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Engineering Notes

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Stability in Ornithopter Longitudinal Flight Dynamics

John M. Dietl* and Ephrahim Garcia†
Cornell University, Ithaca, New York 14853

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I. Introduction

PRACTICAL ornithopter designs have long eluded the aerospace engineering profession as engineers have systematically improved performance in other aerodynamic regimes. The design of flapping-wing vehicles has progressed, however, leaving a rich history of improvement and imagination. Leonardo da Vinci provided an early impetus to powered flight, misleading engineers for centuries from the simpler fixed-wing design that has proven practical [1]. Alphonse Penaud's rubber-band powered model showed the possibility of powered ornithopter construction [2]. After the Wright brothers' famous flights, ornithopter research was mostly abandoned in favor of the more promising fixed-wing designs. Certain inventors such as Alexander Lippisch and Percival Spencer [2], however, continued developing models for manned and unmanned flight. Cox et al. worked on piezoelectrically actuated ornithopters with novel control schemes [3]. Finally, DeLaurier successfully built a piloted ornithopter and it flew for 14 s in 2006 [4].

A major obstacle to these pursuits has been the counterintuitive aerodynamic behavior of air around moving wings. Wagner [5] and Theodorsen [6] provided an early mechanism for fixed wings in flutter which has been applied by Jones [7] and DeLaurier [8] to accelerating wings. DeLaurier expanded this to cover the root-flapping wings of an ornithopter. That particular characterization is not difficult to implement for practical computation, and it was compared to actual flapping models with success [8,9]. Whether these methods, based on potential flow, are applicable for micro-air-sized vehicles is undetermined, however.

Entomologists and their cohorts working along a different vein have produced aerodynamic models for insect flight. Weis-Fogh and Jensen [10] applied quasi-steady analysis to analyze hovering insects and produced estimates of the lift and drag coefficients of insect wings. Ellington [11] produced a seminal review of insect-flight aerodynamics, mainly using this quasi-steady viewpoint, but with disturbingly high lift coefficients [12]. Computers became sufficiently powerful during the 1990s to allow two-dimensional time-dependent simulation of oscillating airfoils, led by Wang [13] and Russel and Wang [14]. Several 3-D approaches have also been attempted, albeit with a deficiency in accuracy requiring excessive computing time [13]. During this same time, experiments with mechanical wings have been developed to confirm these computational results for a hawk moth and a fruit fly [15], providing helpful visualization as well. Finally, Wang et al. [16] provided a quasi-steady approximation to their numerical simulations that will be further outlined in this paper.

The problem this paper addresses is that of designing a flapping-wing micro air vehicle: in particular, we want to know how it will fly. There exists little literature that provides a practical outline of the ornithopter design process, which includes predicting such things as vehicle configuration, power requirements, stress–strain analysis for the wings and internal structures, proper wing kinematics for maneuvering, actuator selection, and control system design. Here, we concentrate on dynamically modeling ornithopter flight as a function of selected vehicle geometry, control surface deflections, and wing kinematics. The authors have developed a coupled vehicle dynamics/aerodynamics model for longitudinal flight, which is then used to analyze flight dynamics patterns for predetermined wing kinematics functions, and is used to study trim states for sustained forward flight. Similar to the work of Taylor et al. [17], this work studies the stability of flapping-wing vehicles. Taylor applies continuous-time linear time-invariant averaging methods to study dragonfly flight dynamics, and this produces eigenvalue estimates for the averaged system. Because of the much faster time scale of dragonflies' flapping frequency compared with the characteristic time scales of the dragonflies' flight dynamics modes, the flight dynamics are largely uncoupled from the flapping dynamics and the averaging method works excellently. This paper studies larger ornithopters where the flapping frequency's time scale is closer to the characteristic time scale of the vehicle's dynamic modes, thereby making averaging methods less applicable. To analyze an ornithopter with significantly more motion coupling between body dynamics and wing beating, the authors use a method of limit-cycle analysis (accounting for nonlinear dynamics effects) to produce eigenvalue calculations independent of flapping time scales.

II. Modeling

To design ornithopter features to provide enough lift to overcome weight and to produce enough thrust to overcome drag, the authors have modeled a standard ornithopter configuration consisting of a fuselage, a pair of symmetric wings, and a standard airplane empennage (Fig. 1). The empennage contains control authority over the rudder and elevator, but there are no ailerons on the wings (the longitudinal assumption makes this moot, but this will be more significant with further analyses, as DeLaurier's ornithopter relies on yaw-roll coupling in place of ailerons). The ornithopter simulated by the authors has a wingspan of 0.72 m. The vehicle's mass is 0.12 kg, with each wing 0.0079 kg. The vehicle's center of mass and tail's quarter-chord line are 9.5 and 30.5 cm rear of the wings' quarter-chord line. The wings' planform is 803 cm^2 and the tail's planform is 209 cm^2.

The wings are attached to the fuselage via a hinged joint, allowing two rotational degrees of freedom (Fig. 1). The first, and most prominent, is the vertical plunging (or heaving) of the wings $\phi(t)$. This is the characteristic oscillating dihedral motion of avian forward flight, requiring the most energy of all the controlled motions. All other kinematics on the ornithopter are referred to this oscillatory

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*Graduate Student, Sibley School of Mechanical & Aerospace Engineering, 226 Upson Hall. Student Member AIAA.

†Associate Professor, Sibley School of Mechanical & Aerospace Engineering, 224 Upson Hall. Member AIAA.