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Reduced-order modeling and feedback control of a flexible wing at low Reynolds numbers

Massimiliano Nardini *, Simon J. Illingworth, Richard D. Sandberg

Department of Mechanical Engineering, University of Melbourne, Parkville 3010, VIC, Australia

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ABSTRACT

A state-space reduced-order model for the lift generated by the unsteady deflection of a two-dimensional flexible wing is presented. The wing's deflection is decomposed using a truncated Fourier series in the contribution of single deflection modes; the global lift is then obtained using superposition. The presented model is an extension of the model introduced in Brunton et al. (2013) for rigid pitching and plunging. A realization of the model is obtained using lift pulse responses from Direct Numerical Simulation (DNS) at a Reynolds number of 100. The performance of the deflection modes are discussed from a feedback control point of view and controllers for mode 1, mode 2 and pitching are designed using loop-shaping techniques and tested, comparing the results with DNS. The performance limitations of mode 1 and mode 2 are overcome by using a multi-input controller that uses both deflection modes together. Finally, the controllers are tested in an off-design condition at a higher Reynolds number of 1000.

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1. Introduction

A correct representation of the unsteady aerodynamic loads generated by the interaction of an object with a flow is pivotal in the design and the optimization of a variety of modern engineering applications. Small-scale bio-inspired aerodynamics represents one of the most discussed and challenging examples. Reduced-size flyers such as insects, birds or artificial unmanned micro-air vehicles (MAVs) are capable of performing agile maneuvers because, due to their small-scale, the inertia forces are of the same order of magnitude as the aerodynamic loads, and, consequently, the aerodynamic and the flight dynamic time scales are comparable. On the other hand, their reduced size makes small flyers sensitive to external disturbances such as gusts. Therefore, for small-scale flyers the unsteady aerodynamics generated by the interaction of the wing and the airflow plays a pivotal role in enabling fast maneuvers and responding to disturbances (Shyy et al., 2013).

Many natural flyers, such as bats, present flexible wings whose shape constantly changes (both actively and passively) during flight, significantly improving aerodynamic performance (Song et al., 2008; Kang et al., 2011). For such flyers, wing flexibility and wing morphing, combined with flapping flight, play a fundamental role in the generation of lift and thrust, as well as in the rejection of external disturbances (Yu and Guan, 2015; van Oorschot et al., 2016; Lentink et al., 2007; Carruthers et al., 2007). Hence, the idea, investigated in the present work, of exploiting the extra degrees of freedom provided by flexibility to achieve desired aerodynamic performance and to improve controllability and maneuverability of small-scale air vehicles.

In order to address the problem of controllability and maneuverability of a wing at low Reynolds numbers, a framework that is able to accurately represent the unsteady aerodynamics loads acting on the wing is necessary. Small-scale aerodynamics of flapping flight for flexible wings is a challenging and multi-disciplinary topic and it is characterized by complex

* Corresponding author.
E-mail address: mnardini@student.unimelb.edu.au (M. Nardini).

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unsteady nonlinear fluid-dynamics phenomena such as added-mass effects, leading and trailing edge vortex shedding and flow separation (Shyy et al., 2013; Ansari et al., 2006; Ho et al., 2003). Flapping flight is also a fluid–structure interaction problem, since the aerodynamic loads are generated by the unsteady motion of a wing immersed in a fluid. Due to the complexity of the phenomena involved, high-fidelity Direct Numerical Simulation (DNS) has been proven to be a powerful tool to investigate the unsteady aerodynamics of rigid and flexible moving wings at low Reynolds numbers and it represents a valid alternative to wind tunnel experiments. DNS is a high-fidelity framework, but it is also computationally expensive and does not offer insights on the relationship between design variables and performance of the wing. From an engineering design-oriented point of view, an investigation of the mechanism of flapping flight does not only have to understand the underlying physics, but has to obtain general relations that can be used to design flapping-wing MAVs with desired performance. The goal is to link performance-related aerodynamic parameters of interest such as, for example, lift, drag and thrust, to design variables such as flapping frequency, wing kinematics or wing flexibility. Hence, there is need of a reduced-order aerodynamic model that is able, under certain assumptions, to preserve the accuracy of the DNS in predicting the aerodynamic loads generated by the deflection of a flexible wing, significantly reducing the computational cost.

