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Brief Communication

Thrust augmentation of flapping airfoils in low Reynolds number flow using a flexible membrane☆

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ABSTRACT

The unsteady aerodynamic thrust and aeroelastic response of a two-dimensional membrane airfoil under prescribed harmonic motion are investigated computationally with a high-order Navier–Stokes solver coupled to a nonlinear membrane structural model. The effects of membrane prestress and elasticity are examined parametrically for selected plunge and pitch–plunge motions at a chord-based Reynolds number of 2500. The importance of inertial membrane loads resulting from the prescribed flapping is also assessed for pure plunging motions. This study compares the period-averaged aerodynamic loads of flexible versus rigid membrane airfoils and highlights the vortex structures and salient fluid–membrane interactions that enable more efficient flapping thrust production in low Reynolds number flows.

1. Introduction

Designers of micro air vehicles (MAVs) are currently looking to biological flight to address the technical challenges of low Reynolds number fliers. These challenges include the aerodynamics of transitional flow, flight vehicle resilience to gusty environments, lightweight design, and propulsion. Biological observations (Song et al., 2008), experimental measurements (Mueller et al., 2010), and aeroelastic computations (Gordnier, 2009; Molki and Breuer, 2010) indicate that deformable membrane-airfoils may offer an engineering solution to these design issues, and that the existence of membrane flexibility may enable and enhance the thrust production of flapping wings in low Reynolds number flows.

In order to better understand the physics of a lifting membrane airfoil in a fluid flow, recent research has focused on the correlation between high-order aeroelastic simulations and experiment for the canonical configuration of Rojratsirikul et al. (2009, 2010), also considered in the present work, where a thin latex sheet is stretched tautly between two small, teardrop-shaped mounts; Arbós-Torrent et al. (2013) have extended experimental consideration to the effects of other leading- and trailing-edge mount shapes on the aeromechanics of such membrane airfoils at fixed angles of attack. Previous computational works by Gordnier (2008) and Gordnier and Attar (2009) have investigated membrane airfoil aeroelasticity over a range of steady angles of attack, membrane elasticity and prestress, and Reynolds numbers of up to 48 500 where laminar, transitional, and turbulent flows may be present simultaneously. Their implicit large-eddy simulation (LES) approach (Visbal et al., 2003) exploited a well-validated, robust, sixth-order Navier–Stokes solver to compute the

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Nomenclature

A	cross-sectional area of membrane
c	membrane chord length
C_L	section lift normalized by $\rho_\infty V_\infty^2 c/2$
C_M	section moment about the pitch axis, positive nose-up, normalized by $\rho_\infty V_\infty^2 c^2/2$
C_p	pressure normalized by $\rho_\infty V_\infty^2/2$
C_{Power}	aerodynamic power normalized by $\rho_\infty V_\infty^3 c/2$
C_T	section thrust normalized by $\rho_\infty V_\infty^2 c/2$
$\mathbf{d}$	membrane deformation vector normalized by c, $\mathbf{d} = \lfloor u, w \rfloor^{\mathrm{T}}$
e_{xx}	membrane strain
E	elastic modulus normalized by $\rho_\infty V_\infty^2$
h^*	plunge amplitude normalized by c
h_s	membrane thickness normalized by c
k	reduced frequency, $k = \omega c/(2V_\infty)$
M	Mach number
Re	Reynolds number based on membrane chord length and freestream velocity
${}^0S$	membrane prestress normalized by $\rho_\infty V_\infty^2$
t	time
u	in-plane membrane deformation normalized by c
V_∞	freestream fluid velocity
w	out-of-plane membrane deformation normalized by c
$\mathbf{x}$	position vector in local coordinate system normalized by c, $\mathbf{x} = \lfloor x, z \rfloor^{\mathrm{T}}$
$\mathbf{x}_{\mathrm{O}}$	normalized local position vector to pitch axis, $\mathbf{x}_{\mathrm{O}} = \lfloor x_{\mathrm{O}}, z_{\mathrm{O}} \rfloor^{\mathrm{T}}$
$\mathbf{X}$	position vector in global coordinate system normalized by c, $\mathbf{X} = \lfloor X, Z \rfloor^{\mathrm{T}}$
$\mathbf{X}_{\mathrm{R}}$	normalized global position vector to pitch axis of local coordinate system, $\mathbf{X}_{\mathrm{R}} = \lfloor X_{\mathrm{R}}, Z_{\mathrm{R}} \rfloor^{\mathrm{T}}$
α	geometric angle of attack
η_{p}	propulsive efficiency
ρ_∞	freestream fluid density
ρ_{s}	membrane density normalized by ρ_∞
τ	nondimensional time, $\tau = V_\infty t/c$
$\overline{\tau}$	nondimensional time scaled by the period of prescribed motion, $\overline{\tau} = \tau k/\pi$
$\mathbf{\Phi}$	external loading on membrane normalized by $\rho_\infty V_\infty^2$, $\Phi = \lfloor \Phi_x, \Phi_z \rfloor^{\mathrm{T}}$
ω	radian frequency
$\overline{(\,)}$	period-averaged value
$(\,)'$	spatial derivative; $\partial(\,)/\partial x$
$\dot{(\,)}$	$\partial(\,)/\partial\tau$
$(\,)_\infty$	freestream condition

