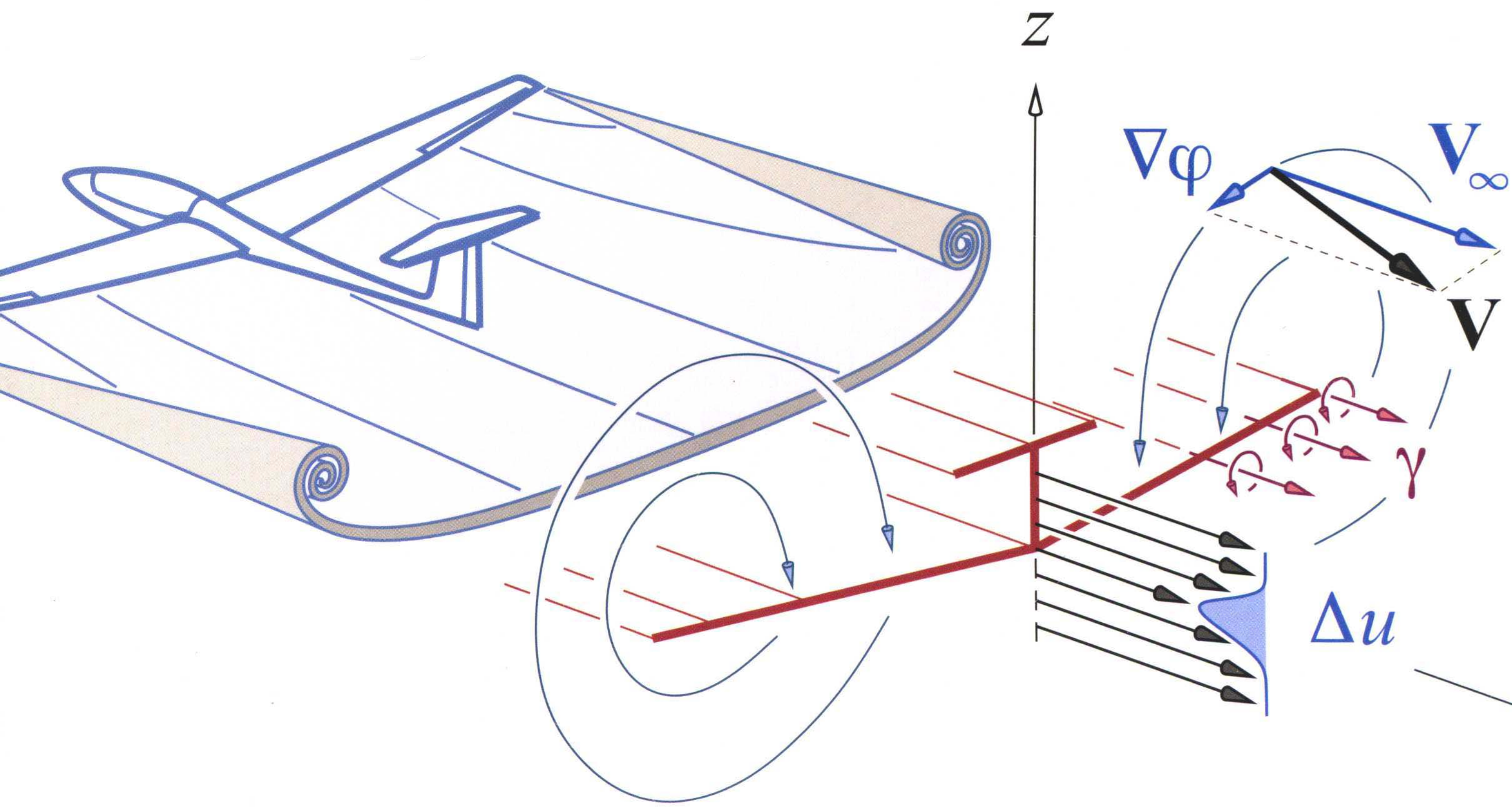

Flight Vehicle Aerodynamics

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The MIT Press
Cambridge, Massachusetts
London, England

MIT Press books may be purchased at special quantity discounts for business or sales promotional use. For information, please email special_sales@mitpress.mit.edu.

