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Role of wing morphing in thrust generation

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Abstract In this paper, we investigate the role of morphing on flight dynamics of two birds by simulating the flow over rigid and morphing wings that have the characteristics of two different birds, namely the Giant Petrel and Dove Prion. The simulation of a flapping rigid wing shows that the root of the wing should be placed at a specific angle of attack in order to generate enough lift to balance the weight of the bird. However, in this case the generated thrust is either very small, or even negative, depending on the wing shape. Further, results show that morphing of the wing enables a significant increase in the thrust and propulsive efficiency. This indicates that the birds actually utilize some sort of active wing twisting and bending to produce enough thrust. This study should facilitate better guidance for the design of flapping air vehicles.

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Keywords bird flight, thrust generation, wing morphing

Birds can fly by gliding,[1,2] soaring,[3] or flapping,[4,5] depending on atmospheric conditions and the desired flight path. During gliding, the wings are held out to the side of the body and do not flap. The aerodynamic forces that hold the bird up in the air are similar to those generated on a fixed wing.[6] Soaring differs from gliding flight in that the bird maintains its height relative to the ground and can climb even without flapping its wings. One way to accomplish this is to benefit from a rising air current. To generate sufficient aerodynamic forces for flight, and overcome gust and turbulence in the incoming freestream, birds can also rely on flapping motion whereby they reciprocate their wings, moving them up and down. The flapping motion consists of two half-strokes: a downstroke, which produces most of the useful lift and thrust, and an upstroke, which can also provide some thrust, depending on the geometric properties of the bird's wing.

To date, understanding the role of wing motions and morphing in bird flight has been based on experimental observations. By combining these observations with simplified aerodynamic models, several researchers were able to characterize flight kinematics of birds. A detailed review of the aerodynamic models used to understand flight dynamics of birds and insects has been recently presented by Taha et al.[7] They noted the observation by Holst and Kuchemann[8] who observed that maximum thrust is obtained when the phase shift between the plunge and pitch motions is

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set at 90°. Parry[9] used this observation to calculate the maximum thrust caused by plunging oscillations of tails of whales. Taha et al.[7] gave more examples of observed flight dynamics and their relation to aerodynamic forces. Although connecting experimental observations with simplified aerodynamic models can be helpful in assessing specific flight mechanisms, we believe that exploring the dynamics of birds' flight through higher fidelity numerical simulations of the flow and its interaction with the wing motions can provide a more substantial characterization of the physics and dynamics associated with such flight. Such an understanding and characterization should facilitate better guidance for the design of engineered flying systems.

The objective of this effort is to determine the role of wing morphing in the generation of thrust and lift forces. To this end, we simulate the flow over morphing wings that have the characteristics of two different birds, namely the Giant Petrel and Dove Prion. We consider a prescribed symmetric flapping motion about the wing root subjected to a freestream velocity and place the wing root at a fixed angle of attack α. Then, we use active shape (spline-based) morphing to optimize the flight performance of these two birds. By optimizing the flight performance, we mean reducing the power required for their forward motion under the constraint of generating a minimum lift that is set equal to the bird's weight. The simulations and the optimization exercise are designed to determine the relation between morphing, aerodynamic forces, and flight efficiency.

To compute the aerodynamic forces and power, we use a three-dimensional version of the unsteady vortex lattice method (UVLM) to simulate the flow over flapping wings that have the characteristics of the Giant Petrel and Dove Prion (see Table 1). This allows us to investigate the relation between morphing, aerodynamic forces, and flight efficiency. The UVLM applies only to incompressible, inviscid flows where the separation lines are known a priori. Furthermore, the current implementation of UVLM does not cover the cases of flow separation at the leading-edge and extreme situations where strong wing-wake interactions take place. In spite of these restrictions, the use of UVLM remains adequate for the application of our interest.[10–16]

A detailed implementation and validation for the use of the UVLM on flapping flights are presented by Ghommem et al.[12] In summary, the UVLM simulation of a flapping wing includes the following. The wing surface is discretized into a lattice of vortex rings. Each vortex ring consists of four short straight vortex segments, with a collocation point placed at its center. A no-penetration condition is imposed at the collocation points; that is, the normal component of the velocity due to wing-wing interactions, wake-wing interactions, and free-stream velocities is assumed to vanish at each collocation point. The Biot–Savart law is used to compute velocities in terms vorticity circulations. The wake vorticity is introduced by shedding vortex segments from the trailing edge. These vortices are moved with the fluid particle velocity and their individual circulation remains constant. The vorticity circulation strength of the wakes obtained for a rectangular flapping wing is shown in Fig. 1. Examining the wake pattern and vorticity distribution is helpful to gain insight into the generation of aerodynamic quantities. The pockets of highest circulation are observed in the wake aft of the flapping wing during the downstroke. The pressure is evaluated at each collocation point based on the unsteady Bernoulli equation and then integrated over the wing surface to compute the aerodynamic forces, power, and propulsive efficiency.[12,13]

For each bird, hypothetical rectangular and swept/tapered wings are considered in order to examine how the wing geometry influences the flight performance. The latter shape is based on