of Time Accurate Solutions	9-35
Figure 9-33	Flight Condition 51: Surface C_p along Various F-16XL Fuselage Stations (FS) for Flight Test, Computed Mean, and Computed Max and Min Values	9-36
Figure 9-34	Flight Condition 46: F-16XL Surface C_p for Butt Line Station (BL) 55	9-37
Figure 9-35	Flight Condition 46: F-16XL Surface C_p for Butt Line Station (BL) 70	9-38
Figure 9-36	Flight Condition 46: F-16XL Surface C_p for Butt Line Station (BL) 153.5	9-38
Figure 9-37	BL 153.5 C_p versus x/c for DES and DDES Turbulence Models and Flight Test	9-39
Figure 9-38	Rake 3 Boundary Layer Rake Velocity Scaled by Rake-Edge Velocity Profiles at Flight Condition 7	9-40

Figure 9-39 Rake 4 Boundary Layer Rake Velocity Scaled by Rake-Edge Velocity Profiles at Flight Condition 7 9-40
Figure 9-40 Rake 5 Boundary Layer Rake Velocity Scaled by Rake-Edge Velocity Profiles at Flight Condition 7 9-41
Figure 9-41 Rake 7 Boundary Layer Rake Velocity Scaled by Rake-Edge Velocity Profiles at Flight Condition 7 9-41

CHAPTER 10

Figure 10-1 F-16XL-1 Instrumentation Suite, Port Wing: Dummy Missiles with Built-in Video Cameras, Tufts, Flow-Visualization Paint Scheme, Video Targets; Starboard Wing: Pressure Belts 10-4
Figure 10-2 Computational Grid 10-8
Figure 10-3 Wrinkly Cutting Plane at FS496 Showing the Grid Density off the Aircraft Surface close to the Trailing Edge 10-9
Figure 10-4 Convergence History of different RANS Turbulence Models for FC19: Density Residual versus Number of Iterations 10-10
Figure 10-5 F-16XL-1 Geometry with Position of Butt Lines (BL) and Fuselage Stations (FS) where C_p Was Measured in Flight 10-12
Figure 10-6 Iso-Surface of Helicity, FC46 10-12
Figure 10-7 Predicted and Measured C_p Distribution at FC46 10-13
Figure 10-8 Iso-Surface of Helicity, FC25 10-15
Figure 10-9 Predicted and Measured C_p Distribution at FC25 10-16
Figure 10-10 Iso-Surface of Helicity Colored by cp, $t_1 = 0.416ms$, $\Delta t = 0.0001$, FC25 10-17
Figure 10-11 Iso-Surface of Swirl $t_1 = 0.416ms$, $\Delta t = 0.0001$, FC25 10-18
Figure 10-12 FC70 10-19
Figure 10-13 Predicted and Measured C_p Distribution for different Butt Line (BL) Stations at FC70 10-20
Figure 10-14 Predicted and Measured C_p Distribution for different Fuselage Stations (FS) at FC70 10-21
Figure 10-15 Predicted and Measured Skin Friction Coefficient for FC19 as a Function of Span at FS 330 10-21
Figure 10-16 Predicted and Measured Velocity Profiles for Boundary Layer Rakes at FC07 10-23
Figure 10-17 Solution-Adaptive Mesh Refinement at FC46 10-25
Figure 10-18 Pressure Distribution on Solution-Adapted Grid and on Original Grid Compared to Flight-Test Data at FC46 10-26
Figure 10-19 Predicted and Measured C_p Distribution at FC07 10-31
Figure 10-20 Predicted and Measured C_p Distribution at FC50 10-34
Figure 10-21 Predicted and Measured C_p Distribution at FC51 10-35

CHAPTER 11

Figure 11-1 CAWAPI F-16XL-1 Configuration at Higher Angle of Attack 11-1
Figure 11-2 CAWAPI F-16XL-1 Configuration, Symmetry Plane of the Hybrid Grid Showing the Meshed Inlet Duct and Nozzle 11-2

Figure 11-3 CAWAPI F-16XL-1, FC46, $C_{pBencmark} - C_{psharedmassflow}$ 11-4
Figure 11-4 FC46, Chordwise Comparison of Computed and Measured Surface Pressure Coefficient along Six Butt-Lines (BL) for Case FC46: (a) BL55; (b) BL70; (c) BL80; (d) BL95; (e) BL153.5; and (f) BL184.5 11-5
Figure 11-5 FC46, Velocity Vectors around Inlet Lips 11-6
Figure 11-6 CAWAPI F-16XL-1, FC19, $C_{pBencmark} - C_{psharedmassflow}$ 11-6
Figure 11-7 CAWAPI F-16XL-1, FC07, $C_{pBencmark} - C_{psharedmassflow}$ 11-7
Figure 11-8 FC46, Iso-Surface of Entropy and its Standard Deviation 11-8
Figure 11-9 FC46, Iso-Surface for Standard Deviation of Total Pressure, Mach Number and Velocity 11-9

CHAPTER 12

Figure 12-1 BCFD Convergence History from Sample AVT Solution 12-3
Figure 12-2 Surface Pressure Coefficient and Total Pressure Ratio Contours Computed on the Common Grid at Flight Condition 7 12-4
Figure 12-3 Comparison of Computed Surface Pressure Coefficient for Several Butt-Line Cuts at Flight Condition 7 12-5
Figure 12-4 Comparison of Computed Velocity Profiles at Flight Condition 7 12-6
Figure 12-5 Comparison of Surface Meshes Near the Wing Leading Edge 12-7
Figure 12-6 Surface Pressure Coefficient and Total Pressure Ratio Contours on Boeing Baseline Grid at Flight Condition 7 with the SA Turbulence Model 12-7
Figure 12-7 Cut Through Boeing Baseline and FC7 Adapted Grids at BL 70 Inches 12-8
Figure 12-8 Cut Through Boeing Baseline and FC7 Adapted Grids at BL 153.5 Inches 12-9
Figure 12-9 Surface Pressure Coefficient and Total Pressure Ratio Contours on Boeing Adapted Grid at Flight Condition 7 with the SA Turbulence Model 12-9
Figure 12-10 Surface Pressure Coefficient and Total Pressure Ratio Contours on Boeing Adapted Grid at Flight Condition 7 with SST Turbulence Model 12-10
Figure 12-11 Comparison of Computed Surface Pressure Coefficient for Several Butt-Line Cuts at Flight Condition 25 12-12
Figure 12-12 Surface Pressure Coefficient and Total Pressure Ratio Contours on Boeing Baseline Grid at Flight Condition 25 with the SA Turbulence Model 12-13
Figure 12-13 Surface Pressure Coefficient and Total Pressure Ratio Contours on Boeing Baseline Grid at Flight Condition 25 with the SST Turbulence Model 12-13
Figure 12-14 Surface Pressure Coefficient and Total Pressure Ratio Contours on Boeing Adapted Grid at Flight Condition 25 with the SST Turbulence Model 12-13
Figure 12-15 Cut Through Boeing Baseline and FC25 Adapted Grids at BL 70 Inches 12-14
Figure 12-16 Cut Through Boeing Baseline and FC25 Adapted Grids at BL 153.5 Inches 12-14
Figure 12-17 Time Average Surface Pressure Coefficient and Total Pressure Ratio Contours on Boeing Adapted Grid at Flight Condition 25 with the LESB Turbulence Model 12-16

CHAPTER 13

Figure 13-1 Flight Test Configuration of the F-16XL 13-2
Figure 13-2 Top and Bottom Surface Grid of F-16XL Shows Clustering at Key Locations 13-5
Figure 13-3 Surface Grid on the Symmetry Plane is Clustered Near the Aircraft 13-6

Figure 13-4 Crinkle Cut of Unstructured Mesh at Cut Through Tailfins of Wingtip Missile 13-7
Figure 13-5 F-16XL Mesh was Partitioned to Run on 64 Processors 13-8
Figure 13-6 Surface C_p Distribution for FC7 on Upper Surface and Detail of Outboard Section of Wing 13-9
Figure 13-7 Bounded Total Pressure Cuts Colored by Total Pressure for FC7 Show Locations of Vortices 13-10
Figure 13-8 Streamtubes Colored by Total Pressure for FC7 13-11
Figure 13-9 Comparison of C_p to Flight Test Data for FC7 at Various Buttlines 13-12
Figure 13-10 Pressure Comparison of C_p to Flight Test Data at Various Fuselage Stations for FC7 13-13
Figure 13-11 Pressure Coefficient Comparisons at Various Buttline Locations, Flux Limiter Compression Factors 1.0 and 1.4, FC7 13-14
Figure 13-12 Pressure Coefficient Comparison at Various Fuselage Station Cuts, Flux Limiter Compression Factor of 1.0 and 1.4, FC7 13-15
Figure 13-13 Surface C_p Distribution for FC19 13-16
Figure 13-14 Bounded Total Pressure Cuts for FC19 13-16
Figure 13-15 Streamtubes Colored by Total Pressure for FC19 13-17
Figure 13-16 Comparison of C_p to Flight Test Data for FC19 at Various Buttlines 13-18
Figure 13-17 Comparison of C_p to Flight Test Data for FC19 at Various Fuselage Stations 13-19
Figure 13-18 Surface C_p Distribution for FC70 13-20
Figure 13-19 Mach 1.0 Iso-Surfaces Colored by Total Pressure for FC70 13-21
Figure 13-20 Comparison of C_p to Flight Test Data for FC70 at Various Buttlines 13-22
Figure 13-21 Comparison of C_p to Flight Test Data for FC70 at Various Fuselage Stations 13-23

CHAPTER 14

Figure 14-1 Leading Edge Mesh Showing the Converted Structured Domain Next to an Unstructured Domain 14-2
Figure 14-2 Symmetry Plane Mesh 14-3
Figure 14-3 Top and Bottom Views of the Surface Mesh 14-4
Figure 14-4 Crinkle Cut of Mesh Near the Symmetry Plane at the Inlet 14-5
Figure 14-5 Magnified Views of Symmetry Plane Mesh at the Upper Inlet Lip and the Lower Inlet Lip 14-5
Figure 14-6 Magnified View of Axial Cut Through Tip Missile Fins and Wing 14-6
Figure 14-7 Various Turbulence Modeling Options did not Significantly Improve the Comparison at the Outboard Span Station 14-9
Figure 14-8 Top View of Original Surface Mesh at Outboard Wing Section 14-10
Figure 14-9 Top View of Adapted Surface Mesh at Outboard Wing Section 14-10
Figure 14-10 FC7 Surface Pressure Coefficient Comparisons for Span-Wise Stations 14-11
Figure 14-11 FC7 Surface Pressure Coefficient Comparisons for Axial Stations 14-12
Figure 14-12 FC19 Surface Pressure Coefficient Comparisons for Span-Wise Stations 14-14
Figure 14-13 FC19 Surface Pressure Coefficient Comparisons for Axial Stations 14-15

Figure 14-14 FC46 Surface Pressure Coefficient Comparisons for Span-Wise Stations 14-17
Figure 14-15 FC46 Surface Pressure Coefficient Comparisons for Axial Stations 14-18
Figure 14-16 FC70 Surface Pressure Coefficient Comparisons for Span-Wise Stations 14-20
Figure 14-17 FC70 Surface Pressure Coefficient Comparisons for Axial Stations 14-21
Figure 14-18 FC25 Surface Pressure Coefficient Comparisons for Span-Wise Stations 14-23
Figure 14-19 FC25 Surface Pressure Coefficient Comparisons for Axial Stations 14-24
Figure 14-20 FC50 Surface Pressure Coefficient Comparisons for Span-Wise Stations 14-26
Figure 14-21 FC50 Surface Pressure Coefficient Comparisons for Axial Stations 14-27
Figure 14-22 FC51 Surface Pressure Coefficient Comparisons for Span-Wise Stations 14-28
Figure 14-23 FC51 Surface Pressure Coefficient Comparisons for Axial Stations 14-29
Figure 14-24 Residual History for Case FC07 14-30
Figure 14-25 Integrated Forces Convergence History for Case FC25 14-31
Figure 14-26 Integrated Forces Convergence History for Case FC51 14-31
Figure 14-27 Surface Pressure Coefficient Color Contours for Case FC07 14-32
Figure 14-28 Axial Station Cuts of Contours of Vorticity Magnitude for Case FC07 14-32
Figure 14-29 Surface Pressure Coefficient Color Contours for Case FC25 14-33
Figure 14-30 Axial Station Cuts of Contours of Vorticity Magnitude for Case FC25 14-33
Figure 14-31 Case FC70 Sonic Surface Colored by Pressure 14-33
Figure 14-32 Surface Pressure Coefficient Contours for FC50 and FC51 with Color Range for C_p Values from -1.5 to 0.1 14-34
Figure 14-33 Axial Cuts of Vorticity Contours with Streamlines Tracking the Vortices for Case FC50 14-35

CHAPTER 15

Figure 15-1 F-16XL-1 Airplane Drawing and Pressure Instrumentation Layout 15-2
Figure 15-2 Effect of Turbulence Modeling on C_p from USM3D at FC46 ($M_\infty = 0.527$, $\alpha = 10.4°$, $R_n = 46.9 \times 10^6$) 15-5
Figure 15-3 Effect of Turbulence Model on C_p from USM3D at FC70 ($M_\infty = 0.97$, $\alpha = 4.37°$, $R_n = 88.77 \times 10^6$) 15-10
Figure 15-4 Prediction of C_p Flight Data from USM3D at FC25 ($M_\infty = 0.242$, $\alpha = 19.84°$, $R_n = 32.22 \times 10^6$) 15-15
Figure 15-5 Predicted and Measured C_p Data at FC50 ($M_\infty = 0.434$, $\alpha = 13.56°$, $\beta = +5.31°$, $R_n = 39.41 \times 10^6$) 15-19
Figure 15-6 Predicted and Measured C_p Data at FC51 ($M_\infty = 0.441$, $\alpha = 12.89°$, $\beta = -4.58°$, $R_n = 38.95 \times 10^6$) 15-23
Figure 15-7 Velocity Profiles for Boundary Layer Rakes on F-16XL for FC7 ($M_\infty = 0.304$, $\alpha = 11.89°$, $R_n = 44.4 \times 10^6$) 15-26
Figure 15-8 Four Increasing [(a) -> (d)] Magnification Levels of Total Pressure Contours at FS 300 Obtained from USM3D for FC7 using Linear k-ε Model ($M_\infty = 0.304$, $\alpha = 11.89°$, $R_n = 44.4 \times 10^6$) 15-27
Figure 15-9 Five Increasing [(a) -> (e)] Magnification Levels of Total Pressure Contours at FS 330 Obtained from USM3D for FC7 using Linear k-ε Model ($M_\infty = 0.304$, $\alpha = 11.89°$, $R_n = 44.4 \times 10^6$) 15-28

Figure 15-10	General Arrangement of Rake and Modified Preston Tube Relative Locations on F-16XL-1 Left Wing; Pressure Instruments Oriented for $\alpha = 13°$; $M_\infty = 0.29$; and $R_n = 46.1 \times 10^6$	15-29
Figure 15-11	Skin-Friction Distribution on F-16XL-1 Airplane at FS 330 for FC19 ($M_\infty = 0.36$, $\alpha = 11.85°$, $R_n = 46.8 \times 10^6$)	15-29
Figure 15-A1	Convergence Histories of USM3D Solutions as Expressed in the Log Residual-Ratio for the Mean-Flow Equations on this Grid for FC7, FC19, FC25, FC46, FC50, FC51 and FC70	15-33

