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Experimental study of wings undergoing active root flapping and pitching

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ABSTRACT

This paper presents the results of experiments carried out on mechanical wings undergoing active root flapping and pitching in the wind tunnel. The objective of the work is to investigate the effect of the pitch angle oscillations and wing profile on the aerodynamic forces generated by the wings. The experiments were repeated for a different reduced frequency, airspeed, flapping and pitching kinematics, geometric angle of attack and wing sections (one symmetric and two cambered airfoils). A specially designed mechanical flapper was used, modelled on large migrating birds. It is shown that, under pitch leading conditions, good thrust generation can be obtained at a wide range of Strouhal numbers if the pitch angle oscillation is adjusted accordingly. Consequently, high thrust was measured at both the lowest and highest tested Strouhal numbers. Furthermore, the work demonstrates that the aerodynamic forces can be sensitive to the Reynolds number, depending on the camber of the wings. Under pitch lagging conditions, where the effective angle of attack amplitude is highest, the symmetric wing was affected by the Reynolds number, generating less thrust at the lowest tested Reynolds value. In contrast, under pure flapping conditions, where the effective angle of attack amplitude was lower but still significant, it was the cambered wings that demonstrated Reynolds sensitivity.

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1. Introduction

Flapping flight has been the subject of research since the dawn of the science of aerodynamics; early examples of analysis include work by Von Karman and Burgers (1935) and Garrick (1937). Recently, due to growing interest in Micro Air Vehicles (MAV), flapping flight has re-emerged as a popular research area. A number of works have been published since the 1990s, aiming at understanding and optimising flapping flight for low Reynolds numbers. In general, flapping flight research can be grouped into insect-based and bird-based. Insect flapping is characterised by higher frequencies and by persistent flow separation over significant parts of the wings (Ellington et al., 1996). Bird flapping involves lower frequencies and the flow can be fully attached at all times for specific flight conditions. Nevertheless, dynamic stall is generally thought to play a significant role even in bird flight; several mechanisms involving separated flow have been reported, such as the Leading Edge Vortex (LEV) (Hubel and Tropea, 2010; Yu et al., 2013) or clap and fling (Bennett, 1997). Such mechanisms are discussed in detail by Shyy et al. (2010), albeit mostly within the context of insect and hovering bird flight.

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Research on plunging and pitching 2D airfoils has shown that the best propulsive efficiency is obtained when the pitch leads the plunge by a phase difference or around 90° (Anderson et al., 1998; Platzer et al., 2008). This type of flapping kinematics is commonly referred to as pitch-leading and can result in propulsive efficiencies of up to 75%. Nudds et al. (2004) and Schouveiler et al. (2005) showed that, for plunging and pitching wings, maximum propulsive efficiency is achieved at Strouhal numbers of 0.21–0.25. The experiments by Schouveiler et al. (2005) also demonstrated that the thrust force increases continuously with the Strouhal number. However, this result concerned a symmetric airfoil pitching.

As the phase difference between the pitch and the plunge moves away from 90°, thrust production reduces significantly because of the occurrence of dynamic stall (Isogai et al., 1999). On the other hand, dynamic stall has been known to increase the instantaneous lift to up to three times the maximum static lift (Francis and Keesee, 1985). It has been theorised (Lighthill, 1975) that this mechanism is used by large birds in order to generate additional lift during some flight phases, such as takeoff. Usherwood et al. (2003) measured the pressure on the wings of Canada geese during takeoff and observed double peaks in pressure at the wingtip during the downstroke. Such peaks may be evidence of the passage of a LEV. One of the most complete experimental investigations of root flapping was carried out by Hubel and Tropea (2009, 2010) on a goose-like flapping wing model featuring wings that could flap but not pitch. The work showed that very high lift forces could be generated during parts of the flapping cycle and the authors demonstrated that this phenomenon is due to the development of a leading edge vortex.

Actively flapping and pitching 3D wings have been recently studied experimentally for insect-like flight (see for example Seshadri et al., 2013) but such work is still rare for bird-like wings. Malhan et al. (2012) studied experimentally a flapping wing at both hover and forward flight conditions but at smaller scales and higher frequencies than typical of most birds. The purpose of the present work is to investigate experimentally the effect of a few key parameters on the generation of aerodynamic forces of a bird-like mechanical model that flaps and pitches its wings. The parameters are the kinematics, reduced frequency and wing profile. As mentioned above, the phase difference between flapping and pitching that gives the best performance is well known. However, the effect of the pitch angle limits (i.e. pitch angle mean and amplitude) has not been as thoroughly investigated. Furthermore, birds have cambered wing sections and a lot of the previous work on propulsion has concentrated on symmetric airfoils. In this work, an asymmetric airfoil is used to investigate pitch leading aerodynamics and the pitch angle range can be altered to determine which range gives the best thrust.

Pitch lagging is the opposite of pitch leading, i.e. a wing motion whereby the pitch lags the flap. Pitch lagging and pure flap kinematics are studied in order to determine the effect of wing camber on separated flapping flows. The frequency, airspeed, phase between pitch and lag can all be varied. Three different wing sections are tested, one symmetric and two cambered. Detailed measurements of the aerodynamic forces acting on the model are carried out by means of an aerodynamic balance. Furthermore, the flowfield around the wing is visualised using Particle Image Velocimetry at distinct instances of the flapping cycle.

2. Experimental setup

The experiments described in this work were conducted in the Multi-Disciplinary Low Speed Wind Tunnel of the University of Liège. The tunnel's aeronautical test section was used, which has dimensions of 2 m $\times$ 1.5 m $\times$ 5 m (width $\times$ height $\times$ length) and is capable of achieving airspeeds of up to 60 m/s in the closed loop configuration. The turbulence level is 0.15% of the windspeed on average. The test section is equipped with a rotating turntable for controlling the model's orientation and a three-component aerodynamic force balance measuring total lift, drag and side force.

2.1. Flapping wing model

The flapping wing wind tunnel model developed for this work is referred to as the Metal Bird (Razak and Dimitriadis, 2009, 2011). Its general specifications are consistent with a medium-sized bird, such as a duck, albeit simpler in kinematic terms. The total wingspan (tip to tip) is 1.3 m and the total aspect ratio is 8.6. The flap angle, γ, was designed to flap between

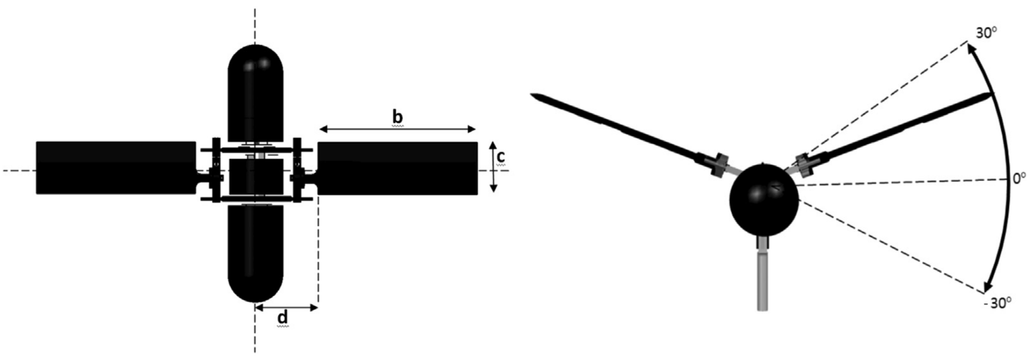

Fig. 1. Diagram of the flapping and pitching mechanical model, front and top view.

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