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On the shape optimization of flapping wings and their performance analysis

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ABSTRACT

The present work is concerned with the shape optimization of flapping wings in forward flight. The analysis is performed by combining a gradient-based optimizer with the unsteady vortex lattice method (UVLM). We describe the UVLM simulation procedure and provide the first methodology to select properly the mesh and time-step sizes to achieve invariant UVLM simulation results under mesh refinement. Our objective is to identify a set of optimized shapes that maximize the propulsive efficiency, defined as the ratio of the propulsive power over the aerodynamic power, under lift, thrust, and area constraints. Several parameters affecting flight performance are investigated and their impact is described. These include the wing's aspect ratio, camber line, and curvature of the leading and trailing edges. This study provides guidance for shape design of engineered flying systems.

1. Introduction

The design and optimization of micro-air vehicles (MAVs) have been recently the topic of many research efforts [5,11,13,14,17,18,20,22,24,29,30,34,38,40,41,47]. The MAV concept is quite new and the associated design space is large and not fully explored yet. These small flying aeroelastic systems are expected to operate in urban environments and confined spaces (i.e., inside buildings, caves, tunnels) and endure a variety of missions such as inspection and observation of harsh environments inaccessible to other types of vehicles or where there is danger to human life. Consequently, their design must satisfy stringent performance requirements, such as high maneuverability at low speeds, hovering capabilities, high lift to sustain flight, and structural strength to survive gust loads and possible impacts. These requirements can be achieved mainly through two propulsion mechanisms: rotating helicopter blades or flapping wings [27]. Through observing and simulating insects and birds flights, it has been concluded that flapping wings offer greater efficiency, especially at small scales [2,35,36]. As a step toward designing efficient flapping-wing vehicles, several studies [7,13,23,32,44–46,49,52] explored and investigated the characteristics of these flying animals.

Although it is well known that natural flyers exploit a variety of mechanisms and aerodynamic aspects to control and maneuver their flights, experimental observations do not enable a complete understanding of the physical aspects and dynamics of flapping flight. As such, there is a need to model the unsteady aerodynamic aspects of flapping-wing vehicles. Computational modeling and simulation are necessary to evaluate the performance requirements associated with flapping flight and to identify the relative impact of different design parameters (e.g., flapping parameters, shape characteristics). Several computational modeling strategies that are based on variable fidelity physics have been reported in the literature [3,4,11,15,21,26,33,38,50,53]. Willis et al. [51] developed a multifidelity computational framework that involves a combination of potential flow models and a Navier–Stokes solver. They showed how the use of different levels of geometric and physical modeling fidelity can be exploited to ease the design process of flapping wing systems. Certainly, the higher-fidelity Navier–Stokes simulations incorporate a more complete physical model of the flapping flight problem, however, the extensive computational resources and time associated with the use of these tools limit the ability to perform optimization and sensitivity analyses in the early stages of MAV design. Thus, to alleviate this burden and enable rapid and reasonably accurate exploration of a large design space, it is fairly common to rely upon a moderate level of modeling fidelity to traverse the design space in an economical manner [15,39,41]. As such, several research efforts have considered the use of the unsteady vortex lattice method (UVLM) for the design of avian-like flapping wings in forward flight [10,13–15,26,37,38,48].

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Nomenclature

$\boldsymbol{A}$	influence matrix
$\boldsymbol{\Gamma}$	vorticity circulation
$\boldsymbol{V}$	velocity
$N_{i,p}$	B-spline basis functions of degree p
$M_{j,q}$	B-spline basis functions of degree q
$\boldsymbol{\mathcal{X}}$	knot vector
$\boldsymbol{\mathcal{Y}}$	knot vector
ξ	parametric coordinate in the B-spline representation
β	parametric coordinate in the B-spline representation
$\boldsymbol{P}_i$	control point
$\boldsymbol{C}$	B-spline curve
$\boldsymbol{S}$	B-spline surface
ϕ	flapping angle
A_ϕ	amplitude of the flapping angle
ω	flapping frequency
κ	reduced frequency
U_∞	free-stream velocity
c	wing's chord
b	wing's span
N_{ts}	number of time step per flapping cycle
C_L	lift coefficient
C_T	thrust coefficient
η	propulsive efficiency
L	lift force
T	thrust force
A	wing's area
θ	distortion angle
P	aerodynamic power
ρ	fluid density
$\boldsymbol{x}$	vector of perturbations introduced to the locations of the control parameters
X	closed and bounded set
N_{DV}	number of design variables
$\overline{(.)}$	time-averaged quantity over a flapping cycle
$(.)^*$	normalized quantity