Printed and bound in the United States of America.

Library of Congress Cataloging-in-Publication Data is available.

ISBN 978-0-262-52644-9

Preface

Objective

This book is intended as a general reference for the physics, concepts, theories, and models underlying the discipline of aerodynamics. An overarching theme is the technique of velocity field representation and modeling via source and vorticity fields, and via their sheet, filament, or point-singularity idealizations. These models provide an intuitive feel for aerodynamic flow behavior, and are also the basis of aerodynamic force analysis, drag decomposition, flow interference estimation, wind tunnel corrections, computational methods, and many other important applications.

This book covers some topics in depth, while offering introductions or summaries of others. In particular, Chapters 3,4 on Boundary Layers, Chapter 7 on Unsteady Aerodynamics, and Chapter 9 on Flight Dynamics are intended as introductions and overviews of those topics, which deserve to be properly treated in separate dedicated texts. Similarly, there are only glancing mentions of the related topic of Propulsion, which is its own discipline.

Computational Fluid Dynamics (CFD) and computational methods in general are indispensable for today's practicing aerodynamicist. Hence a few computational methods are described here, primarily the vortex lattice and panel methods which are based on the source and vorticity flow-field representation. The main goal is to provide improved understanding of the concepts and physical models which underlie such methods.

Most of this book is based on the lecture notes, handouts, and reference materials which have been developed for the course *Flight Vehicle Aerodynamics* (course number 16.110) taught by the author at MIT's Department of Aeronautics and Astronautics. This course is intended for first-year graduate students, but has also attracted a significant number of advanced undergraduates.

Preparation

This book assumes that the reader is well versed in basic physics and vector calculus, and already has had exposure to basic fluid mechanics and aerodynamics. Hence, little or no space is devoted to introduction or discussion of basic concepts such as fluid velocity, density, pressure, viscosity, stress, etc. Chapter 1 on the Physics of Aerodynamics Flows is intentionally concise, since it is intended primarily as a reference for the underlying physical principles and governing equations of fluid flows rather than as a first introduction to these topics. The author's course at MIT begins with Chapter 2.

Some familiarity with aerodynamics and aeronautics terminology is assumed on the part of the reader. However, a summary of advanced vector calculus notation is given in Appendix A, since this is not commonly seen in basic vector calculus texts.

Acknowledgments

The author would like to thank Doug McLean, Alejandra Uranga, and Harold Youngren for their extensive comments, suggestions, and proofreading of this book. It has benefited considerably from their input. Ed Greitzer, and Bob Liebeck have also provided comments and useful feedback on earlier drafts, and helped steer the book towards its final form. Also very helpful have been the comments, suggestions, and error corrections from the numerous students who have taken the *Flight Vehicle Aerodynamics* course at MIT.

Nomenclature

The page numbers indicate where each symbol is first used.

