Aerodynamics of Low Reynolds Number Flyers

Low Reynolds number aerodynamics is important to a number of natural and man-made flyers. Birds, bats, and insects have been investigated by biologists for years, and active study in the aerospace engineering community, motivated by interest in micro air vehicles (MAVs), has been increasing rapidly. The primary focus of this book is the aerodynamics associated with fixed and flapping wings. The book considers both biological flyers and MAVs, including a summary of the scaling laws that relate the aerodynamics and flight characteristics to a flyer's sizing on the basis of simple geometric and dynamics analyses, structural flexibility, laminar–turbulent transition, airfoil shapes, and unsteady flapping-wing aerodynamics. The interplay between flapping kinematics and key dimensionless parameters such as the Reynolds number, Strouhal number, and reduced frequency is highlighted. The various unsteady lift-enhancement mechanisms are also addressed.

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Aerodynamics of Low Reynolds Number Flyers

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Tokyo, Mexico City

Cambridge University Press
32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org
Information on this title: www.cambridge.org/9780521204019

First published 2008
Reprinted 2009
First paperback edition 2011

A catalog record for this publication is available from the British Library

Library of Congress Cataloging in Publication data

Shyy, Wei.
Aerodynamics of low reynolds number flyers : wei shyy . . . [et al.].
p. cm. – (Cambridge aerospace series)
Includes bibliographical references and index.
ISBN 978-0-521-88278-1 (hardback)
1. Aerodynamics. I. Title. II. Series.
TL570.S488 2007
629.132'3 – dc22 2007019227

ISBN 978-0-521-88278-1 Hardback
ISBN 978-0-521-20401-9 Paperback

Additional resources for this publication at www.cambridge.org/9780521204019

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Cambridge University Press
978-0-521-20401-9 - Aerodynamics of Low Reynolds Number Flyers
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Nomenclature

		First Appearance
AR	aspect ratio $= b^2/S$	Eq. (1.9)
AoA	angle of attack	
b	wingspan	Eq. (1.9)
c	chord length	Eq. (1.1)
C_L	lift coefficient $\left(C_L = \frac{L}{0.5\rho U^2 S}\right)$	Eq. (1.3)
C_D	drag coefficient $\left(C_D = \frac{D}{0.5\rho U^2 S}\right)$	Eq. (2.22)
$C_{D,F}$	drag coefficient due to skin friction	Eq. (2.22)
$C_{D,P}$	drag coefficient due to pressure	Eq. (2.22)
C_P	pressure coefficient $\left(C_P = \frac{P}{0.5\rho U^2}\right)$	
C_T	tension coefficient of a membrane sail	Eq. (3.1)
$\mathbf{C}$	right Cauchy–Green deformation tensor	Eq. (3.23)
D_{aero}	total aerodynamic drag	Eq. (1.27)
D_{ind}	induced drag	Eq. (1.26)
D_{par}	parasite drag (drag on the body)	Eq. (1.27)
D_{pro}	profile drag	Eq. (1.26)
D_w	drag on a finite wing	Eq. (1.26)
e	span efficiency factor	Eq. (2.22)
E	elastic modulus	Eq. (3.7)
F_m	force exerted by a muscle	Eq. (1.10)
f	wing-beat frequency	Eq. (1.14)
$f,_{\text{max}}$	maximum flapping frequency	Eq. (1.15)
$f,_{\text{min}}$	minimum flapping frequency	Eq. (1.18)
g	gravitational acceleration	Eq. (1.5)
h_a	flapping amplitude	Eq. (4.4)
h_0	membrane thickness in nondeformed configurations	Eq. (3.27)
$h(t)$	deformed membrane thickness	Eq. (3.27)
$h(t)$	time-dependent flapping displacement	Eq. (4.4)
h	membrane thickness	Eq. (3.7)
H	shape factor	Eq. (2.2)
H_T	shape factor at the transition point	Eq. (2.19)
I	moment of inertia	Eq. (1.12)
J	advance ratio	Eq. (4.15)
J_T	torque	Eq. (1.11)