CHAPTER 16

Figure 16-1	Vortical-Flow Features over Upper Surface for FC25	16-5
Figure 16-2	Chordwise Comparison for FC25 of Pressure Coefficient	16-6
Figure 16-3	Vortical-Flow Features over Upper Surface for FC19	16-8
Figure 16-4	Spanwise Comparison (FS 330) for FC19 of the Magnitude of the Skin Friction Coefficient c_f	16-9
Figure 16-5	FC07, Velocity Profiles Comparison	16-10
Figure 16-6	FC07, Velocity Profiles Comparison; Effect of Turbulence Modeling and Time-Accuracy	16-11
Figure 16-7	Low-Lying Vortices over Upper Surface for FC70	16-12
Figure 16-8	Chordwise Comparison for FC70 of Pressure Coefficient	16-13
Figure 16-9	Surface Grids on Upper Surface	16-17
Figure 16-10	KTH/FOI Inviscid Solution on Upper Surface with Triply-Adapted Mesh	16-18
Figure 16-11	Chordwise Cut Through Three Unstructured Grids in BL80 Section	16-19
Figure 16-12	Chordwise Comparison of Computed and Measured Surface C_p for Case FC70	16-20
Figure 16-13	Span-Wise Cuts at FS337.5 for Three Different Unstructured Solutions, Euler Adapted Mesh, RANS Adapted Mesh, Common RANS Mesh; Magnified Mesh and Total-Pressure-Loss Iso-Lines	16-22
Figure 16-14	Span-Wise Cuts at FS492.5 for Three Different Unstructured Solutions, Euler Adapted Mesh, RANS Adapted Mesh, Common RANS Mesh; Magnified Mesh and Total-Pressure-Loss Iso-Lines	16-23
Figure 16-15	Spanwise Comparison of Computed and Measured Upper Surface C_p for Case FC70	16-24

CHAPTER 17

Figure 17-1	Configuration of the First International Vortex Flow Experiment (VFE-1)	17-1
Figure 17-2	Surface Pressure Distributions on the Wing (Only) of the VFE-1 Configuration at $M = 0.4$, $R_{mac} = 3.1 \times 10^6$, $\alpha = 9°$	17-2
Figure 17-3	Total Pressure Loss Contours in Section x/c = 0.8 on the VFE-1 Configuration at $M = 0.4$, $R_{mac} = 3.1 \times 10^6$, $\alpha = 9°$	17-3
Figure 17-4	VFE-2 Configuration: NASA NTF Delta Wing $A = 1.85$, $\Lambda = 65°$	17-4
Figure 17-5	NASA NTF Tests on the 65° Delta Wing	17-4
Figure 17-6	Available Test Conditions for the 65° Delta Wing Configuration at NASA Langley	17-7
Figure 17-7	Effect of Leading Edge Bluntness on the Pressure Distribution of the 65° Delta Wing Configuration ($A = 1.85$) at $M = 0.4$, $R_{mac} = 6 \times 10^6$, $\alpha = 13°$	17-8

Figure 17-8 Numerical Simulation of Vortex Breakdown for the VFE-1 Configuration at $M = 0.2$, $R = 1.55 \times 10^6$, $\alpha = 21°$ 17-9

CHAPTER 18

Figure 18-1 Basic Features of Separation-Induced Leading-Edge Vortex Flows, Sharp-Edged Delta Wings 18-2
Figure 18-2 Leading-Edge Bluntness Consequences for the Primary Vortex Separation 18-3
Figure 18-3 Delta Wing Configuration for Tests in NTF 18-4
Figure 18-4 Leading-Edge Geometry 18-5
Figure 18-5 National Transonic Facility Test Program 18-6
Figure 18-6 LTPT and NTF Delta Wings 18-7
Figure 18-7 Effect of Leading-Edge Bluntness on Normal Force and Pitching Moment Coefficients 18-7
Figure 18-8 Static Surface Pressure Coefficients for Sharp and Medium Bluntness Delta Wings, $\alpha = 13°$, $M = 0.4$, $R_{mac} = 6 \times 10^6$ 18-8
Figure 18-9 Sketches of Blunt Leading-Edge Dual Co-Rotating Leading-Edge Vortex Separation 18-9
Figure 18-10 Effect of Reynolds Number on Static Surface Pressure Coefficients 18-10
Figure 18-11 Correlation of Leading-Edge Pressure Coefficients with the Onset and Progression of Leading-Edge Vortex Separation 18-11
Figure 18-12 Reynolds Number Effect on Leading-Edge Pressures 18-12
Figure 18-13 Leading-Edge Bluntness and Reynolds Number Effects on the Onset and Progression of Leading-Edge Vortex Separation, $M = 0.4$ 18-13
Figure 18-14 Effect of Compressibility on Normal Force Coefficients 18-14
Figure 18-15 Effect of Compressibility on Static Surface Pressure Coefficients (Medium Bluntness, $x/c_r = 0.6$, $\alpha = 7°$; Data from NTF, LTPT) 18-15
Figure 18-16 Compressibility Effect on Leading-Edge Pressures (Medium Bluntness, $x/c_r = 0.5$, $R_{mac} = 6 \times 10^6$) 18-16
Figure 18-17 Effect of Compressibility on Static Surface Pressure Coefficients (Medium Bluntness, $\alpha = 13°$, $R_{mac} = 60 \times 10^6$; Data from NTF) 18-17
Figure 18-18 Compressibility and Bluntness Effects on Leading-Edge Pressures, $R_{mac} = 6 \times 10^6$, $x/c_r = 0.5$; Data from NTF 18-18
Figure 18-19 Compressibility and Bluntness Effects on Leading-Edge Pressures, $R_{mac} = 60 \times 10^6$, $x/c_r = 0.5$; ; Data from NTF 18-19
Figure 18-20 Compressibility and Reynolds Number Effects on Onset and Progression of Leading-Edge Vortex Separation 18-20

CHAPTER 19

Figure 19-1 Geometry of VFE-2 Configuration 19-2
Figure 19-2 Coated Delta-Wing Model in the Test Section of the DNW-TWG and Arrangement of PSP Cameras 19-5
Figure 19-3 Stereoscopic PIV Arrangement at the TWG and Picture from Inside the Perforated Test Section Showing the Coated Delta-Wing, Light Sheet and the Two Lateral Schlieren Windows 19-6

Figure 19-4	Velocity Vector Field of Primary Vortex for the Delta Wing with Medium Radius Leading Edges at $x/c_r = 0.8$ for M = 0.4, R_{mac} = 2 Million, α = 13.3° Q-value and Out-of-Plane Vorticity Distribution	19-8
Figure 19-5	Comparison of PSI Pressure Distributions Obtained in TWG and in NTF (NASA) of the Uncoated Delta Wing with Rounded Leading Edges at M = 0.85 and R_{mac} = 6 Million for Three Different Angles of Attack	19-9
Figure 19-6	Comparison of PSI Pressure Distributions of the Un-Coated and the Coated Delta Wing with Rounded Leading Edges at M = 0.4 and R_{mac} = 3 Million for Three Different Angles of Attack	19-10
Figure 19-7	Comparison of Surface Pressure Distributions Obtained with PSP at Suction Side of Delta Wing with Sharp and Medium Radius Leading Edge (M = 0.4, R_{mac} = 2 million, α = 10.1°)	19-11
Figure 19-8	Origin Positions of Primary Vortex for α > 10° Obtained from PSP Results for the Delta Wing with Medium Radius Leading Edge for M = 0.4 and 0.8 and R_{mac} = 2 and 3 Million	19-12
Figure 19-9	Surface Pressure Distribution Obtained with PSP at the Suction Side of Delta Wing with Medium Radius Leading Edge for M = 0.4, R_{mac} = 3 Million and α = 10.2°	19-13
Figure 19-10	Time Averaged Pressure, Velocity and Vorticity Distributions above the Delta Wing with Rounded Leading Edges for α = 10.2°, M = 0.4 and R_{mac} = 3 Million	19-14
Figure 19-11	Time Averaged PIV Result at $x/c_r = 0.6$ above the Delta Wing with Medium Radius Leading Edges and M = 0.4, R_{mac} = 3 Million and α = 10.2° Velocity and Vorticity Distributions Q-value Distribution	19-15
Figure 19-12	Surface Pressure Distribution Obtained with PSP at the Suction Side of Delta Wing with Medium Radius Leading Edge for M = 0.4, R_{mac} = 3 Million and α = 13.3°	19-16
Figure 19-13	Time Averaged Pressure, Velocity and Vorticity Distributions above the Delta Wing with Rounded Leading Edges for α = 13.3°, M = 0.4 and R_{mac} = 3 Million	19-17
Figure 19-14	Time Averaged Velocity Fields at Different Chord Positions above the Delta Wing with Medium Radius Leading Edges for M = 0.4, R_{mac} = 3 Million and α = 13.3°	19-19
Figure 19-15	Calculated Circulations of the Inner Vortical Structure or the Inner Vortex and the Outer Primary Vortex against Chord Position for the Medium Radius L.E. and M = 0.4	19-20
Figure 19-16	Surface Pressure Distributions Obtained with PSP at the Suction Side of the Delta Wing with Medium Radius Leading Edges for Different Angles of Attack (M = 0.4, R_{mac} = 3 million)	19-21
Figure 19-17	Surface Pressure Distributions Obtained with PSP at the Suction Side of the Delta Wing with Medium Radius Leading Edges for Different Angles of Attack (M = 0.4, R_{mac} = 2 million)	19-22
Figure 19-18	Time Averaged Pressure, Velocity and Vorticity Distributions above the Delta Wing with Rounded Leading Edges for α = 13.3°, M = 0.4 and R_{mac} = 2 Million	19-23
Figure 19-19	Surface Pressure Distributions Obtained with PSP at the Suction Side of the Delta Wing with Sharp Leading Edges in 0.2° Steps of Angles of Attack (M = 0.8, R_{mac} = 3 Million)	19-25
Figure 19-20	Time Averaged Velocity and Vorticity Distributions for the Delta Wing with Sharp Leading Edges at $x/c_r = 0.6$ (M = 0.8, R_{mac} = 3 Million, α = 25.7°)	19-26

Figure 19-21	Time Averaged Pressure and Velocity Distributions above the Delta Wing with Sharp Leading Edges for M = 0.8, R_{mac} = 3 Million and α = 25.7°	19-27
Figure 19-22	Sketch of Cryogenic Wind Tunnel in Cologne (DNW-KKK)	19-28
Figure 19-23	The 65° Delta Wing of TU-Munich Coated with TSP in the Model Conditioning Room of the DNW-KKK	19-29
Figure 19-24	Delta Wing Model in the Test Section and Measurement Setups for TSP	19-30
Figure 19-25	Left: Stereoscopic PIV Arrangement at the DNW-KKK	19-32
Figure 19-26	TSP Results of the Suction Side of the Delta Wing with Medium Radius Leading Edges at Low Angle of Attack of 5° for Different Reynolds Numbers	19-34
Figure 19-27	TSP Results from the Side View Camera Showing the Distribution along the L.E. of the Port Side of the Delta Wing at an Angle of Attack of 5° and Different Reynolds Numbers	19-35
Figure 19-28	IR Results Showing the Temperature Distributions on the Suction Side of the Front Part of the Delta Wing with Rounded Leading Edges for R_{mac} = 2 Million, M = 0.103 (T = 240 K) for Different Angles of Attack	19-36
Figure 19-29	TSP Results from the Side View Camera Showing the Distribution along the L.E. of the Port Side of the Delta Wing at an Angle of Attack of 10° and 13°	19-37
Figure 19-30	Time Averaged Velocity Field above the Delta Wing with Rounded Leading Edges for α = 13.3° and R_{mac} = 6 Million	19-38

CHAPTER 20

Figure 20-1	Sketches of Model 1 and View in Test Section	20-3
Figure 20-2	Sketch of Model 4 and 5 with Pressure Ports Locations	20-4
Figure 20-3	Views of the Model 1 in Test Section	20-6
Figure 20-4	Pressure Distributions on Model 1 Upper Surface – Solid Walls (Sharp: $Re_{mac} = 10^6$ at L1; $Re_{mac} = 1.5 \times 10^6$ at LTPT – Medium: $Re_{mac} = 10^6$ at L1; $Re_{mac} = 2 \times 10^6$ at LTPT)	20-7
Figure 20-5	Pressure Distributions on Model 1 Upper Surface – Solid Walls (Sharp: $Re_{mac} = 10^6$ at L1; $Re_{mac} = 1.5 \times 10^6$ at LTPT– Medium: $Re_{mac} = 10^6$ at L1; $Re_{mac} = 2 \times 10^6$ at LTPT)	20-8
Figure 20-6	Pressure Distributions on Model 1 Lower Surface (Sharp: $Re_{mac} = 10^6$ at L1; $Re_{mac} = 1.5 \times 10^6$ at LTPT)	20-10
Figure 20-7	Pressure Distributions along the Model 1 Leading Edges	20-10
Figure 20-8	Views of Model 4 and 5 in the Open Jet Tunnel	20-11
Figure 20-9	Lift and Yaw Moment Coefficients in Open Tunnel (Model 4 and 5)	20-11
Figure 20-10	Lift and Lateral Force Coefficients in Open Jet Tunnel when the Wing Undergoes ϕ = ±90° Rotations (Model 4 and 5)	20-12
Figure 20-11	Drag and Pitching Moment Coefficients in Open Jet Tunnel (Model 4 and 5)	20-13
Figure 20-12	Normal Force, Axial Force and Pitching Moment Coefficients at L1 (Model 4 and 5)	20-14
Figure 20-13	Pressure Distribution at L1 in Solid Walls (Model 4 and 5) and Comparison with LTPT (Sharp: $Re_{mac} = 10^6$ at L1; $Re_{mac} = 1.5 \times 10^6$ at LTPT – Medium: $Re_{mac} = 10^6$ at L1; $Re_{mac} = 2 \times 10^6$ at LTPT)	20-15
Figure 20-14	Comparison of Pressure Coefficients Measured in Solid Walls and in Open Jet Tunnel (Upper Surface, h ≤ 0.70)	20-16

Figure 20-15	Comparison of Pressure Coefficients Measured in Solid Walls and in Open Jet Tunnel (Upper Surface, h > 0.70)	20-17
Figure 20-16	Comparison of Pressure Coefficients Measured in Solid Walls and in Open Jet Tunnel (Lower Surface)	20-18
Figure 20-17	Axial Force Variations: L1, Solid Walls, $Re_{mac} = 10^6$	20-19
Figure 20-18	Correlation of Primary Vortex Onset at $\xi = 0.20$ with Medium Leading Edge Upper Surface Pressure Distribution – Model 1 – L1: $Re_{mac} = 10^6$; LTPT: $Re_{mac} = 2 \times 10^6$	20-20
Figure 20-19	Correlation of Primary Vortex Onset with Sharp Leading Edge Upper Surface Pressure Distribution – Model 1 – LTPT: $Re_{mac} = 1.5 \times 10^6$	20-20
Figure 20-20	Influence of the Leading Edge Flow Structure on Suction Rate	20-21
Figure 20-21	Localization of Stereoscopic PIV Plans	20-22
Figure 20-22	Localization of the PIV Plan Parallel to the Wing	20-22
Figure 20-23	Vorticity and Longitudinal Velocity Fields – Model 4 – $\alpha = 24.7°$ – L1: $Re_{mac} = 10^6$, M = 0.133	20-23
Figure 20-24	Vorticity and Longitudinal Velocity Fields – Model 5 – $\alpha = 24.7°$ – L1: $Re_{mac} = 10^6$, M = 0.133	20-24
Figure 20-25	PIV 2C Vorticity and Velocity Fields in a Plan Parallel to Upper Surface – $\alpha = 24.7°$ – Model 5 – L1: $Re_{mac} = 10^6$, M = 0.133	20-25

CHAPTER 21

Figure 21-1	Laser Light Sheets of Vortex Structure above and behind the Wing at $R_{mac} = 5 \times 10^5$ and M = 0.035 for Sharp and Rounded Leading Edges	21-7
Figure 21-2	Surface Oil Flow Visualization at $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp and Rounded Leading Edges	21-9
Figure 21-3	Surface Oil Flow Visualization at $R_{mac} = 2 \times 10^6$ and M = 0.14 for Sharp and Rounded Leading Edges	21-10
Figure 21-4	Flow Topology Based on Laser Light Sheet and Oil Flow Visualization for $\alpha = 13°$ and 18° at $R_{mac} = 2 \times 10^6$	21-11
Figure 21-5	Steady Pressure Distribution at $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp and Rounded Leading Edges	21-13
Figure 21-6	Steady Pressure Distribution at $R_{mac} = 2 \times 10^6$ and M = 0.14 for Sharp and Rounded Leading Edges	21-14
Figure 21-7	Comparison of Steady Pressure Distribution between Sharp and Rounded Leading Edge at $R_{mac} = 1 \times 10^6$ and $R_{mac} = 2 \times 10^6$ in Section $x/c_r = 0.6$	21-16
Figure 21-8	Comparison of Steady Pressure Distribution between NASA and TUM Measurements for Sharp and Rounded Leading Edge at $R_{mac} = 2 \times 10^6$ in Section $x/c_r = 0.6$	21-18
Figure 21-9	Position of the Primary Vortex Axis at $R_{mac} = 5 \times 10^5$ and M = 0.035 (Values Taken at $x/c_r = 0.95$)	21-19
Figure 21-10	Correlation of Separation Onset with Leading Edge Steady Pressure Distribution for Sharp Leading Edge at $R_{mac} = 2 \times 10^6$ in Position $\eta = 0.95$	21-19
Figure 21-11	Mean Velocity Distribution at $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp and Rounded Leading Edges	21-21