A comprehensive literature overview of unsteady flapping flight, including a discussion about the main aerodynamic phenomena related to flapping flight, is presented in Ansari et al. (2006). Brunton et al. (2013) also includes references about CFD and experiment-based models, as well as nonlinear models. A comparison of modern aerodynamic models is presented in Taha et al. (2014), and a discussion is provided on the complexity of the considered models in terms of degrees of freedom and flow characteristics related to flapping-flight that they are able to capture. The choice of the model depends on the problem of interest and on the flow characteristics that we want to represent. For small-scale aerodynamics and, in general, for applications that present large accelerations of a structure in the flow, such as aeroelastic problems, agile maneuvers or gusts response, unsteady aerodynamics effects can dominate and thus a steady or a quasi-steady model (based on the assumption that maneuvers are so slow that the flow is always in an equilibrium state) is not able to represent the unsteady contributions to the lift given by acceleration-related forces (Brunton et al., 2013). An unsteady model is necessary.

In the category of unsteady analytical models, the models of Wagner (1925) (indicial response) and Theodorsen et al. (1935) (lift and momentum response of a two-dimensional rigid flat plate to sinusoidal pitching and plunging) have been widely used for aerodynamic and aeroelastic studies (including fixed-wing and rotary-wing applications, as discussed in Leishman (2002b)). Both models are derived analytically using the small perturbations theory applied to incompressible, potential flows. Their accuracy is thus limited by the hypothesis of inviscid flow and they are not able to represent viscosity-related effects. Although the models of Wagner and Theodorsen remain a fundamental reference for many unsteady applications, they are not high-fidelity enough to be applied to low Reynolds flapping-flight.

With the help of high-fidelity simulations and through a system identification procedure, it is possible to obtain an unsteady aerodynamic model, based on the Theodorsen model, that easily takes into account aerodynamic loads generated by pitching and plunging of a two-dimensional wing. Such a model, introduced in Brunton et al. (2013) and extended in Brunton et al. (2014) to include parametrization of the pitching axis location and the contribution of surge, outperforms the Theodorsen model because it is also able to capture the effects on the aerodynamic loads of the wing given by viscosity-related phenomena, including unsteady transients and the presence of the wake. The model is also low order and in state-space form, hence compatible with a feedback control design framework. The model is linear and it is obtained by linearizing the Navier–Stokes equations about an equilibrium condition, and consequently it does not take into account the contribution to the aerodynamic loads from nonlinear effects such as flow separation or leading-edge vortex shedding, limiting its predictive capability to flows that present weak nonlinearities.

The main contribution of the present work is the extension of the state-space model introduced by Brunton to include the effect of the flexibility of the wing on the generation of the unsteady aerodynamic loads. The wing deflection is decomposed into single deflection modes using a truncated Fourier series; each mode represents an input to the model, and the contribution of the global deflection on the aerodynamic forces is reconstructed using linear superposition of effects. We present the mathematical formulation of the extended reduced-order model with the inclusion of the wing's flexibility, as well as the system identification procedure used to obtain the coefficients of the models from lift pulse responses generated via DNS. We will mainly focus our attention on the lift of the wing, even though many of the concepts can be generalized to other parameters such as pitching moment and drag. The contributions to the lift from pitching, deflection from odd modes and deflection from even modes are considered individually, in order to highlight the mechanisms of lift generation for each category and to obtain useful information for lift feedback control using rigid motion and flexibility.

The novel state-space model is used to understand how the flexible wing can be actuated in order to achieve good aerodynamic performance in terms of reference lift tracking and disturbance rejection. This is achieved by designing closed-loop controllers for the degrees of freedom of the wing using feedback control theory, especially focusing on rigid pitching and on the first two deflection modes. The main discussion will focus on the performance limitations associated with actuating the wing using the first two deflection modes individually. We will see how the present reduced-order models offer insights on how to overcome these limitations by introducing a multi-input single-output framework and actuating the wing using a combination of modes simultaneously. From a computational perspective, the performance of the controllers is tested by comparing the lift step response from reduced-order model and DNS. A test case with a disturbance in the form of a convected vortex is also used to compare the disturbance rejection capabilities of each controller. All the tests are performed at Reynolds 100 (the controller's design condition), and are repeated for Reynolds 1000, in order to investigate the robustness of the controllers and their applicability to off-design cases.

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