Roman letters

a	Speed of sound, p. 1
a	Boundary layer edge velocity power-law exponent, p. 71
A	Cross-sectional area, p. 45
$\mathcal{AR}$	Aspect ratio, p. 113
A_{ij}	Aerodynamic influence coefficient (AIC) matrix, p. 114
$\mathcal{A}$	G-beta constant for equilibrium turbulent flow, p. 73
$\mathcal{A}_n$	Fourier coefficients of spanwise circulation distribution, p. 113
$\mathcal{A}_n$	Fourier coefficients of airfoil's vortex sheet strength distribution, p. 254
$\bar{\bar{\mathbf{A}}}$	Flight-dynamics system matrix, p. 207
b	Boundary layer lateral width parameter, p. 75
b	Wingspan, p. 104
b	Reference span, p. 209
B	Wind tunnel cross-section aspect ratio, p. 233
B_{ij}	Source-influence matrix for the potential, p. 151
$\mathcal{B}$	G-beta constant for equilibrium turbulent flow, p. 73
$\mathcal{B}_n$	Fourier coefficients airfoil thickness distribution, p. 257
$\bar{\bar{\mathbf{B}}}$	Flight-dynamics control matrix, p. 207
c	Airfoil chord, p. 9
c	Reference chord, p. 209
c_d	2D section drag coefficient, p. 40
C_D	Drag coefficient, p. 125
$c_{\mathcal{D}}$	Dissipation coefficient (locally normalized), p. 66
c_f	Skin friction coefficient (locally normalized), p. 65
C_f	Skin friction coefficient, p. 12
$\bar{C}_f$	Average skin friction coefficient, p. 88
c_ℓ	2D section lift coefficient, p. 40
C_L	Lift coefficient, p. 125
C_ℓ	Rolling moment coefficient, p. 125
C_m	Pitching moment coefficient, p. 125
C_n	Yawing moment coefficient, p. 125

C_p	Pressure coefficient, p. 12
c_p	Specific heat at constant pressure, p. 2
c_v	Specific heat at constant volume, p. 2
C_Y	Sideforce coefficient, p. 125
C	Theodorsen function, p. 156
d	Body diameter, p. 115
$\mathcal{D}$	Dissipation integral, p. 66
D	Drag, p. 100
D'	Drag per unit span (in 2D), p. 40
D_i	Induced drag, p. 105
D_p	Profile drag, p. 105
D_w	Wave drag, p. 188
e	Specific energy, p. 2
e	Span efficiency, p. 113
$\dot{E}$	Energy rate (power), p. 59
$\mathbf{f}$	Body force per unit mass field, p. 4
F	Force, p. 59
$\mathbf{F}$	Force vector, p. 124
$\mathcal{F}_\theta$	Momentum thickness growth function, p. 81
g	Gravitational acceleration magnitude, p. 19
$\boldsymbol{g}$	Gravitational acceleration vector, p. 4
g	Gain of control variable on surface deflection, p. 132
G	Clauser shape parameter, p. 73
h	Specific enthalpy, p. 2
h	Unsteady airfoil heave displacement, p. 152
h	Hyperbolic radius, p. 185
h	Wind tunnel cross-section height, p. 239
$\hat{\mathbf{h}}$	Hinge-axis unit vector, p. 132
$\mathbf{h}$	Angular momentum of onboard rotors, p. 205
H	Boundary layer shape parameter, p. 65
H^*	Kinetic energy shape parameter, p. 66
H^{**}	Density flux thickness shape parameter, p. 66
$\mathbf{H}$	Total aircraft angular momentum, p. 205
$\bar{\bar{\mathbf{I}}}$	Unit tensor, identity matrix, p. 6
$\bar{\bar{\mathbf{I}}}$	Mass moment of inertia tensor, p. 205
I	Moment of inertia component, p. 206
k	Heat conductivity, p. 1
k	Reduced frequency, p. 156
K	Kernel function for scalar field, p. 32
$\mathbf{K}$	Kernel function for vector field, p. 25