Figure 21-12	Mean Velocity Distribution at $R_{mac} = 2 \times 10^6$ and M = 0.35 for Sharp and Rounded Leading Edges	21-22
Figure 21-13	Comparison between Stereo-PIV and HWA Results for $\alpha = 18°$ at $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp and Rounded Leading Edge in Section $x/c_r = 0.6$	21-24
Figure 21-14	Pressure Fluctuation Intensity at $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp and Rounded Leading Edges	21-26
Figure 21-15	Pressure Fluctuation Intensity at $R_{mac} = 2 \times 10^6$ and M = 0.14 for Sharp and Rounded Leading Edges	21-27
Figure 21-16	Amplitude Spectra of Fluctuating Pressure Coefficient for Sharp and Rounded Leading Edge at $\alpha = 13°$, $R_{mac} = 2 \times 10^6$ and M = 0.14	21-29
Figure 21-17	Amplitude Spectra of Fluctuating Pressure Coefficient for Sharp and Rounded Leading Edge at $\alpha = 18°$, $R_{mac} = 2 \times 10^6$ and M = 0.14	21-30
Figure 21-18	Amplitude Spectra of Fluctuating Pressure Coefficient for Sharp and Rounded Leading Edge at $\alpha = 23°$, $R_{mac} = 2 \times 10^6$ and M = 0.14	21-31
Figure 21-19	Turbulence Intensity Distribution of the Axial Velocity Fluctuations at $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp and Rounded Leading Edge in Section $x/c_r = 0.6$	21-33
Figure 21-20	Turbulence Intensity Distribution of the Lateral Velocity Fluctuations at $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp and Rounded Leading Edge in Section $x/c_r = 0.6$	21-34
Figure 21-21	Turbulence Intensity Distribution of the Vertical Velocity Fluctuations at $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp and Rounded Leading Edge in Section $x/c_r = 0.6$	21-35
Figure 21-22	Shear Stress Distribution of the Axial and Lateral Velocity Fluctuations at $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp and Rounded Leading Edge in Section $x/c_r = 0.6$	21-36
Figure 21-23	Shear Stress Distribution of the Axial and Vertical Velocity Fluctuations at $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp and Rounded Leading Edge in Section $x/c_r = 0.6$	21-37
Figure 21-24	Power Spectral Density Distributions of the Axial Velocity Fluctuations at $\alpha = 18°$, $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp Leading Edge	21-39
Figure 21-25	Power Spectral Density Distributions of the Axial Velocity Fluctuations at $\alpha = 18°$, $R_{mac} = 1 \times 10^6$ and M = 0.07 for Rounded Leading Edge	21-40
Figure 21-26	Power Spectral Density Distributions of the Axial Velocity Fluctuations at $\alpha = 23°$, $R_{mac} = 1 \times 10^6$ and M = 0.07 for Sharp Leading Edge	21-41
Figure 21-27	Power Spectral Density Distributions of the Axial Velocity Fluctuations at $\alpha = 23°$, $R_{mac} = 1 \times 10^6$ and M = 0.07 for Rounded Leading Edge	21-42
Figure 21-28	Dominant Reduced Frequency Correlation Based on Unsteady Surface Pressure and Velocity Measurements	21-44
Figure 21-29	Surface Pressure Fluctuation Intensity, Surface Flow and Boundary Layer Profiles for Sharp Leading Edge in Section $x/c_r = 0.6$ at $\alpha = 13°$, $R_{mac} = 1 \times 10^6$ and M = 0.07	21-45
Figure 21-30	Surface Pressure Fluctuation Intensity, Surface Flow and Boundary Layer Profiles for Rounded Leading Edge in Section $x/c_r = 0.6$ at $\alpha = 13°$, $R_{mac} = 1 \times 10^6$ and M = 0.07	21-46
Figure 21-31	Surface Pressure Fluctuation Intensity, Surface Flow and Boundary Layer Profiles for Sharp Leading Edge in Section $x/c_r = 0.6$ at $\alpha = 18°$, $R_{mac} = 1 \times 10^6$ and M = 0.07	21-46

Figure 21-32 Surface Pressure Fluctuation Intensity, Surface Flow and Boundary Layer Profiles for Rounded Leading Edge in Section $x/c_r = 0.6$ at $\alpha = 18°$, $R_{mac} = 1 \times 10^6$ and $M = 0.07$ 21-47

Figure 21-33 Surface Pressure Fluctuation Intensity, Surface Flow and Boundary Layer Profiles for Sharp Leading Edge in Section $x/c_r = 0.6$ at $\alpha = 23°$, $R_{mac} = 1 \times 10^6$ and $M = 0.07$ 21-47

Figure 21-34 Surface Pressure Fluctuation Intensity, Surface Flow and Boundary Layer Profiles for Rounded Leading Edge in Section $x/c_r = 0.6$ at $\alpha = 23°$, $R_{mac} = 1 \times 10^6$ and $M = 0.07$ 21-48

CHAPTER 22

Figure 22-1 Model Geometry 22-2

Figure 22-2 (a): Test Set Up; (b): Test Set Up (Alternative View) 22-3

Figure 22-3 Balance and Inclinometer Attachment to the Delta Wing 22-4

Figure 22-4 Model in the Glasgow University Argyll Wind Tunnel 22-5

Figure 22-5 Delta Wing Flowfield 22-6

Figure 22-6 The Development of the Oil Flow for the Sharp-Edged Wing, $R_{mac} = 1 \times 10^6$ and $\alpha = 13.3°$ 22-8

Figure 22-7 The Development of the Oil Flow for the Medium Radius Wing, $R_{mac} = 1 \times 10^6$ and $\alpha = 13.3°$ 22-8

Figure 22-8 Flow Visualization Images for the Sharp Edge Configuration at $R_{mac} = 2 \times 10^6$ and Angles of Attack (a) 13.3°, (b) 18.5° and (c) 23° 22-9

Figure 22-9 Comparison of Oil Flow Patterns for (a) Rounded and (b) Sharp Leading Edge Configurations at $R_{mac} = 2 \times 10^6$, $\alpha = 13.3°$ 22-10

Figure 22-10 Flow Visualization Images for the Rounded Edge Configuration at $R_{mac} = 2 \times 10^6$ and Angles of Attack (a) 13.3°, (b) 18.5° and (c) 23° 22-11

Figure 22-11 Comparison of Oil Flow Patterns for the Round Edged Configuration at (a) $Re = 1 \times 10^6$ and (b) $R_{mac} = 2 \times 10^6$, $\alpha = 13.3°$ 22-12

Figure 22-12 The Development of the Primary Vortex for the Large-Edged, $R_{mac} = 2 \times 10^6$ and $\alpha = 13.3°$ 22-13

Figure 22-13 Comparison of Normal Force Coefficients for the Three Test Cases 22-14

Figure 22-14 Comparison of Axial Force Coefficients for the Three Test Cases 22-15

Figure 22-15 Comparison of Pitching Moment Coefficients for the Three Test Cases 22-16

CHAPTER 23

Figure 23-1 Ankara Wind Tunnel Sketch 23-2

Figure 23-2 Wind Tunnel Model 23-3

Figure 23-3 Model-Internal Balance-Sting Interface 23-5

Figure 23-4 Test Set-up 1 23-5

Figure 23-5 Test Set-up 2 23-6

Figure 23-6 Sharp LE Oil Flow Visualization Pictures 23-8

Figure 23-7 Medium Radius LE Oil Flow Visualization Pictures 23-9

Figure 23-8 Ankara Wind Tunnel Force-Moment Results 23-11

Figure 23-9 Axial Force Comparison 23-12
Figure 23-10 Normal Force Comparison 23-12
Figure 23-11 Pitching Moment Comparison 23-13
Figure 23-12 Drag Force Comparison 23-13
Figure 23-13 Lift Force Comparison 23-13

CHAPTER 24

Figure 24-1 VFE-2 Configuration: NASA Delta Wing, $\Lambda = 65°$, A = 1.85 24-2
Figure 24-2 NASA NTF Tests on the 65° Delta Wing 24-2
Figure 24-3 Effect of Bluntness on Experimental Normal Force and Pitching Moment Coefficients for the VFE-2 Configuration with Sharp and Medium Radius Rounded Leading Edges at M = 0.4, $R_{mac} = 6 \times 10^6$ 24-3
Figure 24-4 Effect of Mach Number on Experimental Normal Force Coefficients for the VFE-2 Configuration with Medium Radius Rounded Leading Edge at $R_{mac} = 6 \times 10^6$ or 8×10^6 24-4
Figure 24-5 Effect of Bluntness on Experimental Normal and Axial Force Coefficients for the VFE-2 Configuration with Sharp and Medium Radius Rounded Leading Edge at M = 0.1, $R_{mac} = 1 \times 10^6$ 24-5
Figure 24-6 Effect of Leading Edge Bluntness on the Pressure Distribution of the VFE-2 Configuration at M = 0.4, $R_{mac} = 6 \times 10^6$, $\alpha = 13°$ 24-6
Figure 24-7 Experimental Pressure Distribution on the VFE-2 Configuration with Medium Radius Rounded Leading Edges for M = 0.4, $R_{mac} = 3 \times 10^6$, $\alpha = 13°$ 24-7
Figure 24-8 Pressure (Surface Color), Velocity (Vectors) and Vorticity (Vector Color) Distributions above the VFE-2 Configuration with Rounded Leading Edges (Medium Radius) for M = 0.4, $R_{mac} = 3 \times 10^6$, $\alpha = 13°$ 24-8
Figure 24-9 Pressure Distributions on the VFE-2 Configuration with Rounded Leading Edges (Medium Radius) for M = 0.4, $R_{mac} = 3 \times 10^6$ at Various Angles of Attack from the PSP Experiments at DLR Goettingen 24-10
Figure 24-10 Pressure Distributions on the VFE-2 Configuration with Rounded Leading Edges (Medium Radius) for M = 0.4, $\alpha = 13°$ at Different Reynolds Numbers from the PSP Experiments at DLR Goettingen 24-11
Figure 24-11 Pressure Distributions and Flow Fields on the VFE-2 Configuration with Rounded Leading Edges (Medium Radius) for M = 0.4, $\alpha = 13°$ at Different Reynolds Numbers from the PSP and PIV Experiments at DLR Goettingen 24-11
Figure 24-12 Comparison of Oil Flow Patterns for the Round Edged Configuration at $\alpha = 13.3°$ from the Low-Speed Measurements at Glasgow University 24-12
Figure 24-13 Surface Oilflow Patterns and Flow Topology for the VFE-2 Configuration with Rounded Leading Edges (Medium Radius) for M = 0.14, $R_{mac} = 2 \times 10^6$, $\alpha = 13°$ from the Measurements at TU Munich 24-13
Figure 24-14 Pressure Distributions on the VFE-2 Configuration with Rounded Leading Edges (Medium Radius) at $R_{mac} = 2 \times 10^6$ and $\alpha = 13°$ for Different Mach Numbers from the PSP Experiments at DLR Goettingen 24-14
Figure 24-15 Flow Field on the VFE-2 Configuration with Rounded Leading Edges (Medium Radius) at $R_{mac} = 2 \times 10^6$ and $\alpha = 13°$ for Different Mach Numbers from the PIV Experiments at DLR Goettingen 24-14

Figure 24-16	Results of Boundary Layer Measurements on the VFE-2 Configuration with Rounded Leading Edges (Medium Radius) for M = 0.07, R_{mac} = 1 x 10^6 and α = 13° at Two Stations in the Section x/c_r = 0.6 from the Hot-Wire Anemometry at TU Munich	24-15
Figure 24-17	Pressure Fluctuations on the VFE-2 Configuration with Rounded Leading Edges (Medium Radius) for M = 0.14, R_{mac} = 2 x 10^6 and α = 13° in Four Sections from the Measurements at TU Munich	24-16
Figure 24-18	Pressure Distributions on the VFE-2 Configuration with Sharp and Rounded Leading Edges (Medium Radius) at R_{mac} = 2 x 10^6 and α = 18° for Two Mach Numbers According to the PSP Experiments at DLR Goettingen	24-17
Figure 24-19	Flow Field around the VFE-2 Configuration with Sharp and Rounded Leading Edges (Medium Radius) at M ≈ 0.1, R_{mac} = 1 x 10^6, α = 18° – PIV Results from TU Munich for the Time-Averaged Velocity in Various Cross Sections: x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95	24-18
Figure 24-20	Flow Field around the VFE-2 Configuration with Sharp and Rounded Leading Edges (Medium Radius) at M ≈ 0.1, R_{mac} = 1 x 10^6, α = 18° – HWA Results from TU Munich for the Velocity Fluctuations u_{rms}/U_∞ and $\overline{u'w'}/U_\infty^2$ in the Plane at x/c = 0.6	24-19
Figure 24-21	Flow Field around the VFE-2 Configuration (65° Delta Wing) with Sharp Leading Edges at M ≈ 0.1, R_{mac} = 1 x 10^6, α = 18°	24-20
Figure 24-22	Normal Force Power Spectrum for Sharp and Blunt Edged Wings, R_{mac} = 2 x 10^6, α = 18.5° from the Low-Speed Measurements at Glasgow University	24-21
Figure 24-23	Flow Field around the VFE-2 Configuration with Medium Radius Rounded Leading Edges at M = 0.14, R_{mac} = 2 x 10^6, α = 23°	24-22
Figure 24-24	Flow Field around the VFE-2 Configuration with Medium Radius Rounded Leading Edges at M ≈ 0.1, R_{mac} = 1 x 10^6, α = 23°	24-23
Figure 24-25	Pressure Distributions on the VFE-2 Configuration with Sharp and Rounded Leading Edges (Medium Radius) at R_{mac} = 2 x 10^6 and α = 25° for Different Mach Numbers According to the PSP Experiments at DLR Goettingen	24-24

CHAPTER 25

Figure 25-1	Geometry of VFE-2 Delta Wing	25-3
Figure 25-2	3-D Grid Structure	25-4
Figure 25-3	Effect of Leading Edge Bluntness, M = 0.4, Re = 6 x 10^6, α = 13°	25-5
Figure 25-4	Effect of Large Reynolds Number Variation in the Experiments, M = 0.4, α = 13°	25-6
Figure 25-5	Effect of Large Reynolds Number Variation in the Calculations (RANS, Wilcox k-ω, M = 0.4, α = 13°)	25-7
Figure 25-6	Comparisons of Surface Pressure with Experiments for M = 0.4, Re = 6 Mio, α = 13° With and Without Transition	25-8
Figure 25-7	Effect of a Small Reynolds Number Variation in the Calculation (RANS, Wilcox k-ω, M = 0.4, α = 13°)	25-9
Figure 25-8	Comparison of Numerical and Experimental Surface Pressure Contours for Case 4.5 (M = 0.4, Re = 3 x 10^6, α = 13°)	25-9
Figure 25-9	Comparison of Numerical and Experimental Surface Pressure Distributions for Case 4.5 (M = 0.4, Re = 3 x 10^6, α = 13°)	25-10
Figure 25-10	Surface Pressure Contours and Iso-Surface of 5% Total Pressure Loss for Case 4.5 (M = 0.4, Re = 3 x 10^6, α = 13°)	25-11

