JOURNAL OF AIRCRAFT
Vol. 46, No. 5, September–October 2009

Numerical Analysis on Aerodynamic Force Generation of Biplane Counter-Flapping Flexible Airfoils

Jr-Ming Miao[*] and Wei-Hsin Sun[†]
National Defense University, Tao-Yuan 355, Taiwan, Republic of China
and
Chang-Hsien Tai[‡]
National Pingtung University of Science and Technology,
Pingtung 912, Taiwan, Republic of China

DOI: 10.2514/1.43181

This study explores the effect of chordwise flexible deformation on unsteady aerodynamic characteristics for biplane counter-flapping dual NACA0014 airfoils with various combinations of Reynolds number and reduced frequency. Unsteady laminar viscous flows over duel rigid and flexible airfoils executing counter-plunge motion are computed with time-dependent two-dimensional laminar Reynolds-averaged Navier–Stokes equations coupled with conformal hybrid meshes. The tested Reynolds number with an airfoil characteristic chord length is 10^2, 10^3, and 10^4, and the reduced frequency ranges from 0.5 to 3.5. The dynamic mesh technique is applied to illustrate the flapping deformation modes of the flexible airfoils. To investigate the influence of the chordwise flexure extent on the aerodynamic performance of the flapping airfoils, the present study considers various different curvature deformations of flapping foils with flexure extent ranging from 0 to 0.3 times the chord length at 0.05 intervals. The visualized particle-tracing paths clearly revealed the formation and evolution of leading-edge vortices along the body of the flexible airfoil as it undergoes biplane counter-plunge motion. The generation of thrust-indicative wake structure or the drag-indicated wake structure behind the flexible airfoils depended on the degree of flexure extent of the airfoil at a fixed range of reduced frequency. The thrust force for each airfoil with biplane counter-flapping mode will be enhanced 6.32% more than that for a rigid single flapping airfoil. Present results show that flexible airfoils with flexure extent 0.25 times the chord length in counter-plunge flapping motion could get maximum propulsive efficiency and produce about 64.65% more than that of biplane rigid airfoils. The outcome indicates that appropriate flexible biplane flapping flight could not only increase the thrust force, but also boost the propulsive performance.

Nomenclature

a_o = flexure amplitude of the airfoil
C_d = drag coefficient
C_l = lift coefficient
c = chordwise length of the airfoil
F_n = force normal to the surface of the airfoil
F_x = x direction force on the surface of the airfoil
$\bar{F}_x$ = period-averaged thrust force
f = flapping frequency
h = instantaneous plunge position
h_o = nondimensional plunge amplitude
k_r = reduced frequency, $\omega c/U_\infty$
Re = Reynolds number, $\rho U_\infty c/\mu$
$\bar{P}$ = period-averaged consumption power rate
St = Strouhal number, $2h_o f/U_\infty$
T = flapping period, $2\pi/\omega$
t = dimensional time
t' = nondimensional time, tU_∞/c
U_∞ = freestream velocity
x, y = Cartesian coordinate axis
δ = period-averaged input-power coefficient
η = propulsive efficiency, ξ/δ
ξ = period-averaged thrust-power coefficient
ρ = density of fluid
ψ = phase angle between plunging and flexing of the airfoil
ω = circular frequency of flapping oscillations, $2\pi f$

I. Introduction

THE flapping flight of birds and insects has fascinated biological scientists and researchers for hundreds of years. Many examples can be found in nature of winged creatures exhibiting excellent aerodynamic characteristics, and the flying capabilities of these creatures surpass those manifested by man-made aircraft. The outstanding flying performance of birds and insects to take off, land, hover, etc., via flapping mode has inspired researchers and engineers to think of equipping aircraft with flapping mechanisms rather than rotating propellers as a means of generating thrust and lift forces. Researchers focused on the low-Reynolds-number lift force and propulsive capability of flapping wings in hovering mode or forward-flight mode. Both experimental and numerical investigations on the kinematics, dynamics, and unsteady aerodynamic characteristics of 2-D/3-D flapping wings can be found in the recent open literature. For example, Ellington [1] pointed out that the classical steady-state model is not a practical tool to predict aerodynamic forces in flapping flight, because the calculated lift force during a cycle is not sufficient to sustain the weight of insects/birds even in forward-flight mode. Tang et al. [2] confirmed that the unsteady-force-generation mechanism is strongly related to the flapping paths of wings during upstroke and downstroke periods. To understand the unsteady-lift-generation mechanisms, such as clap-and-fling mechanism, delay dynamic stall associated with large scale of leading-edge vortices, fast pitch-up rotation, and wake capturing, several studies either in wind tunnels or by directly solving the time-dependent Navier–

Presented as Paper 3817 at the 38th Fluid Dynamics Conference and Exhibit, Seattle, WA, 23–26 June 2008; received 12 January 2009; revision received 12 June 2009; accepted for publication 17 May 2009.

[*] Professor, Department of Mechatronic, Energy and Aerospace Engineering, Chung Cheng Institute of Technology; jmmiao@ccit.edu.tw.

[†] Ph.D. Student, Graduate School of Defense Science Studies, Chung Cheng Institute of Technology.

[‡] Professor, Department of Vehicle Engineering.