Subscripts

wi	wing
wa	wake
n	normal component
bl	baseline case
cr	critical angle

Superscripts

wi–wi	wing–wing influence
wa–wi	wake–wing influence
t	time
Δt	time step

The present work is concerned with shape optimization of flapping wings in forward flight. Our approach to the problem combines a local gradient-based optimizer with UVLM. The optimizer is based on the globally convergent (to a stationary point, not necessarily a global solution) method of moving asymptotes (GCMMA) [42,43]. It belongs to the class of sequential approximate optimization methods and employs conservative convex separable approximations for solving inequality constrained nonlinear programming problems. It searches by generating approximate subproblems at each iteration, in which both the objective and constraint functions are replaced by convex functions. The construction of these approximating functions is based mainly on gradient information at the current iteration point in the design space.

The unsteady vortex lattice method computes the forces generated by pressure differences across the wing surface resulting from acceleration- and circulation-based phenomena. This accounts for unsteady effects such as added mass forces, the growth of bound circulation, and the wake. Since the formulation of UVLM requires that fluid leaves the wing smoothly at the trailing edge (through imposing the Kutta condition), it does not cover the cases of flow separation at the leading-edge and extreme situations where strong wing–wake interactions take place. In other words, UVLM applies only to ideal fluids, incompressible, inviscid, and irrotational flows where the separation lines are known a priori. Nevertheless, Persson et al. [26] showed through a detailed comparison between UVLM and higher-fidelity computational fluid dynamics simulations for flapping flight that the UVLM schemes produce accurate results for attached flow cases and even remain trend-relevant in the presence of flow separation. As such, in [26] the authors recommended the use of an aerodynamic model based on UVLM to perform preliminary standard design studies of flapping wing vehicles, specifically, for cruise configurations where there is no flow separation nor substantial wing–wake interactions that would degrade the performance of the vehicle. The reduced fidelity afforded by UVLM makes its associated simulation time for each flow configuration is on the order of minutes on a desktop.

In this paper, we seek to identify a set of optimized shapes that maximize the propulsive efficiency of a flapping wing under several constraints. We explicitly include lift, thrust, and area constraints. The wing geometry is described using B-spline parameterizations, which are the standard technology for describing geometries in computer-aided design (CAD) [6,9,28,31]. This choice simplifies the design optimization process by enabling mesh generation directly from the CAD model. The associated basis functions can be used to smoothly discretize wing shapes with few degrees of freedom. The location of the control points constitutes the design variables. Results suggest that changing the shape yields significant improvement in the flapping wings performance. This study is our first step towards constructing a unified framework that will facilitate the design of engineered flying systems. An important contribution of this work is the methodology described in Section 4.2 to achieve mesh independent UVLM simulation results.

The remainder of the paper is organized as follows: first, the aerodynamic model used to simulate flapping flights is detailed. The B-spline representation that defines the wing geometry is then introduced, followed by the formulation of the shape optimization problem. The optimal shapes obtained for different flight configurations are reported and insights of the trailing and leading edges curvatures, camber, and aspect ratio effects on the flapping flight performance are presented. The work concludes with a discussion of the main features of the optimal shapes.

2. Aerodynamic modeling of flapping wings

We use a three-dimensional version of the unsteady vortex lattice method (3D UVLM) to simulate the aerodynamic response of flapping wings in forward flight. This aerodynamic tool is capable of simulating incompressible and inviscid flow past moving thin wings and capturing the unsteady effects of the wake, but not the viscous effects, flow separation at the leading-edge, and extreme situations with strong wing–wake interactions. Unlike standard computational fluid dynamics schemes, this method requires meshing of the wing planform only and not of the whole flow