Figure 25-11	Total Pressure Loss Contours in Different Cross Sections for Case 4.5 (M = 0.4, Re = 3 x 10^6, α = 13°)	25-12
Figure 25-12	Velocity Vectors and Total Pressure Loss Contours in Two Cross Sections for Case 4.5 (M = 0.4, Re = 3 x 10^6, α = 13°) – x/c_r = 0.20 and x/c_r = 0.40	25-13
Figure 25-13	Velocity Vectors and Total Pressure Loss Contours in Two Cross Sections for Case 4.5 (M = 0.4, Re = 3 x 10^6, α = 13°) – x/c_r = 0.50 and x/c_r = 0.55	25-13
Figure 25-14	Velocity Vectors and Total Loss Contours in Two Cross Sections for Case 4.5 (M = 0.4, Re = 3 x 10^6, α = 13°)	25-14
Figure 25-15	3-D Flow Features (Stream Traces by 3-Volume Ribbons) for Case 4.5 (M = 0.4, Re = 3 x 10^6, α = 13°)	25-15
Figure 25-16	Effect of Decreasing Reynolds Number on Surface Pressure Contours for Case 4.5 (M = 0.4, Re = 3 x 10^6, α = 13°)	25-16
Figure 25-17	Effect of Decreasing Reynolds Number for Case 4.5 (M = 0.4, Re = 3 x 10^6, α = 13°)	25-16
Figure 25-18	3-D Flow Features (Stream Traces by 3-Volume Ribbons) for Case 14 (M = 0.4, Re = 6 x 10^6, α = 18°)	25-17
Figure 25-19	Comparison of Numerical Surface Pressure Contours with Experimental Data for Case 18 (M = 0.4, Re = 6 x 10^6, α = 18°)	25-18
Figure 25-20	Comparison of Numerical and NASA LTPT Surface Pressure Distributions for Case 14 (M = 0.4, Re = 6 x 10^6, α = 18°)	25-19

CHAPTER 26

Figure 26-1	Structured Grids	26-2
Figure 26-2	Sharp Leading Edge Results – α = 13°	26-4
Figure 26-3	Sharp Leading Edge Results – α = 19°	26-5
Figure 26-4	Sharp Leading Edge Results for PG – α = 23°	26-6
Figure 26-5	Velocity Distribution and Streamlines – Sharp Leading – α = 23° – PG	26-6
Figure 26-6	Comparison CFD Results / LTPT Data	26-7
Figure 26-7	Surface Pressure Distribution for the Sharp Leading Edge – PG – α = 28°	26-8
Figure 26-8	Streamline at the Apex of the Sharp Leading Edge – α = 8° – CG	26-8
Figure 26-9	Axial Vorticity around the Sharp Leading Edge – CG – α = 8°	26-9
Figure 26-10	Effect of Turbulence Model for the Medium Leading Edge – α = 13° – PG	26-10
Figure 26-11	Medium Leading Edge Results – M = 0.4, R_{mac} = 3 x 10^6, α = 13°	26-11
Figure 26-12	Comparison Pressure Distributions – Medium Leading Edge – M = 0.4, R_{mac} = 3 x 10^6, α = 13° – CG	26-11
Figure 26-13	Medium Leading Edge Results – M = 0.4, R_{mac} = 3 x 10^6, α = 13° – CG	26-12
Figure 26-14	Medium Leading Edge – Surface Pressure Distributions – PG	26-13
Figure 26-15	Medium Leading Edge Results – Axial Vorticity – PG	26-13
Figure 26-16	Mesh for Unsteady CFD on the Suction Side of the VFE-2 Delta Wing	26-14
Figure 26-17	Representation of the Flow Unsteadiness	26-15
Figure 26-18	Distribution of C_p on the Suction Side for the M = 0.4 Case	26-16
Figure 26-19	Evolution of the Longitudinal Velocity in Several Planes Perpendicular to the Surface of the Wing	26-18

Figure 26-20 Representation of the Cross-Flow Shock Waves 26-19
Figure 26-21 Representation of Time-Averaged Flow in the M = 0.8 Case 26-20
Figure 26-22 Positions of the Two Probes P_1 and P_2 Relatively to the Time-Averaged Flow 26-21
Figure 26-23 PSD of the Non-Dimensional Longitudinal Velocity at P_1 and P_2 26-21

CHAPTER 27

Figure 27-1 Computational Grid in Four Cross-Flow Planes: (a) Grid for the Sharp Leading Edge Wing; (b) Adapted Grid for the Large Radius Leading Edge Configuration at $M_\infty = 0.85$, $\alpha = 10.2°$, $Re_{mac} = 60 \times 10^6$ 27-2
Figure 27-2 Comparison of Computed Distributions for the Sharp Leading Edge Delta Wing ($M_\infty = 0.85$, $\alpha = 10.4°$ or 14.5°, $Re_{mac} = 6$ or 36×10^6): (a) Upper Surface Pressure Distributions; (b) Projections of the Vortex Core Trajectory as Detected from Upper Surface Minimum Pressure 27-5
Figure 27-3 Comparison of Computed and Experimental Upper Surface Peak Pressures along Vortex Trajectory for the Sharp Leading Edge Delta Wing ($M_\infty = 0.85$, $\alpha = 10.4°$ or 14.5°, $Re_{mac} = 6$ or 36×10^6) 27-6
Figure 27-4 Comparison of Computed and Experimental Spanwise Pressure Distributions for the Sharp Leading Edge Wing at $x/c_r = 0.60$: (a) $M_\infty = 0.85$, $\alpha = 10.4°$, $Re_{mac} = 6$ or 36×10^6; (b) $M_\infty = 0.85$, $\alpha = 14.5°$, $Re_{mac} = 6$ or 36×10^6 27-6
Figure 27-5 Comparison of Computed and Experimental Spanwise Pressure Distributions for the Sharp Leading Edge Wing at $x/c_r = 0.80$: (a) $M_\infty = 0.85$, $\alpha = 10.4°$, $Re_{mac} = 6$ or 36×10^6; (b) $M_\infty = 0.85$, $\alpha = 14.5°$, $Re_{mac} = 6$ or 36×10^6 27-7
Figure 27-6 Topology of Computed Separation and Re-attachment Patterns on the Upper Surface of the Sharp Leading Edge Delta Wing: (a) $M_\infty = 0.85$, $\alpha = 10.4°$, $Re_{mac} = 6 \times 10^6$; (b) $M_\infty = 0.85$, $\alpha = 14.5°$, $Re_{mac} = 36 \times 10^6$ 27-8
Figure 27-7 Influence of Reynolds Number on the Position of the Upper Surface Separation and Re-attachment Lines for the Sharp Leading Edge Delta Wing: (a) $M_\infty = 0.85$, $\alpha = 10.4°$, $Re_{mac} = 6$ or 36×10^6; (b) $M_\infty = 0.85$, $\alpha = 14.5°$, $Re_{mac} = 6$ or 36×10^6 27-9
Figure 27-8 Comparison of Computed and Experimental Normal Force and Pitch Moment Coefficient as a Function of Angle of Attack for the Sharp Leading Edge Delta Wing 27-10
Figure 27-9 Comparison of Computed Distributions for the Large Radius Leading Edge Delta Wing ($M_\infty = 0.85$, $(\alpha, Re_{mac}) = (10.4°, 6 \times 10^6)$, $(10.2°, 36 \times 10^6)$, $(10.2°, 60 \times 10^6)$ or $(10.4°, 120 \times 10^6)$): (a) Upper Surface Pressure Distributions; (b) Projections of the Vortex Core Trajectory as Detected Form Upper Surface Minimum Pressure 27-12
Figure 27-10 Comparison of Computed and Experimental Upper Surface Peak Pressures along Vortex Trajectory for the Large Radius Leading Edge Delta Wing ($M_\infty = 0.85$, $(\alpha, Re_{mac}) = (10.4°, 6 \times 10^6)$, $(10.2°, 36 \times 10^6)$, $(10.2°, 60 \times 10^6)$ or $(10.4°, 120 \times 10^6)$) 27-13
Figure 27-11 Comparison of Computed and Experimental Spanwise Pressure Distributions for the Large Radius Leading Edge Wing at $x/c_r = 0.60$: (a) $M_\infty = 0.85$, $(\alpha, Re_{mac}) = (10.4°, 6 \times 10^6)$, $(10.2°, 36 \times 10^6)$, $(10.2°, 60 \times 10^6)$ or $(10.4°, 120 \times 10^6)$; (b) $M_\infty = 0.85$, $\alpha = 10.2$ or 14.4°, $Re_{mac} = 60 \times 10^6$ 27-13
Figure 27-12 Comparison of Computed and Experimental Spanwise Pressure Distributions for the Large Radius Leading Edge Wing at $x/c_r = 0.80$: (a) $M_\infty = 0.85$, $(\alpha, Re_{mac}) = (10.4°, 6 \times 10^6)$, $(10.2°, 36 \times 10^6)$, $(10.2°, 60 \times 10^6)$ or $(10.4°, 120 \times 10^6)$; (b) $M_\infty = 0.85$, $\alpha = 10.2°$ or 14.4°, $Re_{mac} = 60 \times 10^6$ 27-14

Figure 27-13 Topology of Computed Separation and Re-attachment Patterns on the Upper Surface of the Large Radius Leading Edge Delta Wing ($M_\infty = 0.85$, $\alpha = 10.4°$, $Re_{mac} = 6 \times 10^6$) 27-15

Figure 27-14 Influence of Reynolds Number on the Position of the Upper Surface Separation and Re-attachment Lines for the Large Radius Leading Edge Delta Wing ($M_\infty = 0.85$, $(\alpha, Re_{mac}) = (10.4°, 6 \times 10^6), (10.2°, 36 \times 10^6), (10.2°, 60 \times 10^6)$ or $(10.4°, 120 \times 10^6)$) 27-15

CHAPTER 28

Figure 28-1 Computational Grid, Multi-Block Mesh Structure 28-3

Figure 28-2 Close View of Sub Domains 28-3

Figure 28-3 C_p Comparisons at $x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95$ Chord Wise Locations and Surface C_p Plot (Case 1, Table 28-1) 28-6

Figure 28-4 Vorticity Magnitude Contours and Stream Lines (Case 1, Table 28-1) 28-7

Figure 28-5 Comparison of Normal Force Coefficients for Sharp Leading Edge Configuration for 0.4 and 0.85 Mach Numbers 28-8

Figure 28-6 C_p Comparisons at $x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95$ Chord Wise Locations (Point No 144, Table 28-5) 28-9

Figure 28-7 Streamlines Close to the Surface on the Suction Side of the Wing (Point No 144, Table 28-5) 28-9

Figure 28-8 C_p Comparisons at $x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95$ Chord Wise Locations (Point No 147, Table 28-5) 28-10

Figure 28-9 Streamlines Close to the Surface on the Suction Side of the Wing (Point No 147, Table 28-5) 28-10

Figure 28-10 C_p Comparisons at $x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95$ Chord Wise Locations (Point No 1945, 1950, Table 28-5) 28-11

Figure 28-11 C_p Comparisons at $x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95$ Chord Wise Locations (Case 11-12, Table 28-2) 28-12

Figure 28-12 C_p Comparisons at $x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95$ Chord Wise Locations, (Case 26-27, Table 28-2) 28-13

Figure 28-13 C_p Comparisons at $x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95$ Chord Wise Locations (Case 5 ,14, 23, Table 28-3) 28-14

Figure 28-14 Surface Pressure Contours (Case 23 and 26, Table 28-4) 28-15

Figure 28-15 Streamlines Close to the Surface (Case 23 and 26, Table 28-4) 28-15

Figure 28-16 Vorticity Magnitude Isolines at Various Chord Wise Locations (Case 23 and 26, Table 28-4) 28-16

Figure 28-17 C_p Lines at $x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95$ Chord Wise Locations (Case 23 and 26, Table 28-4) 28-16

Figure 28-18 Surface Pressure Contours (Case 11 and 12, Table 28-2) 28-17

Figure 28-19 Streamlines Close to the Surface (Case 11 and 12, Table 28-2) 28-18

Figure 28-20 Vorticity Magnitude Isolines at Various Chord Wise Locations (Case 11 and 12, Table 28-2) 28-18

Figure 28-21 C_p Lines at $x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95$ Chord Wise Locations (Case 11 and 12, Table 28-2) 28-19

Figure 28-22 Surface Pressure Contours (Case 26 and 27, Table 28-2) 28-19

Figure 28-23 Streamlines Close to the Surface (Case 26 and 27, Table 28-2) 28-20

Figure 28-24	Vorticity Magnitude Isolines at Various Chord Wise Locations (Case 26 and 27, Table 28-2)	28-20
Figure 28-25	C_p Lines at x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95 Chord Wise Locations (Case 26 and 27, Table 28-2)	28-21
Figure 28-26	Surface Pressure Contours (Case 5, 14 and 23, Table 28-3)	28-22
Figure 28-27	C_p Lines at x/c_r = 0.2, 0.4, 0.6, 0.8, 0.95 Chord Wise Locations (Case 5, 14 and 23, Table 28-3)	28-22
Figure 28-28	Streamlines Close to the Surface (Case 5, Table 28-3)	28-23
Figure 28-29	Vorticity Magnitude Isolines at Various Chord Wise Locations (Case 5, Table 28-2)	28-23
Figure 28-30	Streamlines Close to the Surface (Case 14, Table 28-3)	28-24
Figure 28-31	Vorticity Magnitude Isolines at Various Chord Wise Locations (Case 14, Table 28-2)	28-24
Figure 28-32	Streamlines Close to the Surface (Case 23, Table 28-3)	28-24
Figure 28-33	Vorticity Magnitude Isolines at Various Chord Wise Locations (Case 23, Table 28-2)	28-24

CHAPTER 29

Figure 29-1	VFE-2 65° Delta Wing Geometry Used in Investigation	29-2
Figure 29-2	Vortex Breakdown Location for Both Computational and Experimental Results	29-3
Figure 29-3	Comparison of Computational Results and Experimental Data, M = 0.4 and Re = 6 x 10^6	29-5
Figure 29-4	Comparison of Computational Results (Glasgow) and Experimental Data (NTF), M = 0.85 and Re = 6 x 10^6	29-6
Figure 29-5	Pressure Coefficient Distribution from Glasgow Code at the Symmetry Plane on the Wing for Both Angles of Incidence	29-7
Figure 29-6	Isosurface of *x* Vorticity Coloured by Pressure Coefficient Showing Primary Vortex Shear Layer and Normal Shock Shape for Both Angles of Incidence (from the Glasgow Code)	29-8
Figure 29-7	Comparison of Glasgow Results between the H-H Grids for Transonic Conditions at α = 18.5° and 23° (from the Glasgow Code)	29-9
Figure 29-8	Contours of Surface Pressure Coefficient Showing Effect of Turbulence Model on Flow Solution with Comparison to Experiment for α = 23°, M = 0.85 and Re = 6 x 10^6	29-10
Figure 29-9	Surface Pressure Coefficient Contours for Structured Codes, M = 0.85, Re = 6 x 10^6	29-10
Figure 29-10	Time Averaged Surface Pressure Coefficient Contours for Unsteady Results, M = 0.85, Re = 6 x 10^6	29-11
Figure 29-11	Pressure Distribution (from the Glasgow Code) through Vortex Cores for Both Angles of Incidence	29-12
Figure 29-12	Rossby Number Distribution from the KTH Code against Root Chord Location for Pre- and Post-Breakdown Cases	29-13
Figure 29-13	Pressure Distribution through Vortex Cores for EADS, NLR and USAFA (Time Averaged) Solutions	29-16
Figure 29-14	Comparison between *u* Velocity Contours for Experimental PIV and Computational Results for M = 0.80 on a Slice at x/c_r = 0.5	29-18

Figure 29-15 *u* Velocity through Vortex Core for Computational Results Compared to Experimental PIV Data for M = 0.80, α = 26° 29-18
Figure 29-16 Vortex Breakdown Position for the KTH Solution 29-19
Figure 29-17 Sub-Frames Presenting Each in Clockwise Order, Starting from the Lower-Right Corner: Normal-View on Symmetry Plane Showing Mach Number Range from Subsonic, Sonic and Supersonic; Frontal-Isometric View of Half-Span Suction Side Showing Surface Pressure Coefficient and Reversed Flow Isosurface 29-20