K	Boundary layer kinetic energy defect, p. 59
K_f	Profile drag form factor, p. 89
Kn	Knudsen number, p. 1
ℓ	Body length, p. 1
ℓ	Coordinate on surface (of $s\ell n$ system), p. 26
l	Circuit or control volume integration coordinate, p. 41
L	Lift, p. 100
L'	Lift per unit span (in 2D), p. 40
$\mathcal{L}$	Rolling moment, p. 124
$\mathcal{L}$	Lagrangian function, p. 118
m	Boundary layer mass defect, p. 49
m	Aircraft mass, p. 205
$\dot{m}$	Mass flow, p. 49
M	Mach number, p. 10
$\mathbf{M}$	Moment vector, p. 124
$\mathcal{M}$	Pitching moment, p. 124
n	Coordinate normal to surface (of $s\ell n$ system), p. 26
$\hat{\mathbf{n}}$	Unit normal vector, p. 4
$\tilde{N}$	Laminar instability amplitude exponent, p. 93
$\mathcal{N}$	Yawing moment, p. 124
p	Pressure, p. 1
p'	Dynamic part of pressure field, p. 20
p	Roll rate, p. 124
$\bar{p}$	Dimensionless roll rate ($= pb_{\text{ref}}/2V_\infty$), p. 125
Pr	Prandtl number, p. 10
P	Boundary layer momentum defect, p. 59
q	Pitch rate, p. 124
$\bar{q}$	Dimensionless pitch rate ($= qc_{\text{ref}}/2V_\infty$), p. 125
$\dot{q}_S$	Heating rate per unit area, p. 6
$\dot{q}_V$	Heating rate per unit volume, p. 5
$\dot{\mathbf{q}}$	Heat flux vector, p. 6
q_∞	Freestream dynamic pressure ($= \frac{1}{2}\rho_\infty V_\infty^2$), p. 12
Q	Freestream dynamic pressure, for flight dynamics, p. 209
Q	Coefficient in PP2 equation, p. 170
$\mathbf{r}$	Cartesian position vector ($= x\,\hat{\mathbf{x}} + y\,\hat{\mathbf{y}} + z\,\hat{\mathbf{z}}$), p. 3
r	Magnitude of Cartesian position vector, ($= \sqrt{x^2+y^2+z^2}$), p. 3
r	Distance to x axis in axisymmetric cases ($= \sqrt{y^2+z^2}$), p. 187
r	Yaw rate, p. 124
$\bar{r}$	Dimensionless yaw rate ($= rb_{\text{ref}}/2V_\infty$), p. 125
R	Specific gas constant, p. 2

R	Radius kernel function, p. 38
R	Radius of axisymmetric body, p. 139
Re	Reynolds number, p. 10
Re_θ	Momentum thickness Reynolds number, p. 81
$\mathbf{R}$	Position vector in Earth frame, p. 145
$\mathbf{R}_o$	Position vector of body-axes origin in Earth frame, p. 149
s	Specific entropy, p. 13
s	Coordinate on surface (of $s\ell n$ system), p. 26
S	Reference area, p. 209
St	Strouhal number, p. 11
$\mathcal{S}$	Surface area, p. 7
$\mathcal{S}$	Sonic discriminator ($= 1 - M^2$), p. 196
$\bar{\bar{\mathbf{S}}}$	Stability-axes to body-axes xz rotation matrix, p. 210
t	Time, p. 7
t	Airfoil thickness, p. 41
T	Temperature, p. 1
$\mathcal{T}$	Normalized skin friction function, p. 81
T_S	Sutherland's constant for air ($= 110\,\mathrm{K}$), p. 1
$\bar{\bar{\mathbf{T}}}$	Rotation matrix (direction cosine matrix), p. 124
u	Cartesian x-velocity component, p. 3
u_1	Streamwise velocity component of 3D boundary layer, p. 76
u_2	Crossflow velocity component of 3D boundary layer, p. 76
U	Normalized boundary layer velocity ($= u/u_\mathrm{e}$), p. 60
$\mathbf{U}$	Body velocity vector, p. 4
v	Cartesian y-velocity component, p. 3
V	Fluid speed, p. 4
$\mathbf{V}$	Fluid velocity, p. 4
V_h	Horizontal-tail volume coefficient, p. 218
V_v	Vertical-tail volume coefficient, p. 219
$\mathbf{v}$	Flight-dynamics eigenvector, p. 207
$\dot{\mathcal{V}}$	Volume outflow rate, p. 31
$\mathcal{V}$	Volume, p. 7
w	Cartesian z-velocity component, p. 3
$\dot{w}_S$	Work rate per unit area, p. 6
$\dot{w}_\mathcal{V}$	Work rate per unit volume, p. 5
x	Cartesian coordinate, p. 3
$\hat{\mathbf{x}}$	Cartesian x unit vector, p. 3
$\mathbf{x}$	Flight-dynamics state vector, p. 206
X	Axial force, p. 206
X	Normalized wind tunnel coordinate, p. 225