k	reduced frequency	Eq. (1.1)
k	turbulent kinetic energy	Eq. (2.6)
l	characteristic length	Eq. (1.6)
L	lift	Eq. (1.3)
L_0	unstrained membrane length	Eq. (3.2)
L/D	lift-to-drag ratio, or glide ratio ($= C_L/C_D$)	Eq. (2.20)
m	body mass	Eq. (1.5)
m_l	mass of a limb	Eq. (1.12)
m_p	mass of the pectoral muscles	Eq. (1.24)
m_s	mass of the supracoracoideus muscles	Eq. (1.25)
$\tilde{n}$	amplification factor	Eq. (2.12)
N	threshold value that triggers turbulent flow in e^N method	Eq. (2.17)
p	static pressure	Eq. (2.5)
$\overline{p}$	normalized static pressure	Eq. (4.19)
P_{aero}	total aerodynamic power	Eq. (1.28)
p_{center}	pressure at the center of a vortex core rotating as a rigid body	Eq. (2.23)
P_{ind}	induced power (required for generating lift and thrust)	Eq. (1.30)
P_{iner}	inertial power (required for moving the wings)	Eq. (1.31)
P_{pro}	profile power (required for overcoming form and friction drag of the wings)	Eq. (1.30)
P_{par}	parasite power (required for overcoming form and friction drag of the body)	Eq. (1.30)
P_{tot}	total power required for flight	Eq. (1.31)
q_∞	far-field dynamic pressure	Eq. (3.12)
r_1	radius of the vortex core rotating as a rigid body	Eq. (2.23)
R	wing length	Eq. (4.20)
Re	Reynolds number	
Re_{f2}	Reynolds number for 2D flapping airfoils	Eq. (4.7)
Re_{f3}	Reynolds number for 3D flapping wing	Eq. (4.8)
Re_T	turbulent Reynolds number	Eq. (2.10)
Re_θ	momentum-thickness Reynolds number	Eq. (2.12)
Re_{θ_0}	critical Reynolds number	Eq. (2.12)
$Re_{\theta T}$	momentum-thickness Reynolds number at transition point	Eq. (2.19)
S	wing area	Eq. (1.3)
S	second Piola–Kirchoff stress tensor	Eq. (3.23)
S_0	membrane prestress	Eq. (3.7)
St	Strouhal number	Eq. (4.9)
T	wing-stroke time scale	Eq. (1.14)
T	thrust (for hovering)	Eq. (1.29)
T_i	free-stream turbulence intensity	Eq. (2.17)
t	time	Eq. (2.5)
U	forward-flight velocity (free-stream velocity)	Eq. (1.2)
U_{ref}	reference velocity	Eq. (1.1)
u_e	edge velocity	Eq. (2.2)
u_i	velocity vector in Cartesian coordinates	Eq. (2.4)

$\overline{u_i}$	normalized velocity vector in Cartesian coordinates	Eq. (4.19)
U_f	flapping velocity	Eq. (1.2)
U_{mp}	velocity for minimum power (forward flight)	Eq. (1.33)
U_{Mr}	velocity for maximum range (forward flight)	Eq. (1.33)
U_r	relative flow velocity	Eq. (1.2)
w	vertical velocity in the far wake	Eq. (4.22)
w_i	downwash (induced) velocity	Eq. (1.2)
W	weight	Eq. (1.3)
W	out-of-plane membrane displacement	Eq. (3.20)
W/S	wing loading	Eq. (1.7)
x_i	spatial coordinate vector	Eq. (2.4)
x_l	leg length	Eq. (1.19)
x_T	transition onset position	Eq. (2.19)
α	angle of attack	Eq. (3.1)
$\alpha(t)$	feathering angle (pitch angle) of a flapping wing	Eq. (4.3)
α_0	initial pitch angle at the beginning of the stroke	Eq. (4.5)
α_a	pitch amplitude	Eq. (4.5)
β	stroke-plane angle	Eq. (4.21)
γ	membrane tension	Eq. (3.3)
$\hat{\gamma}$	dimensionless membrane tension	Eq. (3.7)
Γ	circulation	Eq. (2.23)
δ^*	boundary-layer displacement thickness	Eq. (2.3)
$\overline{\delta}$	nominal membrane strain	Eq. (3.8)
ε	dimensionless excess length of a membrane	Eq. (3.2)
θ	boundary-layer momentum thickness	Eq. (2.1)
$\theta(t)$	elevation angle of a flapping wing	Eq. (4.2)
ζ, η	curvilinear coordinates along the membrane airfoil	Eq. (3.3)
ν	kinematic viscosity	Eq. (2.5)
ν_{Te}	effective eddy viscosity	Eq. (2.18)
ν_T	turbulent eddy viscosity	Eq. (2.6)
Π_1	aeroelastic parameter (elastic-strain-dominated membrane tension)	Eq.(3.16)
Π_2	aeroelastic parameter (pretension-dominated membrane tension)	Eq. (3.18)
$\phi(t)$	positional angle of a flapping wing	Eq. (4.1)
Φ	stroke angular amplitude	Eq. (4.7)
φ	phase difference between plunging and pitching motion	Eq. (4.4)
ρ	(air) density	Eq. (1.3)
τ_{ij}	Reynolds stress tensor	Eq. (2.6)
τ	tangential surface traction for 2D membrane	Eq. (3.4)
ω	angular velocity of a flapping wing $= 2\pi f$	Eq. (1.1)
ω	dissipation rate for k–ω turbulence model	Eq. (2.7)
ω	frequency	Eq. (2.21)
$\dot{\omega}$	angular acceleration	Eq. (1.13)