CHAPTER 30

Figure 30-1 Three-View Sketch of Numerical Model – Exact NASA-NTF Geometry and Sting Close-Off Surface 30-2
Figure 30-2 Initial Blunt Leading Edge Computational Grid for the $R_{mac} = 2 \times 10^6$ and $R_{mac} = 6 \times 10^6$ Cases 30-5
Figure 30-3 Comparison of Surface Elements on Suction Side and Additional Tetrahedral Elements after Second Solution-Based Adaptation for Case α = 13.3°, M = 0.4, $R_{mac} = 3 \times 10^6$ 30-6
Figure 30-4 C_p Plots for Different x/c_r – Turbulence Model Comparison for Case α = 18.5°, M = 0.4, $R_{mac} = 6 \times 10^6$ 30-8
Figure 30-5 Convergence Behaviour for Case α = 18.5°, M = 0.4, $R_{mac} = 6 \times 10^6$, Scaled Residuals (Logarithmic Scale) and Force Coefficients 30-9
Figure 30-6 C_p Plots for Different x/c_r – Comparison of the Solution on the Initial Grid to Two Further Levels of Refinement and Experimental Data 30-9
Figure 30-7 Surface Pressure Coefficient, x-Vorticity Iso-Contours and Skin Friction Lines for Case α = 18.5°, M = 0.4, $R_{mac} = 6 \times 10^6$ 30-10
Figure 30-8 Surface Pressure Coefficient, x-Vorticity Iso-Contours and Skin Friction Lines for Case α = 18.5°, M = 0.4, $R_{mac} = 60 \times 10^6$ 30-11
Figure 30-9 Skin Friction Lines and Topological Interpretation – Case α = 18.5°, M = 0.4, $R_{mac} = 60 \times 10^6$ 30-11
Figure 30-10 C_p Plots for Different x/c_r – Case α = 18.5°, M = 0.4, $R_{mac} = 60 \times 10^6$ 30-12
Figure 30-11 Surface Pressure Coefficient – View on the Suction Side, Perpendicular above the Flat Delta Wing Central Part; α = 23.3°, M = 0.4 30-12
Figure 30-12 Surface Pressure Coefficient, x-Vorticity Iso-Contours and Skin Friction Lines for Case α = 23.3°, M = 0.4, $R_{mac} = 60 \times 10^6$ 30-13
Figure 30-13 Skin Friction Lines and Topological Interpretation – α = 23.3°, M = 0.4, $R_{mac} = 60 \times 10^6$ 30-14
Figure 30-14 C_p Plots for Different x/c_r – Case α = 23.3°, M = 0.4, $R_{mac} = 2 \times 10^6$ 30-14
Figure 30-15 C_p Plots for Different x/c_r – Case α = 23.3°, M = 0.4, $R_{mac} = 6 \times 10^6$ 30-14
Figure 30-16 C_p Plots for Different x/c_r – Case α = 23.3°, M = 0.4, $R_{mac} = 60 \times 10^6$ 30-15
Figure 30-17 Outer Primary Vortex Separation Onset 30-15
Figure 30-18 Inner and Outer Primary Vortex Separation Onset 30-16
Figure 30-19 Experimental Pressure Coefficient Surface Plot for α = 13.3°, M = 0.4, $R_{mac} = 3 \times 10^6$ 30-17
Figure 30-20 Surface Pressure Coefficient on Half-Span Suction Side – CFD Result for the Inviscid Case 30-17

Figure 30-21	Surface Pressure Coefficient on Half-Span Suction Side – CFD Results for the Viscous Cases	30-18
Figure 30-22	C_p Plots for Different x/c_r – Case $\alpha = 13°$, $M = 0.2$, $R_{mac} = 2 \times 10^6$ – Comparison between CFD Results and Experimental Data	30-19
Figure 30-23	C_p Plots for Different x/c_r – Case $\alpha = 13.3°$, $M = 0.4$, $R_{mac} = 6 \times 10^6$ – Comparison between CFD Results and Experimental Data	30-19
Figure 30-24	C_p Plots for Different x/c_r – Case $\alpha = 13.3°$, $M = 0.4$, $R_{mac} = 3 \times 10^6$ – Comparison between CFD Results and Experimental Data	30-20
Figure 30-25	C_p Plots for Different x/c_r – Case $\alpha = 13.3°$, $M = 0.4$, $R_{mac} = 60 \times 10^6$ – Comparison between CFD Results and Experimental Data	30-20
Figure 30-26	C_p Plots for Different x/c_r – Case $\alpha = 13.3°$, $M = 0.4$ – Comparison of CFD Results for Different Reynolds Numbers and Inviscid Computation	30-21
Figure 30-27	C_p Plots for Different x/c_r – Case $\alpha = 13.3°$, $M = 0.4$ – Comparison of CFD Results for Different Reynolds Numbers and Inviscid Computation – Magnification on Inner Vortical Region	30-21
Figure 30-28	$M = 0.2$, $R_{mac} = 2 \times 10^6$ – Color-Coded Skin Friction Lines on Suction Side	30-22
Figure 30-29	$M = 0.2$, $R_{mac} = 2 \times 10^6$ – Skin Friction Lines and Field Lines of Force Projected on x/c_r Planes	30-22
Figure 30-30	$\alpha = 13.3°$, $M = 0.4$, $R_{mac} = 3 \times 10^6$ – Cut Plane at $x/c_r = 0.35$	30-23
Figure 30-31	Oil-Flow Image of Blunt Leading-Edge Suction Side – $\alpha = 13°$, $M = 0.14$, $R_{mac} = 2 \times 10^6$	30-24
Figure 30-32	Inviscid Case – Skin Friction Lines	30-25
Figure 30-33	Inviscid Case – Isometric Views of Skin Friction Lines and Field Lines of Force Projected on x/c_r Planes	30-25
Figure 30-34	Upper Surface of the Initial Numerical Grid of the Sharp Leading Edge Geometry	30-28
Figure 30-35	Re-Meshed Grid for Case $\alpha = 23.0°$, $M = 0.85$, $R_{mac} = 6 \times 10^6$ Mid-Span Cut Through Volume ($\eta = 0.5$)	30-28
Figure 30-36	Constrained Volume Cut of the RANS Solution for Case $\alpha = 23.0°$, $M = 0.85$, $R_{mac} = 6 \times 10^6$	30-30
Figure 30-37	Comparison between Re-meshed Grid and Initial Grid for Case $\alpha = 23.0°$, $M = 0.85$, $R_{mac} = 6 \times 10^6$	30-30
Figure 30-38	Comparison between Sting-Less and Sting-Fitted Solution for the Sharp and Blunt Geometries – RANS Solutions for Case $\alpha = 23.0°$, $M = 0.85$, $R_{mac} = 6 \times 10^6$	30-31
Figure 30-39	Rossby Number Comparison between Sting-Less and Sting-Fitted Solution for the Sharp and Blunt Geometries – RANS Solutions for Case $\alpha = 23.0°$, $M = 0.85$, $R_{mac} = 6 \times 10^6$	30-32
Figure 30-40	Effect of Sideslip Angle on Solution – CFD Solutions for Case $\alpha = 23.0°$, $M = 0.85$, $R_{mac} = 6 \times 10^6$ at Various Sideslip Angles (β)	30-34

CHAPTER 31

Figure 31-1	Schematic View of the Flow over a Sharp Edged Delta Wing – (a) Vortex Formation; (b) Pressure Distribution in a Cross Section	31-1
Figure 31-2	NASA 65° Delta Wing in the NTF-Wind Tunnel at NASA-Langley Research Center	31-4

Figure 31-3	Pressure Distribution on the Upper Side of the Wing Using PSP-"Pressure Sensitive Paint" – M = 0.4, Re = 3 x 10^6, α = 13.3°	31-5
Figure 31-4	Pressure Distribution on the Upper Surface and PIV Measurement at x/c_{ref} = 0.6 – M = 0.4, Re = 3 x 10^6, α = 13.3°	31-6
Figure 31-5	Model Setup for PIV Measurements in the TWG-"Transonic Wind Tunnel Göttingen"	31-6
Figure 31-6	Numerical Model Topology and Computational Grid of the Symmetry Plane	31-7
Figure 31-7	Slice through the Computational Grid Close to the Trailing Edge Regarding the Prismatic Layer in Red and the Pre-Refined Grid Area at the Outer Wing in Dark Blue	31-7
Figure 31-8	Flow Topology on the Upper Surface of the 65° Delta Wing with Medium Radius Leading-Edge	31-8
Figure 31-9	Comparison of Pressure Distribution at Angle of Attack α = 13.3° (Left: CFD Calculation Using the k-ω Turbulence Model; Right: PSP Measurement – M = 0.4, Re = 2 x 10^6)	31-9
Figure 31-10	Comparison of Pressure Distribution at Angle of Attack α = 13.3° (Left: CFD Calculation Using the k-ω Turbulence Model; Right: PSP Measurement – M = 0.4, Re = 3 x 10^6)	31-9
Figure 31-11	Comparison of Pressure Distribution at Angle of Attack α = 13.3° (Left: PSI Measurement; Right: CFD Calculation Using the k-ω Turbulence Model – M = 0.4, Re = 2 x 10^6)	31-10
Figure 31-12	Comparison of Pressure Distribution at Angle of Attack α = 13.3° (Left: PSI Measurement; Right: CFD Calculation Using the k-ω Turbulence Model – M = 0.4, Re = 3 x 10^6)	31-11
Figure 31-13	Comparison of Pressure Distribution at Angle of Attack α = 13.3° (Left: CFD Calculation Using the Spalart-Allmaras Turbulence Model; Right: PSP Measurement – M = 0.4, Re = 2 x 10^6)	31-12
Figure 31-14	Comparison of Pressure Distribution at Angle of Attack α = 13.3° (Left: CFD Calculation Using the Spalart-Allmaras Turbulence Model; Right: PSP Measurement – M = 0.4, Re = 3 x 10^6)	31-12
Figure 31-15	Comparison of Pressure Distribution at Angle of Attack α = 13.3° (Left: PSI Measurement; Right: CFD Calculation Using the Spalart-Allmaras Turbulence Model – M = 0.4, Re = 2 x 10^6)	31-13
Figure 31-16	Comparison of Pressure Distribution at Angle of Attack α = 13.3° (Left: PSI Measurement: Right: CFD Calculation Using the Spalart-Allmaras Turbulence Model – M = 0.4, Re = 3 x 10^6)	31-13
Figure 31-17	CFD Simulation with the DLR TAU-Code	31-14
Figure 31-18	Comparison of Surface Pressure Distribution at an Angle of Attack of α = 13.3° and α = 13.0°	31-15
Figure 31-19	Comparison of Pressure Distribution at Slices x = const at an Angle of Attack of α = 13.3° and α = 13.0°	31-15
Figure 31-20	Friction Lines and Pressure Distribution on the Upper Surface of the Delta Wing	31-16
Figure 31-21	Vorticity Slices on the Upper Surface of the Delta Wing	31-17
Figure 31-22	Streamlines and Pressure Distribution on the Upper Surface of the Delta Wing	31-18
Figure 31-23	Streamlines and Pressure Distribution on the Upper Surface of the Delta Wing	31-19
Figure 31-24	Streamlines and Pressure Distribution on the Upper Surface of the Delta Wing	31-19

CHAPTER 32

Figure 32-1	Schematic View of the Flow over a Sharp Leading Edge Delta Wing: (a) Vortex Formation; (b) Pressure Distribution in a Cross Flow Plane	32-2
Figure 32-2	NASA 65° Delta Wing in the NTF Wind Tunnel at NASA Langley Research Center	32-7
Figure 32-3	Pressure Distribution on the Upper Side of the Wing Using PSP (Pressure Sensitive Paint) – M = 0.4, $R_{mac} = 3 \times 10^6$, $\alpha = 14°$	32-7
Figure 32-4	Model Setup for PIV Measurements in the Transonic Wind Tunnel Göttingen (TWG)	32-8
Figure 32-5	Pressure Distribution on the Upper Surface and PIV Measurement at $x/c_{ref} = 0.6$ for M = 0.4, $R_{mac} = 3 \times 10^6$ and $\alpha = 14°$	32-8
Figure 32-6	Slice through the Computational Unstructured Grid	32-9
Figure 32-7	Slice through the Computational Unstructured Grid at Four Different x = Constant Positions	32-10
Figure 32-8	Pressure Distribution on the Upper Surface of the Wing – Comparison of CFD Calculation and PSP Measurement for $R_{mac} = 2 \times 10^6$, M = 0.4 and $\alpha = 13.3°$	32-11
Figure 32-9	Pressure Distribution on the Upper Surface of the Wing – Comparison of CFD Calculation and PSP Measurement for $R_{mac} = 3 \times 10^6$, M = 0.4 and $\alpha = 13.3°$	32-11
Figure 32-10	Pressure Distribution on the Upper Surface of the Wing – Comparison of CFD Simulations at Different Reynolds Numbers for M = 0.4 and $\alpha = 13.3°$	32-12
Figure 32-11	Pressure Distribution at Positions x = Const. – Comparison of Experiment and CFD Calculation for $R_{mac} = 2 \times 10^6$, M = 0.4 and $\alpha = 13.3°$	32-13
Figure 32-12	Pressure Distribution at Positions x = Const. – Comparison of Experiment and CFD Calculation for $R_{mac} = 3 \times 10^6$, M = 0.4 and $\alpha = 13.3°$	32-13
Figure 32-13	Computed Pressure Distribution on the Upper Surface of the Wing for $R_{mac} = 3 \times 10^6$ and 4.5×10^6 at M = 0.4 and $\alpha = 13.3°$	32-15
Figure 32-14	Pressure Distribution on the Upper Surface of the Wing – Comparison of CFD Calculation ($R_{mac} = 4.5 \times 10^6$) and PSP Measurement ($R_{mac} = 3 \times 10^6$) for M = 0.4 and $\alpha = 13.3°$	32-15
Figure 32-15	Pressure Distribution at Positions x = Const. – Comparison of CFD Calculation ($R_{mac} = 4.5 \times 10^6$) and Experiment ($R_{mac} = 3 \times 10^6$) for M = 0.4 and $\alpha = 13.3°$	32-16
Figure 32-16	Pressure Distribution on the Upper Surface of the Wing – Comparison of CFD Simulations at Different Angles of Attack for $R_{mac} = 6 \times 10^6$ and M = 0.4	32-17
Figure 32-17	Pressure Distribution at Positions x = Const. – Comparison of CFD Calculation ($R_{mac} = 6 \times 10^6$) and Experiment ($R_{mac} = 6 \times 10^6$) for M = 0.4 and $\alpha = 13.3°$	32-17
Figure 32-18	Pressure Distribution at Positions x = Const. – Comparison of CFD Calculation ($R_{mac} = 6 \times 10^6$) and Experiment ($R_{mac} = 6 \times 10^6$) for M = 0.4 and $\alpha = 18.4°$	32-18
Figure 32-19	Pressure Distribution at Positions x = Const. – Comparison of CFD Calculation ($R_{mac} = 6 \times 10^6$) and Experiment ($R_{mac} = 6 \times 10^6$) for M = 0.4 and $\alpha = 23°$	32-18
Figure 32-20	Pressure Distribution on the Upper Surface of the Wing – Comparison of CFD Calculation ($R_{mac} = 3 \times 10^6$) With and Without Transition Line for M = 0.4 and $\alpha = 13.3°$	32-19
Figure 32-21	Pressure Distribution at Positions x = Const. – Comparison of CFD Calculation ($R_{mac} = 3 \times 10^6$) With and Without Transition for M = 0.4 and $\alpha = 13.3°$	32-20
Figure 32-22	Pressure Distribution on the Upper Surface of the Wing – Comparison of CFD Calculation (SARC-DES) and PSP Measurement for $R_{mac} = 3 \times 10^6$, M = 0.4 and $\alpha = 13.3°$	32-21

Figure 32-23 Pressure Distribution at Positions x = Const. – Comparison of CFD Calculation (SARC-DES) and Experiment for R_{mac} = 3 x 10^6, M = 0.4 and α = 13.3° 32-21

Figure 32-24 Pressure Distribution on the Upper Surface of the Wing – Comparison of CFD Calculation (SARC-DDES) and PSP Measurement for R_{mac} = 3 x 10^6, M = 0.4 and α = 13.3° 32-22

Figure 32-25 Pressure Distribution at Positions x = Const. – Comparison of CFD Calculation (SARC-DDES) and Experiment for R_{mac} = 3 x 10^6, M = 0.4 and α = 13.3° 32-22

Figure 32-26 Pressure Distribution on the Upper Surface of the Wing – Comparison of CFD Calculation (SA-DES) and PSP Measurement for R_{mac} = 3 x 10^6, M = 0.4 and α = 13.3° 32-23