y	Cartesian coordinate, p. 3
$\hat{\mathbf{y}}$	Cartesian y unit vector, p. 3
Y	Sideforce, p. 100
Y	Normalized wind tunnel coordinate, p. 225
z	Cartesian coordinate, p. 3
$\hat{\mathbf{z}}$	Cartesian z unit vector, p. 3
Z	Normal force, p. 206
Z	Slender body camberline shape, p. 139
Z	Thin-airfoil camberline shape, p. 152
Z	Normalized wind tunnel coordinate, p. 225
Z'	Airfoil surface slope, p. 174

Greek letters

α	Angle of attack, p. 124
β	Clauser pressure gradient parameter, p. 73
β	Sideslip angle, p. 124
β	Subsonic Prandtl-Glauert factor ($=\sqrt{1-M_\infty^2}$), p. 173
β	Supersonic Prandtl-Glauert factor ($=\sqrt{M_\infty^2-1}$), p. 183
γ	Ratio of specific heats ($=c_p/c_v$), p. 3
γ	Vortex sheet strength, p. 23
$\boldsymbol{\gamma}$	Vortex sheet strength (vector, in 3D), p. 23
Γ	Vortex filament strength, p. 27
$\mathbf{\Gamma}$	Vortex filament strength vector (in 3D), p. 27
$\tilde{\Gamma}$	Circulation about closed circuit, p. 31
δ	Boundary layer normal length scale, p. 70
δ^*	Displacement thickness, p. 49
$\delta_{\rm FS}$	Falkner-Skan boundary layer normal length scale, p. 71
δ^{**}	Density flux thickness, p. 66
Δ^*	Displacement area, p. 75
$\boldsymbol{\delta}$	Flight-dynamics control vector, p. 206
ϵ	Small quantity, p. 169
ε	Maximum camber, p. 175
ε	Wing downwash angle at tail, p. 217
ζ	Damping ratio, p. 212
η	Boundary layer normal coordinate ($=n/\delta$), p. 70
ϑ	Glauert angle coordinate, p. 112
θ	Polar angle coordinate, p. 38
θ	Aircraft pitch angle, p. 202
Θ	Angle kernel function, p. 38
θ	Momentum thickness, p. 59

θ^*	Kinetic energy thickness, p. 59
Θ	Momentum area, p. 75
Θ^*	Kinetic energy area, p. 75
κ	2D doublet strength, p. 29
$\mathcal{K}$	3D doublet strength, p. 29
λ	Molecular mean free path, p. 1
λ	Source sheet strength, p. 23
λ	Thwaites pressure gradient parameter, p. 81
Λ	Scaled pressure gradient parameter, p. 84
λ	Flight-dynamics eigenvalue, p. 207
λ	Wing taper ratio, p. 216
Λ	Source filament strength, p. 27
Λ	Wing sweep angle, p. 77
Λ	Lagrange multiplier, p. 119
μ	Doublet sheet strength, p. 29
μ	Viscosity, p. 1
μ_t	Eddy viscosity, p. 61
ν	Kinematic viscosity ($= \mu/\rho$), p. 17
ξ	Characteristic variable, p. 183
ρ	Density, p. 1
σ	Real part of flight-dynamics eigenvalue (time constant), p. 207
σ	Source density (dilatation rate $\nabla \cdot \mathbf{V}$), p. 6
Σ	Source point strength, p. 27
$\bar{\bar{\boldsymbol{\tau}}}$	Viscous stress tensor, p. 5
$\boldsymbol{\tau}$	Viscous stress vector, p. 5
Υ	Effective wing dihedral angle, p. 216
φ	Perturbation velocity potential, p. 38
ϕ	Velocity potential, p. 19
ϕ	Normalized perturbation potential, p. 170
ϕ	Aircraft roll angle, p. 202
Φ	Wagner function, p. 154
Φ	Full velocity potential, p. 166
χ	Flow curvature from wind tunnel images, p. 228
ψ	Aircraft heading angle, p. 202
Ψ	Küssner function, p. 154
ω	Imaginary part of flight-dynamics eigenvalue (radian frequency), p. 207
ω	Vorticity (in 2D), p. 28
$\boldsymbol{\omega}$	Vorticity vector (in 3D), p. 17
$\boldsymbol{\Omega}$	Body angular velocity vector, p. 4

