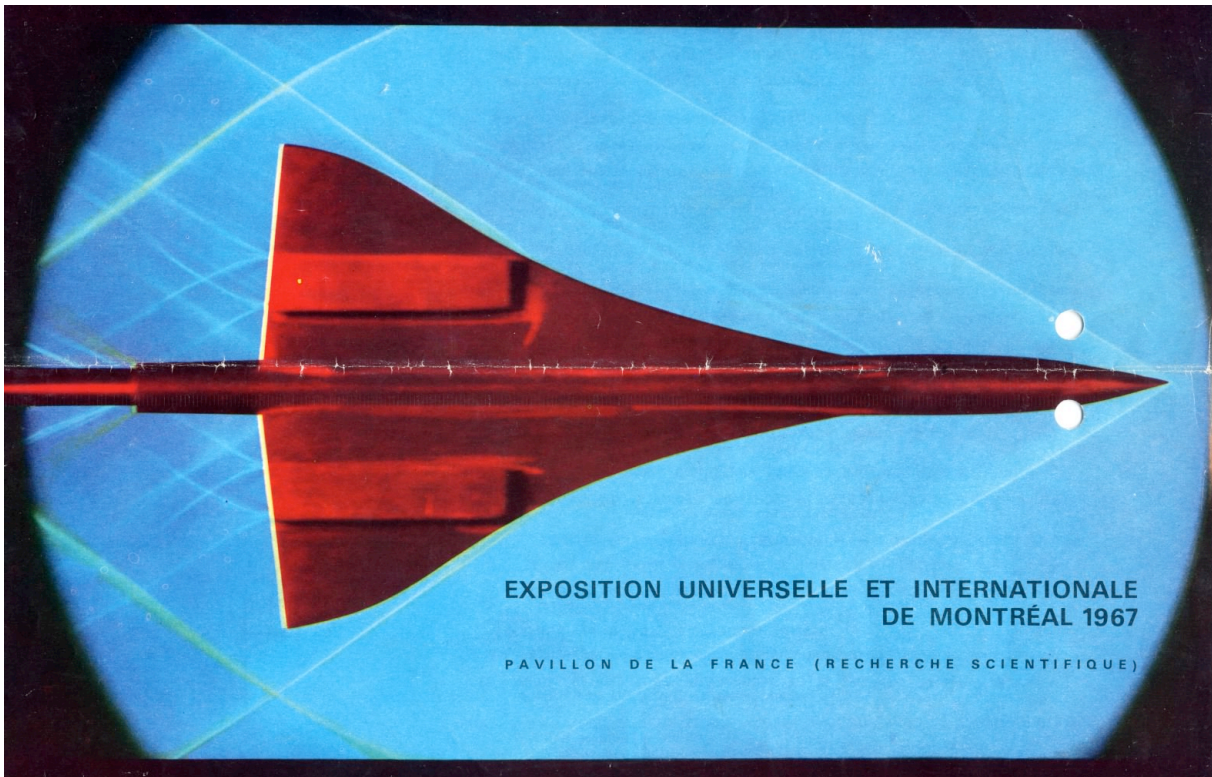


Configuration Aerodynamics

William H. Mason
Virginia Tech
Blacksburg, VA



The front cover of the brochure describing the French Exhibit at the Montreal Expo, 1967.

January 2018

CONTENTS

Configuration Aerodynamics

Preface

1. Introduction to Configuration Aerodynamics

1.1 Purpose	1-1
1.2 Examples of innovative concepts	1-1
1.3 Overview of the Material to be Covered	1-7
1.4 What's left out	1-8
1.5 Exercises	1-8
1.6 References	1-9

2. Getting Ready for Configuration Aerodynamics: Fluid Mechanics Foundations

2.1 Governing Equations of Fluid Mechanics	2-1
2.2 Derivation of the Governing Equations	2-3
2.2.1 Conservation of Mass: the Continuity Equation	2-5
2.2.2 Conservation of Momentum and the Substantial Derivative	2-8
2.2.3 Energy Equation	2-15
2.3 Boundary Conditions	2-19
2.4 Standard Forms and Terminology of Governing Equations	2-20
2.4.1 Nondimensionalization	2-20
2.4.2 Use of Divergence Form	2-21
2.4.3 Standard Form of the Navier-Stokes Equations: Notation	2-22
2.5 The Gas Dynamics Equation and the Full Potential Equation	2-25
2.5.1 The Gas Dynamics Equation	2-25
2.5.2 Derivation of the Classical Gas Dynamics Eqn-Related Energy Equation	2-27
2.5.3 Full Potential Equation	2-28
2.5.4 Equivalent Divergence Form and Energy Equation	2-28
2.5.5 Derivation of another form of the Related Energy Equation	2-29
2.6 Special Cases	2-31
2.6.1 Small Disturbance Form of the Energy Equation	2-31
2.6.2 Small Disturbance Expansion of the Full Potential Equation	2-32
2.6.3 Transonic Small Disturbance Equation	2-34
2.6.4 Prandtl-Glauert Equation	2-35
2.6.5 Incompressible Irrotational Flow: Laplace's Equation	2-36
2.6.6 The Boundary Layer Equations	2-36
2.7 Examples of Zones of Application	2-38
2.8 Mathematical Classification or the "Type" of PDEs	2-38
2.8.1 Elaboration on Characteristics	2-41

