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Reduced-order thrust modeling for an efficiently flapping airfoil using system identification method

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ABSTRACT

This paper presents a novel reduced-order model (ROM) of thrust for an efficiently flapping airfoil using system identification method. A NACA0012 airfoil pitching and plunging at a low Reynolds number of 40,000 is used to test the ROM. Unlike conventional aerodynamic models which introduce the airfoil displacements directly as inputs, this study utilizes the quadratic-terms of displacements as inputs to overcome the frequency-doubling effect of propulsion forces over the oscillation frequency. The autoregressive with exogenous input (ARX) model is adopted to construct mappings between the input and output data. Meanwhile, a heuristic searching strategy is applied for sensitivity analysis of the input variables and the optimal input-vector is determined. The ROMs are then validated in the time domain by comparing their predicted thrust responses with those of CFD simulations under either harmonic or random excitations. Results show that the proposed ROMs can accurately predict the thrust responses of a flapping airfoil with arbitrary motions from moderate to small oscillation amplitudes where a leading-edge vortex does not develop, while the computational cost can be reduced by nearly 2 orders of magnitude compared to the high-fidelity CFD simulation method. Finally, the validity of ROMs is mostly clearly shown by using them for propulsive characteristic analysis of a flapping airfoil. Excellent qualities of the ROMs indicate that they can be used for flapping mode optimization and flapping flight control in future research.

1. Introduction

Flapping flight has many aerodynamic advantages over fixed or rotary wing flight at low Reynolds numbers, and therefore has received increasing research attention in micro air vehicle (MAV) field. Without exception, birds flying in the sky and fish swimming underwater all adopt the flapping wing as propulsion. It is their excellent flying and swimming abilities inspire the exploration and consideration of flapping wing propulsion. For a comprehensive review of the research on various aspects of flapping flight, one can refer to review articles of Ho et al. (2003), Platzer et al. (2008) and Shyy et al. (2010).

Mechanism of flapping propulsion was first investigated by Knoller (1909) and Betz (1912). They found that the flapping motion of an airfoil produces an effective angle of attack resulting in a normal force vector of which the component in forward direction is thrust. This phenomenon was also interpreted by von KÁRMÁN and Burgers (1935) via investigating the position and direction of wake vortices generated by a flapping wing. Moreover, Garrick (1937) deduced a linear dynamics model of thrust using Theodorsen's inviscid and incompressible potential flow theory. Extensive experiments have also been carried out to study the dynamics of flapping airfoils (Anderson et al., 1998; Mazaheri and Ebrahimi, 2011; Heathcote et al., 2012; Baik et al., 2012; Akkala et al., 2015).

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Nomenclature

c	Chord length (characteristic length)
V_∞	Free-stream velocity
f	Oscillation frequency
$h(t)$	Plunge displacement normalized by chord length c
h_0	Plunge amplitude normalized by chord length c
$\dot{h}$	plunge velocity
$\theta(t)$	Pitch angle
θ_0	Pitch amplitude
$\dot{\theta}$	Pitch velocity (angular velocity)
$\alpha(t) = \theta(t) - \tan^{-1}(\frac{1}{V_\infty}\frac{dh(t)}{dt})$	The instantaneous angle of attack of the airfoil
$\alpha^{\max}$	Maximum of the instantaneous angle of attack
$\omega = 2\pi f$	Angular frequency
ϕ	Phase angle between the pitching and plunging motion
A_{TE}	Amplitude of the airfoil trailing-edge net vertical motion (peak to peak)
$k = \omega c/2V_\infty$	Reduced frequency
$St = \frac{fA_{TE}}{V_\infty} = \frac{kA_{TE}}{\pi c}$	Strouhal number
C_L	Lift coefficient
C_T	Thrust coefficient
C_P	Input power coefficient
$\overline{C}_T = \frac{1}{T}\int_0^T C_T(t)dt$	Time-averaged thrust coefficient
$\overline{C}_P = -\frac{1}{T}\int_0^T [C_L(t)\dot{h}(t) + C_M(t)\dot{\theta}(t)]dt$	Time-averaged input power coefficient
$\eta = \frac{\overline{C}_T}{\overline{C}_P}$	Propulsive efficiency

