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RESEARCH ARTICLE

Stereoscopic particle image velocimetry measurements of the three-dimensional flow field of a descending autorotating mahogany seed (*Swietenia macrophylla*)

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SUMMARY

An experimental investigation of near field aerodynamics of wind dispersed rotary seeds has been performed using stereoscopic digital particle image velocimetry (DPIV). The detailed three-dimensional flow structure of the leading-edge vortex (LEV) of autorotating mahogany seeds (*Swietenia macrophylla*) in a low-speed vertical wind tunnel is revealed for the first time. The results confirm that the presence of strong spanwise flow and strain produced by centrifugal forces through a spiral vortex are responsible for the attachment and stability of the LEV, with its core forming a cone pattern with a gradual increase in vortex size. The LEV appears at 25% of the wingspan, increases in size and strength outboard along the wing, and reaches its maximum stability and spanwise velocity at 75% of the wingspan. At a region between 90 and 100% of the wingspan, the strength and stability of the vortex core decreases and the LEV re-orientation/inflection with the tip vortex takes place. In this study, the instantaneous flow structure and the instantaneous velocity and vorticity fields measured in planes parallel to the free stream direction are presented as contour plots using an inertial and a non-inertial frame of reference. Results for the mean aerodynamic thrust coefficients as a function of the Reynolds number are presented to supplement the DPIV data.

Key words: aerodynamics, leading-edge vortex, LEV, spiral vortex, rotary seeds, PIV.

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INTRODUCTION

Seed dispersal distances are a fundamental aspect of plant evolution and conservation (Howe and Smallwood, 1982; Willson, 1993). In order to increase the distance of dispersal, samaras, or winged seeds, descend very slowly by spinning. Mahogany seeds initiate autorotation about their center of mass almost immediately after being released from the host tree by creating a prominent leading-edge vortex (LEV) that is similar to the flow structures that are responsible for the high lift generated by the wings of hovering insects such as fruit flies (Birch and Dickinson, 2003; Fry et al., 2005), hawkmoths (Van den Berg and Ellington, 1997a; Van den Berg and Ellington, 1997b), butterflies (Brodsky, 1991; Willmott et al., 1997), birds (Usherwood, 2009; Usherwood et al., 2005) and bats (Hedenström et al., 2009; Muijres et al., 2008). Ever since Maxworthy (Maxworthy, 1979; Maxworthy, 1981) discovered the LEV on the wings of a scaled-up model of the hawkmoth *Manduca sexta*, the attached LEV has been identified as the responsible for the production of high lift forces and has been subjected to considerable investigation (Birch et al., 2004; Bomphrey et al., 2006; Liu et al., 1998; Wu and Sun, 2004).

Two-dimensional (2D) studies have shown that the growth of the LEV begins at the start of translation and continues until the vortex becomes unstable, detaches from the leading edge (LE) and is shed into the wake (Dickinson and Götz, 1993). Several studies have been performed with the aim of characterizing the unsteady aerodynamics of insect flight (Brodsky, 1991; Ellington et al., 1996; Grodnitsky and Morozov, 1993; Somps and Luttges, 1985; Thomas et al., 2004). Dickinson et al. (Dickinson et al., 1999) performed direct measurements of the forces produced by flapping wings and suggested that the enhanced aerodynamic performance of insects results from three distinct, yet interactive mechanisms: delayed stall, rotational circulation and wake capture. Usherwood and Ellington (Usherwood and Ellington, 2002) determined the steady aerodynamic performance of wings in revolution at low and high Reynolds numbers (*Re*) from 1100 to 26,000 and reported that their aerodynamics are quite insensitive to variations in both wing morphology and kinematics, and that aspect ratio has remarkably little influence on aerodynamic force coefficients at low to moderate angles of attack. Birch and Dickinson (Birch and Dickinson, 2001) systematically mapped the flow generated by a dynamically scaled model insect at Reynolds numbers matching the flows relevant for most insects, and found that the structure of this spanwise flow takes different forms depending on the value of the Reynolds number. Their results demonstrate that flapping wings do not generate a spiral vortex akin to that produced by delta-wing aircraft. Also, they found that limiting spanwise flow with fences and edge baffles did not cause detachment of the LEV. Their findings support the hypothesis that induced downward flow from tip vortices and wake vorticity reduce the effective angle of attack and attenuate the growth of the LEV. Ellington (Ellington, 1984) proposed a scheme to include wing rotation with translation in quasi-steady models. Because the lift in insect flight was significantly higher than expected on the basis of quasi-steady aerodynamics, he suggested that important unsteady flow phenomena play a major role in the force generation process. Dickinson (Dickinson, 1994) investigated rotational parameters by measuring forces on the model wings of *Drosophila*. His results