Figure 32-27 Pressure Distribution at Positions x = Const. – Comparison of CFD Calculation (SA-DES) and Experiment for R_{mac} = 3 x 10^6, M = 0.4 and α = 13.3° 32-24

Figure 32-28 Pressure Distribution on the Upper Surface of the Wing – Comparison of CFD Calculation (SA-DDES) and PSP Measurement for R_{mac} = 3 x 10^6, M = 0.4 and α = 13.3° 32-25

Figure 32-29 Pressure Distribution at Positions x = Const. – Comparison of CFD Calculation (SA-DDES) and Experiment for R_{mac} = 3 x 10^6, M = 0.4 and α = 13.3° 32-25

Figure 32-30 Surface Pressure Distribution and x-Vorticity at Positions x = Const. for R_{mac} = 3 x 10^6, M = 0.4 and α = 13.3° 32-27

Figure 32-31 Surface Pressure Distribution and Streamlines for R_{mac} = 3 x 10^6, M = 0.4 and α = 13.3° 32-27

Figure 32-32 Skin Friction Lines and Surface Pressure Distribution – R_{mac} = 3 x 10^6, M = 0.4 and α = 13.3° 32-28

CHAPTER 33

Figure 33-1 NTF 65° Delta Wing 33-3

Figure 33-2 Streamwise Leading-Edge Contours for NTF Delta Wings 33-4

Figure 33-3 Reynolds Number and Mach Number Conditions 33-4

Figure 33-4 Delta Wing, t/c and r/c Variations with y/s for Rounded Edge Models 33-5

Figure 33-5 Models with Small, Medium and Large Roundness, Flow Separation (LE Vortex) Onset and Movement, Effect of R_{mac}, Mach 0.4 33-6

Figure 33-6 Model with Medium Round LE, Flow Separation Onset and Movement, Effect of Compressibility, Mach 0.4, 0.6 & 0.85, R_{mac} = 6 Million 33-6

Figure 33-7 Models with Small, Medium and Large Roundness LE, Flow Separation Onset and Movement, Effect of Compressibility, Mach 0.4, 0.6 & 0.85, R_{mac} = 6 Million 33-7

Figure 33-8 Model with Medium LE, Flow Separation Onset and Movement, Effect of Compressibility and R, Mach 0.4 & 0.6, R_{mac} = 6 Million & 60 Million 33-7

Figure 33-9 Extended Qualification of Vortex Flow Onset, Breakdown and Control, Starting from Lamar's Work 33-8

Figure 33-10 Different Stages in Evaluation Method Incorporating Attained Thrust, LE Suction Analogy and Vortex Breakdown Empiricisms, Symmetric and Asymmetric Situations 33-10

Figure 33-11 Key Features and Various Steps of the Attained Thrust Prediction Method 33-11

Figure 33-12 C_{plim} and Mach Number Relationships 33-12

Figure 33-13	Typical Theoretical C_p Distributions and Local Force Coefficients c_t and c_n	33-13
Figure 33-14	Family of Aerofoil Sections, Differing t/c, Maximum Thickness t_{max} at Mid-Chord	33-14
Figure 33-15	An Example of K_T Variation for AoA Increasing, Vacuum Limit	33-15
Figure 33-16	Dependence of K_T on Normal Mach Number and Normal Reynolds Number, Experiment and Theory ($e_m = 0$, see Figure 33-17)	33-16
Figure 33-17	C_{plim} Variation with Normal Mach and Normal Reynolds Number, Experiment and Theory (e_m Finite as Defined)	33-16
Figure 33-18	Variation of K_T and C_{plim} as Given by Carlson's Formula (e_m Finite as in Figure 33-17)	33-17
Figure 33-19	Variation of K_T with R_n, $e_m = 0$	33-18
Figure 33-20	Updated Variation of K_T, R_n Varies between 10^4 and 10^{10}	33-18
Figure 33-21	More Detail of Updated Variation of K_T, R_n Varies between 10^5 and 10^7	33-19
Figure 33-22	Dependence of Thrust Factor K_T on Normal Aerofoil Parameters and Normal Mach Number (see also Figure 33-23)	33-20
Figure 33-23	Sweep Theory and Definition of Normal Aerofoil Sections from Streamwise Sections of 3-D Wings	33-20
Figure 33-24	Pressure Distributions over Unswept and Swept Wings	33-21
Figure 33-25	Spanwise Flow and Alleviation of Gradients on Aft-Swept Wings	33-21
Figure 33-26	Vortex Lines Near the Centre and Tip of a Plane Swept Wing	33-22
Figure 33-27	Streamlines Straightening at Wing Root and at Tip	33-22
Figure 33-28	Typical Variation of P_L	33-22
Figure 33-29	Determination of the Separation Onset	33-24
Figure 33-30	Onset of Separation at Wing-Tip, Theory and Expt. Small, Medium and Large Roundness Models, R_{mac} = 6 Million	33-27
Figure 33-31	Development of Onset of Separation along Wing, Theory and Experiment, Small Roundness Model, R_{mac} = 6 Million, Mach Varies	33-28
Figure 33-32	Development of Onset of Separation along Wing, Theory and Experiment, Medium Roundness, R_{mac} = 6 Million, Mach Varies	33-29
Figure 33-33	Development of Onset of Separation along Wing, Theory and Experiment, Large Roundness, R_{mac} = 6 Million, Mach Varies	33-30
Figure 33-34	Development of Onset of Separation along Wing, Theory, Mach 0.4, R_{mac} = 6 Million, Small, Medium and Large Roundness Models	33-31
Figure 33-35	Development of Onset of Separation along Wing, Theory, Mach 0.4, R_{mac} = 60 Million, Small, Medium and Large Roundness Models	33-32

CHAPTER 34

Figure 34-1	Configuration of the First International Vortex Flow Experiment (VFE-1)	34-3
Figure 34-2	Configuration of the Second International Vortex Flow Experiment (VFE-2)	34-4
Figure 34-3	Comparison of Vortical Flow Features for Sharp and Rounded Leading Edge Delta Wings	34-6
Figure 34-4	Dual Primary Vortex System for MRLE Delta Wing with PIV and PSP, M = 0.4, Re = 3 x 10^6, $\alpha = 13°$	34-7

Figure 34-5 Flow Features for Case 4.5: MRLE, M = 0.40, α = 13°, Re = 3 x 10^6 34-9

Figure 34-6 Surface Pressure Maps and Onset of Leading-Edge Vortex for Case 4.5: MRLE, M = 0.40, α = 13°, Re = 3 x 10^6 34-10

Figure 34-7 Comparison of Surface Pressures and Experimental Data for Case 4.5: MRLE, M = 0.40, α = 13°, Re = 3 x 10^6 34-11

Figure 34-8 Comparison of Computed Surface Skin Friction Data for Case 4.5: MRLE, M = 0.40, α = 13°, Re = 3 x 10^6 34-12

Figure 34-9 Surface Grid Density Comparison for Various Predictions 34-13

Figure 34-10 Surface Pressure Maps and Onset of Leading-Edge Vortex for Case 5: MRLE, M = 0.40, α = 13°, Re = 6 x 10^6 34-14

Figure 34-11 Comparison of Surface Pressures and Experimental Data for Case 5: MRLE, M = 0.40, α = 13°, Re = 6 x 10^6 34-15

Figure 34-12 Impact of Transition on Surface Flow for Case 5 (EADS-Solution, see Chapter 25): MRLE, M = 0.40, α = 13°, Re = 6 x 10^6 34-16

Figure 34-13 Effect of Reynolds Number on Surface Flows for Case 5: MRLE, M = 0.40, α = 13°, Re = 6 x 10^6 34-17

Figure 34-14 Flow Features for Case 14: MRLE, M = 0.40, α = 18°, Re = 6 x 10^6 34-18

Figure 34-15 Surface Pressure Maps for Case 14: MRLE, M = 0.40, α = 18°, Re = 6 x 10^6 34-19

Figure 34-16 Comparison of Surface Pressures and Experimental Data for Case 14: MRLE, M = 0.40, α = 18°, Re = 6 x 10^6 34-20

Figure 34-17 Surface Pressure Maps for Case 15: SLE, M = 0.40, α = 18°, Re = 6 x 10^6 34-21

Figure 34-18 Comparison of Surface Pressures and Experimental Data for Case 15: SLE, M = 0.40, α = 18°, Re = 6 x 10^6 34-22

Figure 34-19 Flow Features for Case 24: SLE, M = 0.40, α = 23°, Re = 6 x 10^6 34-23

Figure 34-20 Surface Pressure Maps for Case 24: SLE, M = 0.40, α = 23°, Re = 6 x 10^6 34-24

Figure 34-21 Comparison of Surface Pressures and Experimental Data for Case 24: SLE, M = 0.40, α = 23°, Re = 6 x 10^6 34-25

Figure 34-22 Flow Features for Case 25: SLE, M = 0.85, α = 23°, Re = 6 x 10^6 34-26

Figure 34-23 Surface Pressure Maps for Case 25: SLE, M = 0.85, α = 23°, Re = 6 x 10^6 34-27

Figure 34-24 Comparison of Surface Pressures and Experimental Data for Case 25: SLE, M = 0.85, α = 23°, Re = 6 x 10^6 34-28

Figure 34-25 Comparison of Surface Pressures and Experimental Data for Case 25: SLE, M = 0.85, α = 23°, Re = 6 x 10^6 34-29

Figure 34-26 Surface Pressure Maps for Case 25: SLE, M = 0.85, α = 23°, Re = 6 x 10^6 34-30

Figure 34-27 Comparison of Skin Friction Predictions for Case 25: SLE, M = 0.85, α = 23°, Re = 6 x 10^6 34-31

CHAPTER 35

Figure 35-1 VFE-2 Configuration: NASA Delta Wing Λ = 65° According to [35-1] 35-1

Figure 35-2 Effect of Bluntness on Experimental Normal and Axial Force Coefficients for the VFE-2 Configuration with Sharp (SLE) and Medium Radius Rounded Leading Edge (MRLE) at M = 0.1, R_{mac} = 1 x 10^6 35-3

Figure 35-3 Surface Pressure Distribution on the VFE-2 Configuration with Sharp Leading Edges (SLE) at M = 0.40, α = 18°, Re = 6 x 10^6 35-4

Figure 35-4	Comparison of Calculated Surface Pressures with Experimental Data for the VFE-2 Configuration with Sharp Leading Edges (SLE) at M = 0.40, $\alpha = 18°$, Re = 6 x 10^6	35-4
Figure 35-5	Surface Pressure Distribution on the VFE-2 Configuration with Medium Radius Rounded Leading Edges (MRLE) at M = 0.40, $\alpha = 18°$, Re = 6 x 10^6	35-5
Figure 35-6	Comparison of Calculated Surface Pressures with Experimental Data for the VFE-2 Configuration with Medium Radius Rounded Leading Edges (MRLE) at M = 0.40, $\alpha = 18°$, Re = 6 x 10^6	35-5
Figure 35-7	Flow Field around the VFE-2 Configuration with Sharp (SLE) and Medium Radius Rounded (MRLE) Leading Edges at $M \approx 0.1$, $R_{mac} = 1 \times 10^6$, $\alpha = 18°$	35-7
Figure 35-8	Flow Field around the VFE-2 Configuration with Sharp Leading Edges (SLE) at $M \approx 0.1$, $R_{mac} = 1 \times 10^6$, $\alpha = 18°$ – HWA Results from TU Munich for the Velocity Fluctuations u_{rms}/U_∞ and $\overline{u'w'}/U_\infty^2$ in the Plane at x/c = 0.6	35-8
Figure 35-9	Flow Field around the VFE-2 Configuration with Sharp Leading Edges (SLE) at $M \approx 0.1$, $R_{mac} = 1 \times 10^6$, $\alpha = 18°$ – Power Spectrum Density $(PSD)_u$ for the u-Component of the Velocity as Function of the Reduced Frequency k at x/c = 0.6, $\eta = 0.75$, $\zeta = 0.2$ According to HWA at TU Munich	35-8
Figure 35-10	Surface Oilflow Patterns on the Upper Surface of the Sharp-Edged VFE-1 Cropped Delta Wing (Leading Edge Sweep $\Lambda = 65°$) at M = 0.12, $\alpha = 10°$ for Different Reynolds Numbers	35-10
Figure 35-11	Numerical Simulation of the Flow around the VFE-2 Configuration with Sharp Leading Edge (SLE) for M = 0.4, $R_{mac} = 6 \times 10^6$, $\alpha = 23°$	35-12
Figure 35-12	Flow Field around the VFE-2 Configuration with Medium Radius Rounded Leading Edges (MRLE) at M = 0.14, $R_{mac} = 2 \times 10^6$, $\alpha = 23°$	35-13
Figure 35-13	Flow Field around the VFE-2 Configuration with Medium Radius Rounded Leading Edges (MRLE) at $M \approx 0.1$, $R_{mac} = 1 \times 10^6$, $\alpha = 23°$	35-14
Figure 35-14	Surface Pressure Distribution on the VFE-2 Configuration with Sharp Leading Edges (SLE) at M = 0.40, $\alpha = 23°$, Re = 6 x 10^6	35-15
Figure 35-15	Comparison of Calculated Surface Pressures with Experimental Data for the VFE-2 Configuration with Medium Radius Rounded Leading Edges (MRLE) at M = 0.40, $\alpha = 23°$, Re = 6 x 10^6	35-15
Figure 35-16	Pressure Distributions on the VFE-2 Configuration with Sharp and Medium Radius Rounded Leading Edges (MRLE) at $R_{mac} = 2 \times 10^6$ and $\alpha = 25°$ for Two Mach Numbers According to the PSP Experiments at DLR Goettingen	35-16
Figure 35-17	Comparison of Calculated Surface Pressures with Experimental Data for the VFE-2 Configuration with Sharp Leading Edges (SLE) at M = 0.85, $\alpha = 23°$, Re = 6 x 10^6	35-17
Figure 35-18	Surface Pressure Maps on the VFE-2 Configuration with Sharp Leading Edges (SLE) at M = 0.85, $\alpha = 23°$, Re = 6 x 10^6	35-18
Figure 35-19	Comparison of Vortical Flow Features for Sharp and Blunt Leading Edge Delta Wings According to [35-1], taken from [35-17]	35-19
Figure 35-20	Effect of Bluntness on Experimental Normal Force and Pitching Moment Coefficients for the VFE-2 Configuration with Sharp (SLE) and Medium Radius Rounded Leading Edges (MRLE) at M = 0.4, $R_{mac} = 6 \times 10^6$	35-20
Figure 35-21	Experimental Pressure Distribution on the VFE-2 Configuration with Medium Radius Rounded Leading Edges (MRLE) for M = 0.4, $R_{mac} = 3 \times 10^6$, $\alpha = 13°$	35-21
Figure 35-22	Pressure (Surface Color), Velocity (Vectors) and Vorticity (Vector Color) Distributions above the VFE-2 Configuration with Medium Radius Rounded Leading Edges (MRLE) for M = 0.4, $R_{mac} = 3 \times 10^6$, $\alpha = 13°$	35-21

Figure 35-23 Surface Pressure Distribution on the VFE-2 Configuration with Medium Radius Leading Edges (MRLE) at M = 0.40, α = 13°, Re = 3 x 10^6 35-22

Figure 35-24 Comparison of Calculated Surface Pressures with Experimental Data for the VFE-2 Configuration with Medium Radius Rounded Leading Edges (MRLE) at M = 0.40, α = 13°, Re = 3 x 10^6 35-23

Figure 35-25 Pressure Distributions on the VFE-2 Configuration with Medium Radius Rounded Leading Edges (MRLE) for M = 0.4, R_{mac} = 3 x 10^6 at Various Angles of Attack 35-24

Figure 35-26 Pressure Distributions on the VFE-2 Configuration with Medium Radius Rounded Leading Edges (MRLE) for M = 0.4, α = 13° at Different Reynolds Numbers 35-25

Figure 35-27 Pressure Distributions on the VFE-2 Configuration with Medium Radius Rounded Leading Edges (MRLE) at R_{mac} = 2 x 10^6 and α = 13° for Different Mach Numbers 35-26

