LOW-ORDER MODELING OF BIOLOGICALLY-INSPIRED FLIGHT MECHANICS

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Summary A low-order phenomenological model for the unsteady and non-linear aerodynamics of biologically-inspired flight is presented. The model is based on the motions of a small number of point vortices with time-varying strengths, coupled with the dynamics of a wing, which may be rigid or elastic. Vortex strengths are determined by the Kutta condition, and are frozen once they meet certain physical criteria. The vortex motion is determined by an evolution equation derived from a principle of impulse continuity at the instant of freezing strength. The accuracy of the model is evaluated against several two-dimensional model problems, including rapid pitch-up of a rigid wing and steady translation of rigid and flexible wings constant angle of attack.

MOTIVATION

Biological mechanisms of flight are generally characterized by flapping flexible wings that shed vorticity from all salient edges, and the flight performance and agility are determined by the coupled non-linear dynamics of the wing and vortex structures. This interaction, significantly more complex than in classical aerodynamics of fixed wings, has thus far eluded simple mathematical description. However, such a simple model is useful, if not essential, for developing flight control strategies in vehicles designed to have the same agility of the creatures from which their are inspired. This work presents ongoing efforts to develop a low-order physics-based model for these biological flight mechanics. The model is predicated on the formation and dynamics of coherent vortex structures, represented here in two-dimensional flows as a small number of point vortices with time-varying strengths. This approach, inspired from early work on leading-edge vortex shedding in delta wing aircraft [1], has also been successful in predicting wakes of flags, falling cards and airfoils in unsteady motion [2, 3, 4].

METHODOLOGY

In the two-dimensional problems analyzed in this work, a point vortex is released from each edge of an infinitely-thin plate. The inviscid motion induced by the rigid plate motion and vortices is derived by mapping the plate to a circle (see Figure 1(a)). (For a flexible plate, we rely on a boundary element method rather than a mapping.) Each point vortex strength is determined by the Kutta condition enforced at the edge from which the vortex was released. When the strength has reached some criterion (e.g. an extremum), it is frozen at the current value and allowed to propagate with the Kirchhoff velocity. While it has variable strength, however, the vortex moves according to an evolution equation derived from a principle of impulse matching: when the vortex strength is frozen, we insist that the impulse and its time derivative remain continuous, to ensure that there is no jump in the force exerted on the plate. This principle uniquely determines the evolution of the vortex. The high-fidelity simulations reported in this work are carried out with the viscous vortex particle method [5].

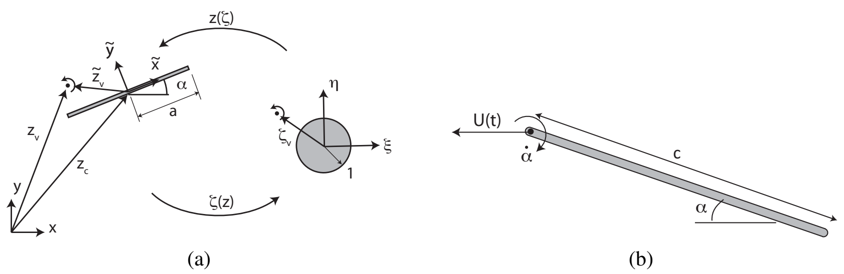

Figure 1: (a) Mapping of rigid plate geometry to circle. (b) Schematic of wing in rectilinear motion undergoing pitch-up.

RESULTS

Rapid pitch-up of a flat plate to large angle of attack

For this case, depicted schematically in Figure 1(b), the plate of length c is pitched steadily upward at angular velocity $\dot{\alpha}_0$ to 90 degrees while translating rectilinearly at constant speed U_0. The resulting flow for a pitch rate $K = \dot{\alpha}_0 c/(2U_0) = 0.7$, shown in Figure 2(a),(c), consists of coherent vortex structures shed from both edges, and is well represented by two point vortices; the high-fidelity simulations are conducted at Reynolds number $U_0 c/\nu = 1000$. The force components generated by this motion are shown in Figure 2(b),(d). The agreement between the high-fidelity simulations (which relies on over 1 million degrees of freedom) and the low-order model (which relies on 6 degrees of freedom) is good, though the