2.9 Requirements for a Complete Problem Formulation	2-43
2.10 Exercises	2-44
2.11 References	2-45

3. Drag: An Introduction

3.1 The Importance of Drag	3-1
3.2 Some Different Ways to View Drag - Nomenclature and Concepts	3-3
3.3 Farfield Drag Analysis	3-9
3.4 Induced Drag	3-17
3.5 Program LIDRAG	3-20
3.6 Multiple Lifting Surfaces and Munk's Stagger Theorem	3-20
3.7 Zero Lift Friction and Form Drag Estimation	3-21
3.8 Supersonic Wave Drag: the Farfield Wave Drag Integral and the Area Rule	3-25
3.9 The Leading Edge Suction Concept	3-36
3.10 Trim Drag	3-42
3.11 Current Issues for Drag Calculation using Computational Aerodynamics	3-47
3.12 Exercises	3-47
3.13 References	3-48

4. Aircraft Configuration Design Options

4.1 Overview	4-1
4.2 Configuration Architecture Options	4-4
4.2.1 Wing Sweep	4-4
4.2.2 Why sweep the wing forward	4-5
4.2.3 Why Canards?	4-6
4.2.4 Why a flying wing?	4-7
4.2.5 Three-surface configurations	4-9
4.2.6 Slender Wings	4-10
4.2.7 Variable Sweep	4-11
4.2.8 Winglets	4-12
4.3 Propulsion System Integration Issues	4-13
4.4 Aircraft Control	4-14
4.5 Significant Recent Configuration Concepts	4-15
4.5.1 The Blended Wing Body	4-15
4.5.2 The Strut-Braced Wing	4-16
4.5.3 The Oblique Wing	4-17
4.6 Morphing Airplanes	4-18
4.7 Decision Issues	4-19
4.8 Design Approaches	4-19
4.9 The role of aerodynamics within the overall design process	4-20
4.10 A concluding comment	4-20
4.11 Exercises	4-21
4.12 References	4-21

5. An Overview of Aerodynamic Design including the use of Computational Aerodynamics	
5.1 Introduction	5-1
5.2 Configuration sizing: Aerodynamic Considerations	5-2
5.3 Overview of the specific aerodynamic design tasks	5-3
5.4 Use of computational aerodynamics in aerodynamic design	5-4
5.4.1 Best practices in solving aerodynamics problems with computers	
5.5 A Review of detailed aerodynamic design approaches	5-5
5.5.1 Analysis vs design	
5.5.2 Review of the detailed design process, including inverse and optimization	
5.5.3 Brief overview of 2D design	
5.5.4 Review of 3D transonic design methods	
5.5.5 Applications of 3D design methods	
5.6 Summary of the status of aerodynamic design	5-19
5.7 Exercises	5-19
5.8 References	5-20
6. Subsonic aerodynamics of airfoils and wings	
6.1 Introduction	6-1
6.2 Airfoils	6-2
6.2.1 Program PANEL and other prediction methods: Accuracy/Validation	6-2
6.2.2 Subsonic Airfoil Aerodynamics	6-9
6.2.3 Airfoil Selection	6-22
6.3 Wings	6-24
6.3.1 Use and Accuracy of the VLM method	6-24
6.3.2 Program VLMpc and the Warren 12 test Case	6-30
6.3.3 Tornado and AVL	6-31
6.3.4 Aerodynamics of High Aspect Ratio Wings	6-31
6.3.5 The relation between airfoils and swept wings	6-41
6.3.6 Wing/Tail and Canard/Wing Aerodynamics	6-43
6.3.7 Ground Effects using a VLM code	6-45
6.3.8 Low Aspect Ratio “Slender Wings”	6-48
6.4 Exercises	6-51
6.5 References	6-54
7. Transonic aerodynamics of airfoils and wings	
7.1 Introduction	7-1
7.2 Physical aspects of flow development with Mach number	7-2
7.3 Technology Issues/developments	7-3
7.3.1 The slotted wall wind tunnel	7-3
7.3.2 Computational challenges/methods	7-4
7.4 Airfoils	7-9
7.4.1 NASA Supercritical Airfoils	7-9
7.4.2 The Divergent Trailing Edge Airfoil	7-12
7.4.3 Transonic Airfoil Performance: The Korn Equation	7-12
7.4.4 Design Methods	7-13
7.5 Wings	7-15