Operators

$\mathrm{D}(\,)/\mathrm{D}t$ Substantial derivative ($= \frac{\partial()}{\partial t} + \mathbf{V} \cdot \nabla(\,)$), p. 8

$\nabla(\,)$ Gradient ($= \frac{\partial()}{\partial x}\hat{\mathbf{x}} + \frac{\partial()}{\partial y}\hat{\mathbf{y}} + \frac{\partial()}{\partial z}\hat{\mathbf{z}} = \frac{\partial()}{\partial s}\hat{\mathbf{s}} + \frac{\partial()}{\partial \ell}\hat{\boldsymbol{\ell}} + \frac{\partial()}{\partial n}\hat{\mathbf{n}}$), p. 6

$\widetilde{\nabla}(\,)$ Surface gradient ($= \frac{\partial()}{\partial s}\hat{\mathbf{s}} + \frac{\partial()}{\partial \ell}\hat{\boldsymbol{\ell}}$), p. 28

$\dot{(\,)}$ Time derivative ($= \frac{\partial()}{\partial t}$), p. 146

Subscripts

$(\,)_0$ Trim-state quantity, p. 207

$(\,)_\infty$ Freestream, p. 9

$(\,)_A$ Apparent-mass force or moment, p. 154

$(\,)_b$ Related to boundary conditions, p. 25

$(\,)_\mathrm{e}$ At edge of boundary layer, p. 47

$(\,)_\mathrm{eff}$ Effective-freestream quantity (excludes near-field contributions), p. 104

$(\,)_\mathrm{i}$ Equivalent Inviscid Flow, p. 47

$(\,)_i$ Related to induced drag or downwash, p. 104

$(\,)_i$ Control-point index in vortex lattice method, p. 132

$(\,)_j$ Horseshoe vortex index in vortex lattice method, p. 132

$(\,)_l$ On lower surface, p. 51

$(\,)_l$ Control variable index in vortex lattice method, p. 132

$(\,)_{LE}$ At leading edge, p. 37

$(\,)_o$ Stagnation (total) quantity, p. 4

$(\,)_Q$ Quasi-steady force or moment, p. 154

$(\,)_\mathrm{ref}$ Reference value, p. 2

$(\,)_\mathrm{SL}$ Sea-level Standard Atmosphere, p. 1

$(\,)_{TE}$ At trailing edge, p. 37

$(\,)_\mathrm{tr}$ At transition location, p. 89

$(\,)_u$ On upper surface, p. 51

$(\,)_\mathrm{u}$ Measured quantity uncorrected for tunnel boundary effects, p. 223

$(\,)_\mathrm{w}$ At wall, p. 47

$(\,)_\perp$ Component or quantity perpendicular to wing, p. 77

$(\,)_\parallel$ Component or quantity parallel to wing, p. 77

Superscripts

$(\,)'$ Dummy variable of integration, p. 2

$(\,)^b$ Vector component in body axes, p. 265

$(\,)^e$ Vector component in Earth axes, p. 265

$(\,)^\mathrm{s}$ Vector component in stability axes, p. 124

$(\,)^\mathrm{w}$ Vector component in wind axes, p. 125

$\bar{(\,)}$ Dimensionless quantity (in Chapters 1, 6), p. 10

$\bar{(\,)}$ Quantity in Prandtl-Glauert space (in Chapter 8), p. 173

Contents