Among them, Anderson et al. (1998) systematically studied the flow features and wake patterns of a harmonic oscillation airfoil and showed that the propulsive efficiency could reach up to 87% under certain wake patterns. They pointed out that the high efficiency is due to the formation of anti-Karman vortex street caused by the interaction between leading-edge vortex and trailing vortices. Baik et al. (2012) experimentally studied the flow field topology, leading-edge vortex and unsteady aerodynamic response characteristics of a flapping airfoil by fixing the time history of effective angle of attack and varying the oscillation frequency and amplitude. They showed that the effective angle of attack and the reduced frequency determine the structure of the flow field, while the Strouhal number (St) is the most important parameter affecting the aerodynamic forces. In addition, Heathcote et al. (2012) experimentally studied the elastic effects on the flapping wing propulsion, and they found that the thrust and propulsive efficiency of flexible wings are higher than that of rigid wings.

With advances in computer science and computational methods, computational fluid dynamics (CFD) has been widely used to study the dynamics of flapping airfoils. Numerous CFD simulations have been carried out and the rich numerical results now have provided a theoretical basis for the analysis and design of flapping-wing drive system. For instance, Tuncer et al. (1998) and Isogai et al. (1999) numerically investigated the dynamic stall phenomenon of a flapping airfoil. Miao and Ho (2006) and Tian et al. (2013) studied the effect of flexure on aerodynamic performance and propulsive efficiency of flapping flexible airfoils. Ashraf et al. (2011) investigated the effects of Reynolds number, thickness and camber on flapping airfoil propulsion. Young and Lai (2004, 2005, and 2007) conducted a wide range of numerical studies, focusing on the lift, thrust, propulsive efficiency and wake patterns. They systematically compared the CFD results with those of experiments, linear potential flow theory and unsteady potential plate method, and ultimately they pointed out the validity and accuracy of these models of different physical levels. In addition, Yang et al. (2005) computed the flows over a flapping airfoil by solving the Euler equations and showed that the computational results depart from the experimental results when the leading-edge vortex appears and become strong enough to interfere with the trailing-edge vortices.

Furthermore, many researchers have performed optimizations based on CFD solver aiming at improving the thrust or propulsive efficiency of a flapping airfoil. For instance, Young et al. (2006) performed a Gradient-descent based optimization against the phase angle between the pitching and plunging motion showing a phase angle between $\phi = 75^\circ$ and 85° for best propulsive efficiency. Culbreth et al. (2011) conducted several optimizations for 2-D airfoils and 3-D wings undergoing periodic motions by coupling high-fidelity CFD solvers with a gradient-based optimization algorithm. They pointed out that pitching and twisting can significantly improve the attainable propulsive efficiency, delay the onset of leading-edge separation, and that the maximal propulsive efficiency appears to operate at the limit of leading-edge separation. Soueid et al. (2009) optimized the motions of a flapping NACA0012 airfoil at a low Reynolds number Re=1100 by using sensitivity functions. Tuncer and Kaya (2012) utilized a numerical optimization method based on the steepest ascent for the maximization of the thrust and/or propulsive efficiency of a single flapping airfoil. Their optimization results showed that high thrust values may be obtained at the expense of propulsive efficiency, and that high propulsive efficiency is usually acquired at relatively low effective angle of attack conditions where large-scale vortex formations at the leading edge are prevented.

High-fidelity numerical simulations can provide detailed spatial and temporal information of the flow field which can deepen our understanding of flapping aerodynamics. However, the computational cost of numerical method is still very large, making it far too computationally expensive to be utilized to multi-variable optimization, real-time simulation and flapping flight control. Hence, it is desirable to establish a reduced-order model (ROM) representation for the CFD-based aerodynamic system to replace the CFD solver for the calculation of aerodynamic responses. Recent years have witnessed increasing interest in ROM approaches for aerodynamic systems and significant progresses have been achieved. Compared with the direct CFD simulation method, ROM method can significantly reduce the dimensions or orders of the full system which results in reduced computational cost, so it can be easily applied to the analysis, design and optimization of multi-point systems (Lucia et al., 2004).

The two most used Reduced-order modeling approaches are: the proper orthogonal decomposition (POD) and system identification method. POD provides a tool to construct a model based on an optimal basis required to represent a dynamic system (Lucia and Beran, 2004). Lewin and Haj-Hariri (2005) established a ROM for a heaving airfoil by using POD-Galerkin method. They