7.5.1	Transonic Transport Wing Concepts	7-16
7.5.2	The Korn Equation applied to drag prediction on wings	7-18
7.5.3	Fighter Wing Concepts/Issue	7-19
7.6	Exercises	7-21
7.7	References	7-22
8. Aerodynamics of high lift devices/powered lift		
8.1	Introduction: Why High Lift?	8-1
8.2	A.M.O. Smith's analysis of the lift: the five considerations	
8.3	Types of Trailing Edge Devices	8-3
8.4	Types of Leading edge devices	8-5
8.5	Aerodynamics of Leading and Trailing Edge Devices	8-7
8.6	Computational methods for high lift	
8.7	Passive and active boundary layer control	8-15
8.8	Powered lift	8-15
8-9	Configuration Integration issues	8-15
8-10	Exercises	8-15
8-11	References	
9. High angle of attack aerodynamics		
9.1	Introduction	9-1
9.2	Basic Aerodynamics of Hi- α	9-2
	9.2.1 Longitudinal	9-2
	9.2.2 Lateral/Directional	9-3
9.3	Flight Mechanics of Hi- α	9-5
	9.3.1 C_n beta dynamic	9-6
	9.3.2 LCDP: the lateral control departure parameter,	9-7
	9.3.3 The spin	9-8
9.4	Control Effectiveness with angle of attack	9-10
9.5	An Example: Putting it all together, the F-22	9-11
9.6	Some configuration issues: Amazing Stories	9-14
9.7	Exercises	9-16
9.8	References	9-16

[An F-18 spin movie](#) is available from the NASA Dryden web site.

10. Supersonic aerodynamics

10.1	Introduction	10-1
10.2	Supersonic Cruise Airplanes	10-1
10.2.1	The B-58	10-2
10.2.2	The SR-71	10-3
10.2.3	The XB-70	10-4
10.2.4	The TU-144	10-6
10.2.5	The Concorde	10-6
10.2.6	The F-22 (and YF-23)	10-7
10.3	The Challenge for Airplane Design	10-7
10.4	Wave Drag	10-10
10.4.1	A curious story:	10-16
10.4.2	Multiple Bodies to Reduce Wave Drag and Favorable Interference	10-17
10.4.3	Planar wing wave drag	10-18
10.5	Wings: lift and drag due to lift	10-19
10.5.1	Arrow wings and conical camber	10-22
10.5.2	Modified arrow wings	10-27
10.6	The aerodynamic center shift	10-27
10.7	The Oblique Wing Concept	10-31
10.8	Aero-Propulsion Integration	10-34
10.9	Computational Methods and Supersonic Aerodynamic Design	10-35
10.9.1	The linear theory starting point	10-36
10.9.2	Modifications to linear theory: Attainable Thrust	10-42
10.9.4	Nonlinear aerodynamics of supersonic wings	10-42
10.10	Supersonic Airplane Configuration Design Examples	10-43
10.10.1	The US SST Story	10-43
10.10.2	Supersonic Maneuver Wing	10-47
10.10.3	HSCT and MDO	10-53
10.10.3.1	Multidisciplinary Design Optimization, MDO	10-54
10.10.4	Design to reduce the strength of the sonic boom	10-56
10.10.5	Modern Efforts	10-58
10.10.5.1	Aerion	10-58
10.10.5.1.1	The 2D Supersonic Airfoil Story	10-59
10.10.5.2	Sonic QueSST	10-63
10.11	Exercises	10-64
10.12	References	10-66

11. Hypersonic aerodynamics

11.1	Introduction	11-1
11.2	Surface pressure estimation	11-2
11.3	Aerodynamic stability and control	11-6
11.4	Aerodynamic Heating	11-12
11.5	Additional Gas Dynamics Considerations	11-16
11.6	High Temperature Gas Dynamics Considerations	11-20
11.7	Hypersonic Vehicle Design	11-25

11.7.1	Minimum drag axisymmetric shapes at hypersonic speeds	11-25
11.7.2	Brief review of hypersonic flight vehicles	11-26
11.7.3.	Engine-airframe Integration and Modern Vehicle Development	11-27
11.8	Exercises	11-30
11.9	References	11-31

12. Endnote

Appendices

A.	Geometry for Aerodynamicists	
A.1	Airfoil Geometry	A-1
A.2	Classic Bodies of Revolution	A-18
A.3	Planform Analysis	A-24
A.4	Conical Camber	A-29
A.5	Three-Dimensional Wing Geometry	A-29
B.	Fifteen Minutes of Stealth in Aircraft Design	B-1
C.	FAR & Mil requirements	C-1
D.	Examples of aerodynamic design using tools from our software suite.	D-1
E.	Software for Aerodynamics and Aircraft Design, with manuals.	E-1
F.	Class Discussion Reading List	F-1
G.	The Configuration Aerodynamicist's Bookshelf	G-1