Figure 35-28 Numerical Solution on a Structured Grid for the Flow around the VFE-2 Configuration with Medium Radius Rounded Leading Edges at M = 0.4, R_{mac} = 3 x 10^6, α = 13.3° 35-27

Figure 35-29 Numerical Solution on an Unstructured Grid for the Flow around the VFE-2 Configuration with Medium Radius Rounded Leading Edges at M = 0.4, R_{mac} = 3 x 10^6, α = 13.3° 35-28

Figure 35-30 Schematic View of the Vortex Formation on the VFE-2 Configuration with Medium Radius Rounded Leading Edge (MRLE) at M = 0.4, R_{mac} = 3 x 10^6, α = 13.3° 35-28

APPENDIX A3.3

Figure A3.3-1 Surface Oil Flow Visualisation at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 13°, α = 18°, α = 23° A3.3-2

Figure A3.3-2 Surface Oil Flow Visualisation at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 13°, α = 18°, α = 23° A3.3-3

Figure A3.3-3 Surface Oil Flow Visualisation at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 10°, α = 12°, α = 20° A3.3-4

Figure A3.3-4 Surface Oil Flow Visualisation at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 16°, α = 20°, α = 21° A3.3-5

Figure A3.3-5 Surface Oil Flow Visualisation at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 22°, α = 24°, α = 25° A3.3-6

Figure A3.3-6 Surface Oil Flow Visualisation at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 26°, α = 27°, α = 28° A3.3-7

Figure A3.3-7 Surface Oil Flow Visualisation at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 29°, α = 30° A3.3-8

Figure A3.3-8 Steady Pressure Distribution at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 0°, α = 5°, α = 10° A3.3-9

Figure A3.3-9 Steady Pressure Distribution at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 12°, α = 14°, α = 16° A3.3-10

Figure A3.3-10 Steady Pressure Distribution at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 20°, α = 21°, α = 22° A3.3-11

Figure A3.3-11 Steady Pressure Distribution at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 24°, α = 25°, α = 26° A3.3-12

Figure A3.3-12 Steady Pressure Distribution at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 27°, α = 28°, α = 29° A3.3-13

Figure A3.3-13 Steady Pressure Distribution at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 30° A3.3-14
Figure A3.3-14 Steady Pressure Distribution at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 0°, α = 5°, α = 10° A3.3-15
Figure A3.3-15 Steady Pressure Distribution at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 12°, α = 14°, α = 16° A3.3-16
Figure A3.3-16 Steady Pressure Distribution at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 20°, α = 21°, α = 22° A3.3-17
Figure A3.3-17 Steady Pressure Distribution at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 24°, α = 25°, α = 26° A3.3-18
Figure A3.3-18 Steady Pressure Distribution at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 27°, α = 28°, α = 29° A3.3-19
Figure A3.3-19 Steady Pressure Distribution at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 30° A3.3-20
Figure A3.3-20 Pressure Fluctuation Intensity at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 0°, α = 5°, α = 10° A3.3-21
Figure A3.3-21 Pressure Fluctuation Intensity at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 12°, α = 14°, α = 16° A3.3-22
Figure A3.3-22 Pressure Fluctuation Intensity at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 20°, α = 21°, α = 22° A3.3-23
Figure A3.3-23 Pressure Fluctuation Intensity at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 24°, α = 25°, α = 26° A3.3-24
Figure A3.3-24 Pressure Fluctuation Intensity at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 27°, α = 28°, α = 29° A3.3-25
Figure A3.3-25 Pressure Fluctuation Intensity at R_{mac} = 1 x 10^6 and M = 0.07 for Sharp and Rounded Leading Edges – α = 30° A3.3-26
Figure A3.3-26 Pressure Fluctuation Intensity at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 0°, α = 5°, α = 10° A3.3-27
Figure A3.3-27 Pressure Fluctuation Intensity at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 12°, α = 14°, α = 16° A3.3-28
Figure A3.3-28 Pressure Fluctuation Intensity at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 20°, α = 21°, α = 22° A3.3-29
Figure A3.3-29 Pressure Fluctuation Intensity at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 24°, α = 25°, α = 26° A3.3-30
Figure A3.3-30 Pressure Fluctuation Intensity at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 27°, α = 28°, α = 29° A3.3-31
Figure A3.3-31 Pressure Fluctuation Intensity at R_{mac} = 2 x 10^6 and M = 0.14 for Sharp and Rounded Leading Edges – α = 30° A3.3-32

APPENDIX A3.5

Figure A3.5-1 Development of the Flow Topology on the Medium-Radius Wing at α = 13.3° and R_{mac} = 1 x 10^6 A3.5-2
Figure A3.5-2 Development of the Flow Topology on the Medium-Radius Wing at α = 13.3° and R_{mac} = 2 x 10^6 A3.5-3

Figure A3.5-3 Development of the Flow Topology on the Sharp-Edged Wing at α = 13.3° and $R_{mac} = 2 \times 10^6$ A3.5-4
Figure A3.5-4 Development of the Flow Topology on the Medium-Radius Wing at α = 18.5° and $R_{mac} = 1 \times 10^6$ A3.5-5
Figure A3.5-5 Development of the Flow Topology on the Medium-Radius Wing at α = 18.5° and $R_{mac} = 2 \times 10^6$ A3.5-6
Figure A3.5-6 Development of the Flow Topology on the Sharp-Edged Wing at α = 18.5° and $R_{mac} = 2 \times 10^6$ A3.5-7
Figure A3.5-7 Development of the Flow Topology on the Medium-Radius Wing at α = 23° and $R_{mac} = 1 \times 10^6$ A3.5-8
Figure A3.5-8 Development of the Flow Topology on the Medium-Radius Wing at α = 23° and $R_{mac} = 2 \times 10^6$ A3.5-9
Figure A3.5-9 Development of the Flow Topology on the Sharp-Edged Wing at α = 23° and $R_{mac} = 2 \times 10^6$ A3.5-10

APPENDIX A3.6

Figure A3.6-1 Geometry of VFE-2 Delta Wing A3.6-1
Figure A3.6-2 3-D Grid Structure A3.6-2
Figure A3.6-3 Grid in Plane of Symmetry A3.6-3
Figure A3.6-4 Grid Structure in Wake Region A3.6-3
Figure A3.6-5 Grid around Leading Edge A3.6-4
Figure A3.6-6 Index Directions i and j A3.6-5
Figure A3.6-7 Index k in the Wing Region A3.6-6
Figure A3.6-8 Orientation of Index k in the Wake Region A3.6-7
Figure A3.6-9 Surface Pressure Contours in Medium Grid A3.6-8
Figure A3.6-10 Pressure Contours in the Fine Grid A3.6-9

APPENDIX A3.7

Figure A3.7-1 Geometry of VFE-2 Delta Wing A3.7-1
Figure A3.7-2 TAU Grid – Surface Topology and Discretization of the Symmetry Plane A3.7-2
Figure A3.7-3 TAU Grid – Prism Layer and Pre-Refined Tetrahedral Grid at 80% Chord Length A3.7-3
Figure A3.7-4 Source Topology for the Tetrahedral Field Sources A3.7-3
Figure A3.7-5 Cobalt Grid – Prism Layer and Pre-Refined Tetrahedral Grid A3.7-4
Figure A3.7-6 Cobalt Grid – Prism Layer and Pre-Refined Tetrahedrals A3.7-5

List of Tables

Table		Page
CHAPTER 3		
Table 3-1	F-16XL-1 Airplane Specifications	3-2
Table 3-2	Planned F-16XL CAWAP Data Comparisons	3-6
Table 3-3	Actual F-16XL CAWAP Data Comparisons	3-7
Table 3-4	Seven Flight Conditions to be Examined	3-28
Table 3-5	Associated Engine Parameters for these Flight Conditions	3-29
CHAPTER 4		
Table 4-1	Details of the Baseline Structured Grid	4-6
CHAPTER 5		
Table 5-1	Computational Details of the Simulations	5-4
Table 5-2	Flight Test Data	5-5
Table 5-3	Engine Parameters	5-5
Table 5-4	Boundary-Layer Rake Locations	5-10
CHAPTER 6		
Table 6-1	Summary of Test Cases	6-4
CHAPTER 7		
Table 7-1	Airplane Specifications	7-5
Table 7-2	Seven Flight Conditions	7-7
Table 7-3	Associated Engine Parameters for these Flight Conditions	7-7
CHAPTER 8		
Table 8-1	Calculated Flight Conditions	8-3
CHAPTER 9		
Table 9-1	Subset of CAWAP Flight Conditions Chosen for CAWAPI	9-5
Table 9-2	Pressure Tap Location in Region of Interest	9-8
CHAPTER 10		
Table 10-1	Flight Conditions (FC) to be Examined (Nominal Altitude, actual Mach Number, actual Angle of Attack, actual Side-Slip Angle, actual Reynolds Number)	10-3
Table 10-2	Propulsion Conditions as a Function of the Flight Condition (FC)	10-10
Table 10-3	Computed Cases: Turbulence Models Used for Computing the different Flight Conditions (FC)	10-11

CHAPTER 11

Table 11-1 Propulsion Conditions as a Function of Flight Conditions 11-2
Table 11-2 Values of Total Pressure in the Mixing Plane 11-7

CHAPTER 13

Table 13-1 The CAWAPI Program Examined Seven Different Flight Conditions 13-3

CHAPTER 14

Table 14-1 Seven Flight Conditions Examined 14-8
Table 14-2 Associated Engine Parameters for these Flight Conditions 14-8

CHAPTER 15

Table 15-1 Seven Flight Conditions to be Examined 15-2
Table 15-2 Associated Engine Parameters for these Flight Conditions 15-3

CHAPTER 16

Table 16-1 Overview of Ten Solutions Generated by the Nine Participating Organizations 16-3
Table 16-2 Computational Grid Sizes 16-16
Table 16-3 Flight Condition FC25, Force/Moment Coefficients (Values provided by respective, listed organization – see Table 16-1) 16-31
Table 16-4 Flight Condition FC25, Force/Moment Coefficients – Statistical Analysis 16-31
Table 16-5 Flight Condition FC19, Force/Moment Coefficients (Values provided by respective, listed organization – see Table 16-1) 16-32
Table 16-6 Flight Condition FC19, Force/Moment Coefficients – Statistical Analysis 16-32
Table 16-7 Flight Condition FC7, Force/Moment Coefficients (Values provided by respective, listed organization – see Table 16-1) 16-32
Table 16-8 Flight Condition FC7, Force/Moment Coefficients – Statistical Analysis 16-32
Table 16-9 Flight Condition FC50, Force/Moment Coefficients (Values provided by respective, listed organization – see Table 16-1) 16-33
Table 16-10 Flight Condition FC50, Force/Moment Coefficients – Statistical Analysis 16-33
Table 16-11 Flight Condition FC50, Force/Moment Coefficients (Values provided by respective, listed organization – see Table 16-1) 16-33
Table 16-12 Flight Condition FC50, Force/Moment Coefficients – Statistical Analysis 16-34
Table 16-13 Flight Condition FC70, Force/Moment Coefficients (Values provided by respective, listed organization – see Table 16-1) 16-34
Table 16-14 Flight Condition FC70, Force/Moment Coefficients – Statistical Analysis 16-34

CHAPTER 17

Table 17-1 Wind Tunnel Models Used in VFE-2 17-10

CHAPTER 19

Table 19-1 Test Cases for PSP Measurements in the TWG 19-5

Table 19-2 Test Cases for PIV Measurements in the TWG 19-7
Table 19-3 Test Cases for IR Measurements in the DNW-KKK 19-31
Table 19-4 Test Cases for TSP Measurements in the DNW-KKK 19-31
Table 19-5 Test Cases for PIV Measurements in the DNW-KKK 19-32

CHAPTER 20

Table 20-1 Geometrical Discrepancy along Three Chord Sections between Each Model and the Analytical Shape: Maximum Variations in mm 20-4
Table 20-2 Geometrical Discrepancy of Pressure Port Locations Reduced by the Diameter d = 0.3 mm of the Orifice 20-5

CHAPTER 21

Table 21-1 Test Cases of the TU München 21-5

CHAPTER 23

Table 23-1 Wind Tunnel Models Used in VFE-2 23-3
Table 23-2 Geometrical Discrepancy along Three Chord Sections between Each Model and the Analytical Shape: Maximum Variations in mm 23-4
Table 23-3 Force-Moment Data for Sharp LE 23-14
Table 23-4 Force-Moment Data for Medium LE 23-15

CHAPTER 25

Table 25-1 CFD Test Cases Used in the Present Calculations 25-2

CHAPTER 28

Table 28-1 Test Cases, Analysed with Baldwin-Lomax Turbulence Model 28-4
Table 28-2 Leading Edge Bluntness Effect 28-5
Table 28-3 Angle of Attack Effect, RLE, Re = 6E+6 28-5
Table 28-4 Mach Number Effect, RLE, Re = 6E+6 28-5
Table 28-5 Test Cases for Turbulence Model Study 28-8

CHAPTER 29

Table 29-1 Summary of Grids and Turbulence Models Used for VFE-2 Structured Grid Comparisons 29-4
Table 29-2 Summary of Shock Strength from the Glasgow Code on Surface Conical Ray at Constant y/s = 0.3 for All Solutions at M = 0.85, Re = 6 x 10^6 and α = 23° Compared to NASA NTF Data 29-14
Table 29-3 Summary of Shock and Vortex Core Data for All Steady State Calculations Using the Glasgow Code at α = 18.5° – 26°, M = 0.85, Re = 6 x 10^6 29-15
Table 29-4 Summary of Maximum Axial Velocity, Shock Strength and Breakdown Location for All Solutions at α = 23°, M = 0.85 and Re = 6 x 10^6 29-17
Table 29-5 Critical Incidence for Transonic Vortex Breakdown to be Found on 65° Delta Wings 29-22

CHAPTER 30

Table 30-1	Test Cases for the AOA-Reynolds Number Dependency Analysis	30-4
Table 30-2	Experimental Cases Selected for Comparison	30-4
Table 30-3	Test Cases for the Flow Topology Study	30-4
Table 30-4	Computational Grid Size for the Low R_{mac} Cases	30-7
Table 30-5	Computational Grid Size for the High R_{mac} Cases at M = 0.4	30-7
Table 30-6	Computational Grid Size for the Inviscid Case at M = 0.4	30-8
Table 30-7	Wall-Normal Dimensionless Distance (y^+) on the Delta Wing Surface for the M = 0.4 Cases	30-8
Table 30-8	Computational Grid Size for the Transonic, Sharp Leading Edge Cases – Increase in Comparison to the Initial Grid is Given in Brackets	30-29
Table 30-9	Computational Grid Size for the Transonic, Blunt Leading Edge Cases – Increase in Comparison to the Initial Grid is Given in Brackets	30-29

CHAPTER 32

Table 32-1	Spalart-Allmaras Turbulence Model Coefficients	32-4

CHAPTER 34

Table 34-1	CFD Cases Chosen for Summary Comparison	34-5
Table 34-2	Organization, Codes, and Turbulence Models for CFD Simulations	34-8
Table 34-A1	Full List of the Cases Considered within VFE-2 Numerical Simulations	34-34

APPENDIX 3.1

Table A3.1-1	NTF Delta Wing Surface Pressure Coefficients	A3.1-2
Table A3.1-2	Normal Force Measurements from LTPT and NTF Experiments	A3.1-3

APPENDIX 3.5

Table A3.5-1	Time Averaged Force and Moment Coefficients for Medium Radius Wing	A3.5-11
Table A3.5-2	Time Averaged Force and Moment Coefficients for Sharp Edged Wing, $R_{mac} = 2 \times 10^6$	A3.5-11
Table A3.5-3	Force and Moment Coefficients Measured at 8 kHz for the Medium Radius Wing at $\alpha = 13.3°$ and $R_{mac} = 2 \times 10^6$	A3.5-12