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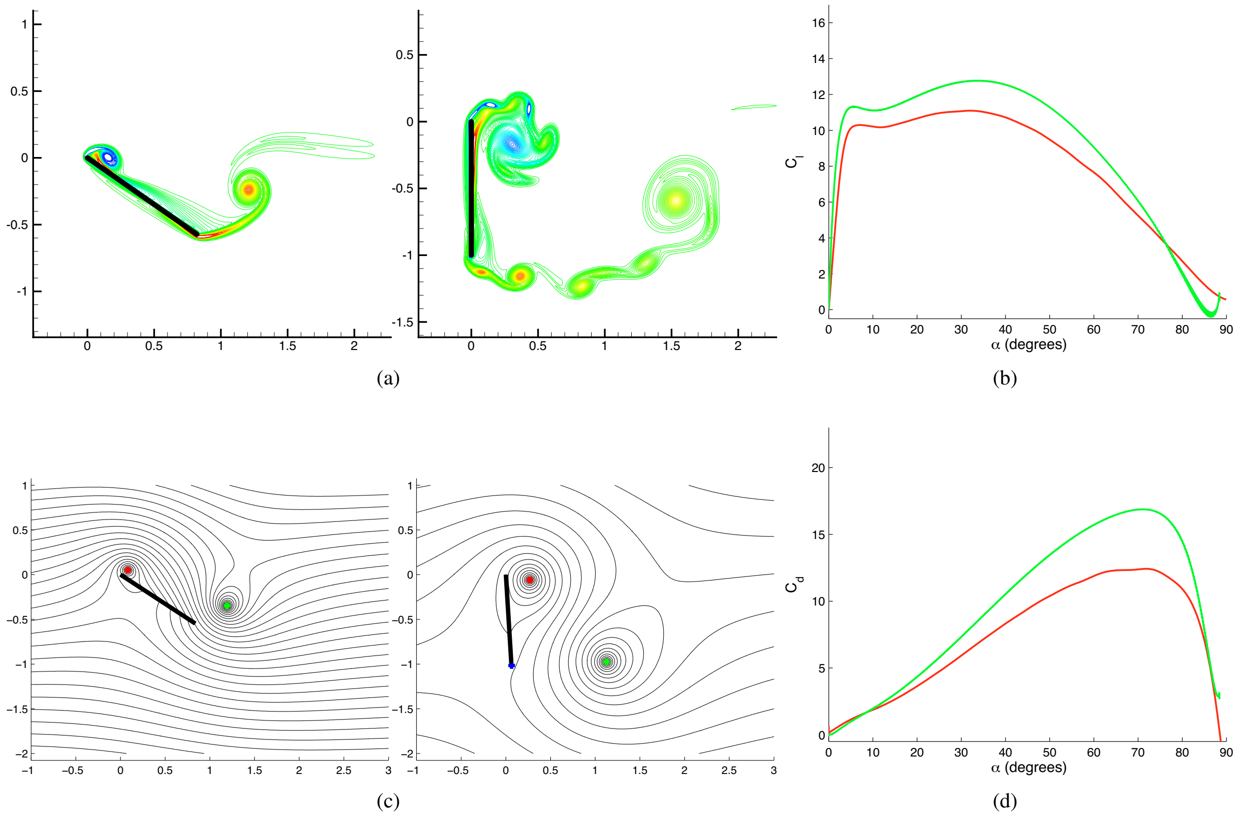

Figure 2: Flow field of perching motion for $K = 0.7$ at $\alpha = 33°$ (left column) and $90°$ (middle column). (a) Vorticity field of VVPM simulation; (c) streamlines from low-order model, with point vortex locations denoted with colored circles. (b) Lift and (d) drag coefficients. Low-order model (—); VVPM simulation (—).

low-order model systematically over-predicts the force. We get similar results at other pitch rates, though the leading-edge vortex tends to lose coherence as pitch rate decreases, which reduces its importance to force generation.

Impulsive translation of a wing at fixed angle of attack

We have also explored the simpler problem of an impulsive start of rigid and elastic flat plates at fixed angle of attack. In this problem, it is possible to investigate the conditions for which the leading-edge vortex makes an important contribution to the force generation. For example, at small angles ($\lesssim 15°$) of a rigid plate, we get better agreement between high-fidelity simulation and model if we suppress vortex shedding from the leading edge. We will present a comprehensive study for a full range of angles of attack. We will also present the capabilities for modeling a plate with simple flexibility (two rigid components connected by a torsion spring) undergoing the same motion. The behavior of this case is determined by the coupled dynamics of the elastically-deforming spring and alternating vortex shedding from the edges.

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