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## The flapping flight of birds

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*The Flapping Flight of Birds*  
Analysis and Application

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# The Flapping Flight of Birds

Analysis and Application

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 on the authority of the  
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 and in accordance with  
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by

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



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## LIST OF ACRONYMS

Acronym	Explanation	Illustration
$\alpha$	angle of attack	Figure 3.3
$\alpha_{eff}$	effective angle of attack	Figure 4.4
$\alpha_{geo}$	geometric angle of attack	Figure 4.4
$\alpha_{in}$	inflow angle	Figure 4.4
$\alpha_{ind}$	induced angle of attack	Figure 6.5
$\Gamma_z$	circulation around the spanwise axis	
$\varepsilon_{bias}$	bias error	Figure 2.7
$\varepsilon_{rms}$	random error	Figure 2.7
$\mu$	fluid dynamic viscosity	
$\nu$	kinematic viscosity	
$\rho$	fluid density	
$\rho_p$	density of a particle	
$\sigma_u$	standard deviation of velocity estimate	Figure 5.2
$\Phi$	excursion angle	Figure 3.3
$\Omega$	vorticity tensor	
$\omega$	angular velocity of the wing	
$\omega_z$	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

*continued on next page*

Acronym	Explanation	Illustration
$C_{D_0}$	drag coefficient at zero degrees angle of attack	
$C_{L,max}$	maximum lift coefficient	
$C_{L_0}$	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
$d_0$	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

*continued on next page*

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 circulatory 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
$S_{\text{vort}}$	circular path around vortex core	
St	Strouhal number	
T	thrust	
t	time	
't-'	3% thick wing	Figure 3.2
$t_{\text{lower}}$	lower velocity threshold	
$t_{\text{upper}}$	upper velocity threshold	
't+'	15% thick wing	Figure 3.2
U	(local) flow velocity	
$U_{\text{gust}}$	instantaneous gust velocity	
$U_{\text{jet}}$	velocity of propeller jet	
$U_{\text{min}}$	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	
$v_{\text{down}}$	vertical velocity downstream of the wing	
$v_{\text{tip}}$	mean wingtip velocity	
$v_{\text{up}}$	vertical velocity upstream of the wing	
$v_{\text{vert}}$	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	
$w_{\text{down}}$	spanwise velocity downstream of the wing	
$w_{\text{up}}$	spanwise velocity upstream of the wing	
z	spanwise position	



