The flapping flight of birds

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The Flapping Flight of Birds
Analysis and Application

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To Line Maye and Malia Luja – you are the best I have ever made.

CONTENTS

LIST OF ACRONYMS

Acronym	Explanation	Illustration
α	angle of attack	Figure 3.3
α_{eff}	effective angle of attack	Figure 4.4
α_{geo}	geometric angle of attack	Figure 4.4
α_{in}	inflow angle	Figure 4.4
α_{ind}	induced angle of attack	Figure 6.5
Γ_z	circulation around the spanwise axis	
ε_{bias}	bias error	Figure 2.7
ε_{rms}	random error	Figure 2.7
μ	fluid dynamic viscosity	
ν	kinematic viscosity	
ρ	fluid density	
ρ_p	density of a particle	
σ_u	standard deviation of velocity estimate	Figure 5.2
Φ	excursion angle	Figure 3.3
Ω	vorticity tensor	
ω	angular velocity of the wing	
ω_z	vorticity around the spanwise axis	
3D	three-dimensional	
A	peak-to-peak amplitude of the wing	
a	acceleration	
A_{disk}	area swept by the rotor	
A_{vort}	area of the vortex core	
A_{wing}	total wing area	
A_r	area of wing element at radius r	
AR	aspect ratio	
b	wing span	
BET	blade-element theory	
c	chord length	Figure 3.1
C	correlation matrix	Figure 2.3
'c-'	0% cambered wing	Figure 3.2

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Acronym	Explanation	Illustration
C_{D_o}	drag coefficient at zero degrees angle of attack	
$C_{L,max}$	maximum lift coefficient	
C_{L_o}	lift coefficient at zero degrees angle of attack	
C_D	drag coefficient	
C_L	lift coefficient	
C_V	vertical force coefficient	
'c+'	10% cambered wing	Figure 3.2
CFD	computational fluid dynamics	
CLAHE	contrast limited adaptive histogram equalization	Figure 2.2
CMOS	complementary metal-oxide-semiconductor	
COT	cost of transport	Figure 1.1
CW	constant wave mode	
d	true displacement	Figure 2.8
D	drag	
D_{ind}	induced drag	
d_{meas}	displacement measured by DPIV	Figure 2.8
d_o	drag at zero degrees angle of attack	
d_p	particle diameter	
D_r	drag of the wing element at radius r	Figure 6.5
DARPA	defense advanced research projects agency	
DCC	direct cross-correlation	Figure 2.4
DCEV	discriminant for complex eigenvalues	
DFT	discrete Fourier transform	Figure 2.4
DOF	degree of freedom	Figure 4.2
DPIV	digital particle image velocimetry	Figure 2.1
DPSS	diode pumped solide state	
E_{fw}	endurance of fixed wing aircraft	Figure 5.7
$E_{k_{min}}$	minimum kinetic energy	
e_i	span efficiency	
E_r	endurance of rotary wing aircraft	Figure 5.7
f	flapping frequency	
F_{tot}	total aerodynamic force	
F_H	horizontal force	Figure 6.5
F_V	vertical force	Figure 6.5

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Acronym	Explanation	Illustration
FFTW	fastest fourier transform in the west	
GPU	graphics processing unit	
h	vertical distance of rotors in coaxial configuration	
I	moment of inertia	
IMU	inertial measurement unit	Figure 5.9
J	advance ratio	
k	reduced frequency	
K_p	constant of proportionality in potential-flow lift term	
K_v	constant of proportionality in vortex lift term	
L	lift	
L/D	lift-to-drag ratio	
L_{circ}	total ciculatory lift	
L'_{circ}	sectional circulatory lift at mid-downstroke	
L_{circ}/D_{ind}	ratio of circulatory lift to induced drag	
l_{max}	maximum dimension	
l_o	lift at zero degrees angle of attack	
L_r	lift of the wing element at radius r	Figure 6.5
LEV	leading-edge vortex	Figure 1.8
LIC	line integral convolution	Figure 2.29
m_{air}	mass of accelerated air	
MAV	micro air vehicle	Figure 5.1
MEMS	microelectromechanical systems	Figure 5.9
n	rotational speed of the rotor	
Nd:YAG	neodym-yttrium-aluminium-garnet	
P_{iner}	inertial power	
PIPM	particle image pattern matching	
Q	Q-criterion	
r	radius of a wing element	
R	rotor radius	
Re	Reynolds number	
ROA	remotely operated aircraft	
RPV	remotely piloted vehicle	
S	rate-of-strain tensor	
s	distance between motor shafts	

continued on next page

Acronym	Explanation	Illustration
's'	standard wing	Figure 3.2
S_{vort}	circular path around vortex core	
St	Strouhal number	
T	thrust	
t	time	
't-'	3% thick wing	Figure 3.2
t_{lower}	lower velocity threshold	
t_{upper}	upper velocity threshold	
't+'	15% thick wing	Figure 3.2
U	(local) flow velocity	
U_{gust}	instantaneous gust velocity	
U_{jet}	velocity of propeller jet	
U_{min}	minimum flight speed	Figure 5.4
U_e	speed of maximum endurance	Figure 5.3
U_f	free flow velocity / forward speed	Figure 1.2
U_p	particle velocity	
U_r	speed of maximum range	Figure 5.3
U_s	velocity lag between fluid and particle	
UAV	unmanned aerial vehicle	Figure 5.1
v	downwash	
v_{down}	vertical velocity downstream of the wing	
v_{tip}	mean wingtip velocity	
v_{up}	vertical velocity upstream of the wing	
v_{vert}	mean vertical wingtip velocity	
v_r	effective velocity of wing element at radius r	Figure 6.5
v_t	tangential velocity	
VTOL	vertical take-off and landing	
W	weight	
w	disk loading	
w_{down}	spanwise velocity downstream of the wing	
w_{up}	spanwise velocity upstream of the wing	
z	spanwise position	