Abstract  The three-dimensional flow that develops around a flapping wing is investigated using a tomographic scanning PIV technique. The acquisition and correlation process employed to achieve such measurements has been carefully validated. Results obtained on a hovering flapping wing which does not involve a revolving motion highlight the influence of the free end condition and the formation of the tip vortex on the leading edge vortices behaviour and wake stabilization.

1. Introduction

Flapping wings have been of interest to biologists for years, and are currently under much consideration by the aeronautical community, due to the recent advent of Micro-Air Vehicles. The problematic associated with such wing concept relies on the comprehension of low Reynolds number unsteady aerodynamic phenomena. Previous studies revealed that mechanisms such as the presence of a Leading Edge Vortex (LEV), the Kramer effect or the wing/wake interactions are responsible for the generation of a strong lifting force (Dickinson et al. 1999).

Despite the fact that two-dimensional configurations bring interesting insight into the aerodynamics of flapping wings (Wang 2000, Kurtulus et al. 2008, Bos et al. 2008, Jardin et al., 2009), the latter is particularly sensitive to the presence of a three-dimensional component. Extended works (Maxworthy 1979, van den Berg & Ellington 1997, Poelma et al. 2006) suggested that spanwise velocities might effectively have an effect on the stability of the LEV. Nevertheless, most researches focused on revolving wing configurations for which the distinction between the effects due to the inertial forces (Coriolis and centrifugal) and that due to the wing tip vortex is delicate. In this paper, we focus on a configuration for which the translation phase is rectilinear, which allows isolating the role of the tip vortex on global flow dynamics.

A high frequency scanning of the high speed laser sheet by an oscillating mirror is used to illuminate a volume of the flow. Different volumes of particles at different times are recorded by means of a high speed camera. 3D iterative correlation by shift windowing and sub pixel accuracy is proposed for the evaluation of the three components of the displacement in the volume. The time interval ($\Delta t=100$ ms) is sufficiently short to obtain, for this application, time resolved velocity measurements.

Schemes of the experimental setups and of the time table are presented to validate the recording of these large volumes. Influence of the magnification in depth, of cylindrical lenses on the laser sheet location will be raised. Concerning the flow, comparison with the 2D flow will be proposed. Finally, interaction of the Leading Edge Vortex, the Tip Vortex, and the Starting Vortex are examined with the wing motion.

2. Experimental Set-up

We are concerned about the flapping motion of a NACA0012 airfoil at a Reynolds number of 1000. The flapping amplitude is set to 6 chords. The airfoil undergoes a constant speed translation at fixed...
angle of attack along 4 chords, after which it is subjected to both rotating and decelerating or accelerating motions whether it respectively ends or starts the upstroke/downstroke phases (Figure 1). The non-dimensional rotating $\Delta \tau_r$ and accelerating/decelerating $\Delta \tau_t$ times are set to $\pi$. The constant translation speed $V_0$ is defined according to the Reynolds number $Re = V_0/c\nu$, where $c$ is the airfoil chord and $\nu$ the fluid kinematic viscosity. The flapping period is computed using the following equation: $T = 4c(2+\pi/2)/V_0$.

![Figure 1: Description of the symmetric flapping motion](image)

The experiments are conducted in a $1\times1\times2\text{ m}^3$ water tank filled with 10 µm diameter hollow silvered glass particles. 10 grams are introduced, corresponding to a number of particles $N_p = 14 \times 10^9$, and to a concentration of particles $C_p \approx 9 \times 10^9 \text{ p/m}^3$. The airfoil is a transparent resin NACA0012 profile connected at one end to a Plexiglas plate, the other end being free (Figure 2). The translating and rotating motions of the airfoil are driven separately through the use of two servo-controlled motors. Their respective mechanical transmissions are achieved by means of an endless screw and a pulley. The aspect ratio $AR=L/c= 4$ (where $L$ is the wingspan) has been studied.