APPENDIX 3.7

Table A3.7-1	Computational Grid Parameters	A3.7-2

Common Notations

Abbreviations

AVT	Applied Vehicle Technology (one of seven technical panels within the RTO)
BART	Basic Aerodynamic Research Tunnel
BL	butt line on airplane, in., positive on right wing (See Chapter 3 – Figure 3-2)
CAWAP	Cranked Arrow Wing Aerodynamics Project
CAWAPI	Cranked Arrow Wing Aerodynamics Project International
CFD	Computational Fluid Dynamics
EFD	Experimental Fluid Dynamics
ESP	Electronic Scanning Pressure
ET	Exploratory Team
FC	Flight Condition
FS	fuselage station on airplane, in., positive aft (See Chapter 3 – Figure 3-2)
HUD	heads-up display
HSCT	High Speed Civil Transport
HSR	High Speed Research
HWA	Hot Wire Anemometry
IR	Infra Red (technique)
ITAR	International Traffic in Arms Regulations
LaRC	Langley Research Center
LE	leading edge
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organisation
PIV	Particle Image Velocimetry
PSF	Performance, Stability & Control and Fluid Physics – one of the standing Technical Committees of the AVT Panel
PSP	Pressure Sensitive Paint
RTB	Research and Technology Board
RTO	Research and Technology Organisation – Scientific Arm of NATO
TSP	Temperature Sensitive Paint
VFE-2	Vortex Flow Experiment-2
VL	Virtual Laboratory
WL	waterline on airplane, in., positive up (See Chapter 3 – Figure 3-2)

CAWAPI Chapters (3 – 16) Nomenclature

CFL3D	name of structured grid flow solver developed at NASA Langley
C_p	surface static pressure coefficient
c_f	local skin friction coefficient
F-16XL-1	an extensively modified version of the single-seat F-16A aircraft which is longer and has a cranked arrow wing instead of a trapezoidal wing with leading-edge strake
h	airplane altitude, ft
iges	Initial Graphics Exchange Specifications –> geometry descriptor
i,j,k	grid indices
M_∞	free-stream Mach number
R_n	Reynolds number, based on aircraft reference chord of 24.7 ft
V/V_{RE}	ratio of velocity magnitude in boundary layer to that at the Rake Extreme total-pressure tube
T	absolute temperature, °R
x/c	fractional distance along the local chord, positive aft
y	normal distance above the surface at a rake location, in.
y^+	Reynolds number like term for flat-plate turbulent boundary layer (See Chapter 3 – Ref. [3-1])
α	angle of attack, deg
β	angle of sideslip, deg
$2y/b_l;\eta$	fractional distance along the wing local semispan, positive toward the right wing tip

Subscripts

avg	average value
l, loc	local
nom	nominal value

VFE-2 Chapters (17 – 35) Nomenclature

A	wing aspect ratio
b	wing span
b_{loc}	local span
c	root chord
$\bar{c}$	mean aerodynamic chord
C_m	pitching moment coefficient, reference point at 2c/3; $= M/q_\infty S\bar{c}$
C_N	normal force coefficient; $= N/q_\infty S$
C_T	tangential force coefficient; $= T/q_\infty S$
C_p	pressure coefficient; $= (p - p_\infty)/q_\infty$
q_∞	free stream dynamic pressure

r	streamwise leading edge radius
R	free stream Reynolds number, based on root chord
R_{mac}	free stream Reynolds number, based on mean aerodynamic chord
S	wing area
x, y, z	wing apex fixed coordinates (x downstream, y spanwise, z upwards)
Λ	leading edge sweep angle
ξ, η, ζ	wing apex fixed dimensionless coordinates; $\xi = x/c$, $\eta = 2y/b_{loc}$, $\zeta = 2z/b_{loc}$

Acknowledgements

AVT-113 expresses its gratitude to the AVT Panel for its support in the formation of this task group and to Charles Hirsch, our panel representative, for his help. AVT-113 is especially grateful for the manifold assistance during the five years of operational working through its Panel Executives Dennis Goege, Ulf Ehlert and Peter Tonn, along with the AVT Panel Assistant Sandra Cheyne. We are also grateful to the RTO for sponsoring two consultants, namely Raj Nangia and John Lamar, to support our scientific work during the period of the task group tenure. The financial support for the work of the task group and the associated travel expenses provided by the national organizations involved are deeply appreciated.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's References	3. Further Reference	4. Security Classification of Document
	RTO-TR-AVT-113 AC/323(AVT-113)TP/246	ISBN 978-92-837-0073-9	UNCLASSIFIED/ UNLIMITED

5. Originator

Research and Technology Organisation
North Atlantic Treaty Organisation
BP 25, F-92201 Neuilly-sur-Seine Cedex, France

6. Title

Understanding and Modeling Vortical Flows to Improve the Technology Readiness Level for Military Aircraft

7. Presented at/Sponsored by

Summary Report of Task Group AVT-113.

8. Author(s)/Editor(s)	9. Date
Multiple	October 2009

10. Author's/Editor's Address	11. Pages
Multiple	1104

12. Distribution Statement

There are no restrictions on the distribution of this document. Information about the availability of this and other RTO unclassified publications is given on the back cover.

13. Keywords/Descriptors

Aerodynamic characteristics
Aerodynamics
Algorithms
Computerized simulation
Control surfaces
Delta wings
Equations of motion
Flight control
Flow control
Flow distribution
Flow visualization
Mathematical models
Methodology
Unsteady flow
Vortex dynamics
Vortex interactions and control
Vortical flows
Vortices
Wings

14. Abstract

The charter and goal for Task Group AVT-113 is expressed in its title: "Understanding and Modeling Vortical Flows to Improve the Technology Readiness Level for Military Aircraft". To that end new experiments and complimentary computational solutions were obtained on a simple 65° delta wing model and new computations were obtained on a complete fighter aircraft (F-16XL) for which flight measurements existed. Studying the resulting vortical flows from these two scale- and shape-perspectives together has provided insight and led to an increased understanding of the dominant flow physics which exists on- and off-the-surface, or in- and out-of-the-boundary-layer. Researchers from Belgium, the Czech Republic, France, Germany, Italy, Slovenia, Sweden, The Netherlands, Turkey, the United Kingdom and the United States of America – representing the commitment of air-frame manufacturers, government laboratories and universities – contributed to the work of this task group.

NORTH ATLANTIC TREATY ORGANISATION

BP 25
F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE
Télécopie 0(1)55.61.22.99 • E-mail mailbox@rta.nato.int

RESEARCH AND TECHNOLOGY ORGANISATION

DIFFUSION DES PUBLICATIONS RTO NON CLASSIFIEES

Les publications de l'AGARD et de la RTO peuvent parfois être obtenues auprès des centres nationaux de distribution indiqués ci-dessous. Si vous souhaitez recevoir toutes les publications de la RTO, ou simplement celles qui concernent certains Panels, vous pouvez demander d'être inclus soit à titre personnel, soit au nom de votre organisation, sur la liste d'envoi.

Les publications de la RTO et de l'AGARD sont également en vente auprès des agences de vente indiquées ci-dessous.

Les demandes de documents RTO ou AGARD doivent comporter la dénomination « RTO » ou « AGARD » selon le cas, suivi du numéro de série. Des informations analogues, telles que le titre est la date de publication sont souhaitables.

Si vous souhaitez recevoir une notification électronique de la disponibilité des rapports de la RTO au fur et à mesure de leur publication, vous pouvez consulter notre site Web (www.rto.nato.int) et vous abonner à ce service.

CENTRES DE DIFFUSION NATIONAUX

ALLEMAGNE
Streitkräfteamt / Abteilung III
Fachinformationszentrum der Bundeswehr (FIZBw)
Gorch-Fock-Straße 7, D-53229 Bonn

BELGIQUE
Royal High Institute for Defence – KHID/IRSD/RHID
Management of Scientific & Technological Research for Defence, National RTO Coordinator
Royal Military Academy – Campus Renaissance
Renaissancelaan 30, 1000 Bruxelles

CANADA
DSIGRD2 – Bibliothécaire des ressources du savoir
R et D pour la défense Canada
Ministère de la Défense nationale
305, rue Rideau, 9e étage
Ottawa, Ontario K1A 0K2

DANEMARK
Danish Acquisition and Logistics Organization (DALO)
Lautrupbjerg 1-5, 2750 Ballerup

ESPAGNE
SDG TECEN / DGAM
C/ Arturo Soria 289
Madrid 28033

ETATS-UNIS
NASA Center for AeroSpace Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320

FRANCE
O.N.E.R.A. (ISP)
29, Avenue de la Division Leclerc
BP 72, 92322 Châtillon Cedex

GRECE (Correspondant)
Defence Industry & Research General Directorate, Research Directorate
Fakinos Base Camp, S.T.G. 1020
Holargos, Athens

HONGRIE
Department for Scientific Analysis
Institute of Military Technology
Ministry of Defence
P O Box 26
H-1525 Budapest

ITALIE
General Secretariat of Defence and National Armaments Directorate
5th Department – Technological Research
Via XX Settembre 123
00187 Roma

LUXEMBOURG
Voir Belgique

NORVEGE
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
NO-2007 Kjeller

PAYS-BAS
Royal Netherlands Military Academy Library
P.O. Box 90.002
4800 PA Breda

POLOGNE
Centralny Ośrodek Naukowej Informacji Wojskowej
Al. Jerozolimskie 97
00-909 Warszawa

PORTUGAL
Estado Maior da Força Aérea
SDFA – Centro de Documentação
Alfragide
P-2720 Amadora

REPUBLIQUE TCHEQUE
LOM PRAHA s. p.
o. z. VTÚLaPVO
Mladoboleslavská 944
PO Box 18
197 21 Praha 9

ROUMANIE
Romanian National Distribution Centre
Armaments Department
9-11, Drumul Taberei Street
Sector 6
061353, Bucharest

ROYAUME-UNI
Dstl Knowledge and Information Services
Building 247
Porton Down
Salisbury SP4 0JQ

SLOVAQUIE
Akadémia ozbrojených síl
M.R. Štefánika, Distribučné a informačné stredisko RTO
Demanova 393, P.O.Box 45
031 19 Liptovský Mikuláš

SLOVENIE
Ministry of Defence
Central Registry for EU and NATO
Vojkova 55
1000 Ljubljana

TURQUIE
Milli Savunma Bakanlığı (MSB)
ARGE ve Teknoloji Dairesi Başkanlığı
06650 Bakanliklar
Ankara

AGENCES DE VENTE

NASA Center for AeroSpace Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320
ETATS-UNIS

The British Library Document Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
ROYAUME-UNI

Canada Institute for Scientific and Technical Information (CISTI)
National Research Council Acquisitions
Montreal Road, Building M-55
Ottawa K1A 0S2, CANADA

Les demandes de documents RTO ou AGARD doivent comporter la dénomination « RTO » ou « AGARD » selon le cas, suivie du numéro de série (par exemple AGARD-AG-315). Des informations analogues, telles que le titre et la date de publication sont souhaitables. Des références bibliographiques complètes ainsi que des résumés des publications RTO et AGARD figurent dans les journaux suivants :

Scientific and Technical Aerospace Reports (STAR)
STAR peut être consulté en ligne au localisateur de ressources uniformes (URL) suivant: http://www.sti.nasa.gov/Pubs/star/Star.html
STAR est édité par CASI dans le cadre du programme NASA d'information scientifique et technique (STI)
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
ETATS-UNIS

Government Reports Announcements & Index (GRA&I)
publié par le National Technical Information Service
Springfield
Virginia 2216
ETATS-UNIS
(accessible également en mode interactif dans la base de données bibliographiques en ligne du NTIS, et sur CD-ROM)

NORTH ATLANTIC TREATY ORGANISATION

BP 25
F-92201 NEUILLY-SUR-SEINE CEDEX • FRANCE
Télécopie 0(1)55.61.22.99 • E-mail mailbox@rta.nato.int

RESEARCH AND TECHNOLOGY ORGANISATION

DISTRIBUTION OF UNCLASSIFIED RTO PUBLICATIONS

AGARD & RTO publications are sometimes available from the National Distribution Centres listed below. If you wish to receive all RTO reports, or just those relating to one or more specific RTO Panels, they may be willing to include you (or your Organisation) in their distribution.

RTO and AGARD reports may also be purchased from the Sales Agencies listed below.

Requests for RTO or AGARD documents should include the word 'RTO' or 'AGARD', as appropriate, followed by the serial number. Collateral information such as title and publication date is desirable.

If you wish to receive electronic notification of RTO reports as they are published, please visit our website (www.rto.nato.int) from where you can register for this service.

NATIONAL DISTRIBUTION CENTRES

BELGIUM
Royal High Institute for Defence – KHID/IRSD/RHID
Management of Scientific & Technological Research for Defence, National RTO Coordinator
Royal Military Academy – Campus Renaissance
Renaissancelaan 30
1000 Brussels

CANADA
DRDKIM2 – Knowledge Resources Librarian
Defence R&D Canada
Department of National Defence
305 Rideau Street, 9th Floor
Ottawa, Ontario K1A 0K2

CZECH REPUBLIC
LOM PRAHA s. p.
o. z. VTÚLaPVO
Mladoboleslavská 944
PO Box 18
197 21 Praha 9

DENMARK
Danish Acquisition and Logistics Organization (DALO)
Lautrupbjerg 1-5
2750 Ballerup

FRANCE
O.N.E.R.A. (ISP)
29, Avenue de la Division Leclerc
BP 72, 92322 Châtillon Cedex

GERMANY
Streitkräfteamt / Abteilung III
Fachinformationszentrum der Bundeswehr (FIZBw)
Gorch-Fock-Straße 7
D-53229 Bonn

GREECE (Point of Contact)
Defence Industry & Research General Directorate
Research Directorate, Fakinos Base Camp
S.T.G. 1020
Holargos, Athens

HUNGARY
Department for Scientific Analysis
Institute of Military Technology
Ministry of Defence
P O Box 26
H-1525 Budapest

ITALY
General Secretariat of Defence and National Armaments Directorate
5th Department – Technological Research
Via XX Settembre 123
00187 Roma

LUXEMBOURG
See Belgium

NETHERLANDS
Royal Netherlands Military Academy Library
P.O. Box 90.002
4800 PA Breda

NORWAY
Norwegian Defence Research Establishment
Attn: Biblioteket
P.O. Box 25
NO-2007 Kjeller

POLAND
Centralny Ośrodek Naukowej Informacji Wojskowej
Al. Jerozolimskie 97
00-909 Warszawa

PORTUGAL
Estado Maior da Força Aérea
SDFA – Centro de Documentação
Alfragide
P-2720 Amadora

ROMANIA
Romanian National Distribution Centre
Armaments Department
9-11, Drumul Taberei Street
Sector 6, 061353, Bucharest

SLOVAKIA
Akadémia ozbrojených síl
M.R. Štefánika, Distribučné a informačné stredisko RTO
Demanova 393, P.O.Box 45
031 19 Liptovský Mikuláš

SLOVENIA
Ministry of Defence
Central Registry for EU & NATO
Vojkova 55
1000 Ljubljana

SPAIN
SDG TECEN / DGAM
C/ Arturo Soria 289
Madrid 28033

TURKEY
Milli Savunma Bakanlığı (MSB)
ARGE ve Teknoloji Dairesi Başkanlığı
06650 Bakanliklar – Ankara

UNITED KINGDOM
Dstl Knowledge and Information Services
Building 247
Porton Down
Salisbury SP4 0JQ

UNITED STATES
NASA Center for AeroSpace Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320

SALES AGENCIES

NASA Center for AeroSpace Information (CASI)
7115 Standard Drive
Hanover, MD 21076-1320
UNITED STATES

The British Library Document Supply Centre
Boston Spa, Wetherby
West Yorkshire LS23 7BQ
UNITED KINGDOM

Canada Institute for Scientific and Technical Information (CISTI)
National Research Council Acquisitions
Montreal Road, Building M-55
Ottawa K1A 0S2, CANADA

Requests for RTO or AGARD documents should include the word 'RTO' or 'AGARD', as appropriate, followed by the serial number (for example AGARD-AG-315). Collateral information such as title and publication date is desirable. Full bibliographical references and abstracts of RTO and AGARD publications are given in the following journals:

Scientific and Technical Aerospace Reports (STAR)
STAR is available on-line at the following uniform resource locator: http://www.sti.nasa.gov/Pubs/star/Star.html
STAR is published by CASI for the NASA Scientific and Technical Information (STI) Program
STI Program Office, MS 157A
NASA Langley Research Center
Hampton, Virginia 23681-0001
UNITED STATES

Government Reports Announcements & Index (GRA&I)
published by the National Technical Information Service
Springfield
Virginia 2216
UNITED STATES
(also available online in the NTIS Bibliographic Database or on CD-ROM)

ISBN 978-92-837-0073-9