three-dimensional flow field, where the aerodynamic forces are coupled to a finite element membrane model that captures geometric nonlinearity. Jaworski and Gordnier (2012) applied the strong form of this membrane model to the high-order, two-dimensional aeroelastic solver by Gordnier (2009) and extended the solver to include the rigid body motion of the membrane airfoil mounts. This enhanced aeroelastic solver was then used to evaluate the aerodynamic performance of a two-dimensional membrane airfoil over a range of plunge amplitudes, prescribed flapping frequencies, and Reynolds numbers from 2500 to 10 000.

The present work employs the aeroelastic solver of Jaworski and Gordnier (2012), fixing the Reynolds number at 2500 to maintain two-dimensional flow and to focus on the structural influences on the fluid–structure behavior. These structural effects are namely the inertial loading due to prescribed rigid body motion and the elastic contributions from membrane elasticity versus prestress. The inertial loading effects on thrust and propulsive efficiency are evaluated for pure plunging motions across a range of amplitudes and reduced frequencies. The exploration of the elastic parameter space for pitching and pitch–plunge motions is motivated by the limited range of membrane prestress values examined in prior work that suggested important trade-offs among the prestress, required flapping power, and potential improvements to the period-averaged thrust and propulsive efficiency. In the spirit of the exploratory study by Streitlien and Triantafyllou (1998), a 'cross' in parameter space for the elastic modulus and prestress is examined to determine their importance on the vortex dynamics and aerodynamic performance, particularly the period-averaged thrust and propulsive efficiency, with the aim to inform the aeroelastic tailoring of more efficient flapping-membrane-airfoil fliers.

2. Computational approach

A detailed account of the governing equations and computational methodologies employed in the present aeroelastic investigation have been given by Jaworski and Gordnier (2012) and therefore only a brief description is given here.

The flow about a dynamically deforming membrane is computed using the two-dimensional, compressible Navier–Stokes equations written in strong conservative form, incorporating a general time-dependent curvilinear coordinate transformation to allow for a deforming mesh. A compact finite-difference approach is employed to discretize the flow equations. An eighth-order filtering technique (Gaitonde et al., 1997; Visbal and Gaitonde, 1999) is applied to the conserved variables to eliminate the long-term growth of spurious high-frequency modes associated with the compact discretization. The implicit, approximate-factorization algorithm of Beam and Warming (1978) marches the flow equations forward in time, and this scheme is augmented by Newton-like subiterations to achieve second-order temporal and sixth-order spatial accuracy.

The structural deformations of the elastic surface are assumed to be governed by a set of nonlinear membrane (Carrier, 1945, 1949) that allow for strain contributions from both in- and out-of-plane displacements u and w, respectively.

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