Flow around a Suddenly Accelerated Rotating Plate at Low Reynolds Number

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Expanding design efforts in the area of Micro Air Vehicles (MAVs) have triggered the research interest in bio-inspired flapping wing aerodynamics, especially over the last decade. Actual natural flapping flight is three-dimensional in essence and combines pitch, plunge and sweeping motions of the wing, with three-dimensional effects being further enhanced by low wing aspect ratio. Previous studies hence revealed that, in consequence of this, it is not possible to explain unsteady force generation mechanisms of flapping flight completely, without taking these three-dimensional effects into account (Birch and Dickinson 2001). This requirement of extending investigations into the third dimension, together with the flow-diagnostic capabilities offered by the availability of three-dimensional Particle Image Velocimetry (PIV) techniques (Scarano 2013) have motivated the experimental investigation for characterizing the flow around three-dimensional wings undergoing flapping motions.

The specific aim of the present study is to investigate the formation of vortical structures and generation of forces on a low-aspect-ratio flat rectangular wing undergoing a revolving surge motion in which the wing starts from rest at a constant angle of attack and accelerates to terminal velocity over a specified distance (in terms of chord length of travel). The angle of attack (α) was varied (30, 45 and 60 degrees) in order to investigate its effect on the three-dimensional flow structures and unsteady loading.

The measurements were performed in an octagonal water tank (Fig.1a) at Reynolds number of 20,000, based on the chord length (c=50 mm) and terminal velocity at 75% span (0.4 m/s). A tomographic Particle Image Velocimetry (Tomographic-PIV) technique was used in order to capture three-dimensional velocity fields at different phases of the rotational motion, in combination with direct force measurements with a six-component water submersible force sensor. The measurement volume of 90x70x25 mm in size was positioned at two different adjacent spanwise locations (Fig. 1b). The volume was illuminated by a double-pulsed Nd:Yag laser at a wavelength of 532 nm. Polyamide spherical particles of 56 µm diameter were employed as tracer particles at a concentration of 0.23 particles/mm. The motion of the tracer particles was captured by four 12 bit CCD cameras with a resolution of 1376×1040 pixels and a pixel pitch of 6.45 µm. Particle images were interrogated using windows of final size 32×32×32 voxels with an overlap factor of 50%. The resultant vector spacing is 1.0 mm in each direction forming a dataset of 87×68×24 velocity vectors in each measurement volume.

Fig.1 (a) Schematic representation of top view (b) Measurement volume arrangement

Fig.2 (a) Lift coefficient vs. chords travelled (cht) for different angles of attack (b) Isosurfaces of Q criterion after 1.5c of travel in the reference plane (75% span) (c) Contours of out-of-plane (spanwise) velocity in the reference plane (d) Contours of out-of-plane vorticity in the reference plane

The evolution of forces (Fig. 2a) have some common features for all cases: initial non-circulatory peak at the end of the acceleration phase; following decrease and increase of both lift and drag to the maximum; and decline to steady-state values. However, the phase of the hump, when the maximum occurs, differs based on the angle of attack. In the first two chords length of travel, coherent vortical structures (Fig. 2b) (i.e. leading edge vortex, tip vortex and trailing edge vortex) appear and develop in size as the motion progresses. The spanwise flow also grows in magnitude within the cores of the leading and trailing edge vortices (Fig. 2c). The tip vortex displays a conical shape with swirling patterns of small scale structures which are most prominent for the case of 45° and 60°. Following an initial coherent growth, the leading edge vortex then detaches from the wing surface (Fig. 2d) and travels downstream while it bursts into small scale structures, however, it does not fully shed from the wing at least until 4 chords of travel. After this phase, no coherent structure is present around the wing and the flow field displays stalled wing characteristics. The spanwise flow structure also changes with the travel of the leading edge vortex from a pattern in the vortex core to a pattern concentrated around the trailing edge.