List of Abbreviations

Abbreviation	*Definition*
2D	two-dimensional
3D	three-dimensional
AoA	angle of attack
AR	aspect ratio
CFD	computational fluid dynamics
CSD	computational structural dynamics
DNS	direct numerical simulation
DPIV	digital particle-image velocimetry
LES	large-eddy simulation
LEV	leading-edge vortex
LSB	laminar separation bubble
MAV	micro air vehicle
RANS	Reynolds-averaged Navier–Stokes
TEV	trailing-edge vortex
TS	Tollmien–Schlichting
WTV	wingtip vortex

Preface

Low Reynolds number aerodynamics is important to a number of natural and manmade flyers. Birds, bats, and insects have been of interest to biologists for years, and active study in the aerospace engineering community has been increasing rapidly. Part of the reason is the advent of micro air vehicles (MAVs). With a maximal dimension of 15 cm and nominal flight speeds of around 10 m/s, MAVs are capable of performing missions such as environmental monitoring, survelliance, and assessment in hostile environments. In contrast to civilian transport and many military flight vehicles, these small flyers operate in the low Reynolds number regime of 10^5 or lower. It is well established that the aerodynamic characteristics, such as the lift-to-drag ratio of a flight vehicle, change considerably between the low and high Reynolds number regimes. In particular, flow separation and laminar–turbulent transition can result in substantial change in effective airfoil shape and reduce aerodynamic performance. Because these flyers are lightweight and operate at low speeds, they are sensitive to wind gusts. Furthermore, their wing structures are flexible and tend to deform during flight. Consequently, the aero/fluid and structural dynamics of these flyers are closely linked to each other, making the entire flight vehicle difficult to analyze.

The primary focus of this book is on the aerodynamics associated with fixed and flapping wings. Chapter 1 offers a general introduction to low Reynolds number flight vehicles, considering both biological flyers and MAVs, followed by a summary of the scaling laws, which relate the aerodynamics and flight characteristics to a flyer's size on the basis of simple geometric and dynamics analyses. In Chapter 2, we discuss the aerodynamics of fixed, rigid wings. Both two- and three-dimensional airfoils with typically low-aspect-ratio wings are considered. Chapter 3 examines structural flexibility within the context of fixed-wing aerodynamics. The implications of laminar–turbulent transition, multiple time scales, airfoil shapes, angles of attack, stall margin, and the structural flexibility and time-dependent fluid and structural dynamics are highlighted.

Unsteady flapping-wing aerodynamics is presented in Chapter 4, in particular, the interplay between flapping kinematics and key dimensionless parameters such as the Reynolds number, Strouhal number, and reduced frequency. The various unsteady lift-enhancement mechanisms are also addressed, including leading-edge vortex, rapid pitch-up, wake capture, and clap-and-fling.

The materials presented in this book are based on our own research, existing literature, and communications with colleagues. At different stages, we have benefited

Cambridge University Press
978-0-521-20401-9 - Aerodynamics of Low Reynolds Number Flyers
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from collaborations and interactions with Peter Ifju, David Jenkins, Rick Lind, Raphael Haftka, Richard Fearn, Roberto Albertani, and Bruce Carroll of the University of Florida; Luis Bernal, Carlos Cesnik, and Peretz Friedmann of the University of Michigan; Michael Ol, Miguel Visbal, and Gregg Abate, and Johnny Evers of the Air Force Research Laboratory; Ismet Gursul of the University of Bath; Charles Ellington of Cambridge University; Keiji Kawachi of the University of Tokyo; Hikaru Aono of Chiba University; Max Platzer of Naval Postgraduate School; and Mao Sun of the Beijing University of Aeronautics and Astronautics. In particular, we have followed the flight vehicle development efforts of Peter Ifju and his group and enjoyed the synergy between us.

MAVs and biological flight is now an active and well-integrated research area, attracting participation from a wide range of talents. The complementary perspectives of researchers with different training and background enable us to develop new biological insight, mathematical models, physical interpretation, experimental techniques, and design concepts.

Thinking back to the time we started our own endeavor a little more than 10 years ago, we see that substantial progress has taken place, and there is every expectation that significantly more will advance in the foreseeable future. We look forward to it!

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December 31, 2006