![Figure 2: Experimental setup and scanning device](image)

Lately, several techniques have been proposed to simultaneously measure the three velocity components inside a volume of the flow, such as algebraic reconstruction tomography or holography. The former requires multiple sensors and restricts the measurements to a narrow laser sheet (few centimetres). Holography allows a thicker laser sheet but is not adapted to the measurement of large flow fields involving a great number of particles. In this work, the flow is investigated using a scanning technique rather similar to that described by Kent (1994), Brücker (1997), Fincham (2003) and Hori and Sakakibara (2005). Tomography relies on the correlation of
three-dimensional particles mapping, i.e. fields of voxels. In the particular case of high-speed scanning tomography, three-dimensional particles mapping is obtained by the high frequency repetition of adjacent planar recordings. When unsteady flows are considered, one should ensure that the relevant frequencies of the flow may be considered negligible with regard to the scanning frequency. Considering actual tools, this issue limits such measurements to low Reynolds number flows.

The volume is illuminated by means of a 2×20 mJ Quantronix Darwin-Duo Nd : YLF laser combined with an oscillating mirror. Its depth is limited to 83 mm by the focal depth of the high-speed camera. The volume is discretized into 100 rigorously parallel and equidistant planes over a time interval of 25 ms, which corresponds to a 4 kHz LASER frequency. The mirror oscillation is imposed by a low frequency generator that delivers a periodic and asymmetric triangular signal of amplitude 12.5 V and frequency 10 Hz, discretized over 1000 points. Note that the signal is asymmetric to ensure a finite time superior to 50 ms between each volume acquisition, as required by Davis 7.2 (LaVision) software. Thus, the back and forth motions of the mirror respectively lasts 34 ms and 66 ms. Besides, the mechanical oscillation of the mirror generates inertial effects that alter the linearity of the laser sheet motion. Therefore, measurements should be conducted during linear phases of the oscillation such that the equidistance between adjacent planes is ensured. This remark implies that the mirror oscillation covers a deeper volume (≈ 100 mm) than is effectively measured. The red Dirac peaks in figure 3 mark the beginning of the linear phases.

The laser beam interacts with a series of lenses: 1) a diverging lens that emphasizes the oscillation angle, 2) a 145 mm convex lens that reorients the laser beam to ensure parallelism between laser sheets and 3) a cylinder lens that spreads the laser beam out to form a laser sheet of 0.8 mm thickness.

Using Davis 7.2 (LaVision) software, the laser is synchronized with a high-speed Photron camera equipped with a 10 bits sensor of resolution 1024×1024 pixels. The camera acquires 100 particle images at a frequency of 4 kHz every 100 ms. Operating at such frequency imposes several restrictions: 1) the finale resolution is set to 1024×784 pixels, 2) the storage capacity (RAM) of the camera being 8 Go, the acquisition time is limited to 8 s (80×100 images), 3) the weak lightening energy returned to the CCD sensor (due to a short time of exposition) imposes F#8 which limits the focal depth and hence fixes the volume depth to 83 mm. Prior to the experiments, the focal depth can be estimated using the following equation (Raffel et al. 1998): δz=2F#d_{diff}(M+1)/M² with M magnification factor and d_{diff} diffraction diameter d_{diff}=2.44F#(M+1)λ. In this work, δz≈63 mm
which implies slightly blurred particle images at both end of the volume. Note that using F#11 would have brought $\delta_z \approx 120$ mm but has the disadvantage of considerably reducing gray levels intensity.

Based on the maximum airfoil translation speed $V_0$, we get the following particle displacements: $\Delta x, y, z = 1.67$ mm. This leads to a 4.5 voxels displacement in the streamwise directions ($x, y$) and to a 2 voxels displacement in the spanwise direction (depth $z$) for a $32 \times 32 \times 8$ voxels windowing. If we consider a spanwise displacement, this implies that a particle located in a laser sheet at the instant $t$ will move to a laser sheet at $t + \Delta t$. In other words, given that the volume acquisition frequency is set to 4 kHz ($T = 1/f = 0.25$ ms), the time step is subjected to an uncertainty of the order of $2 \times 0.25 = 0.5$ ms, corresponding to a displacement uncertainty of less than 0.01 mm.

In addition, considering a characteristic time scale of $(c \times \sin(\alpha))/(St_d \times V_0) = 20$ s with $St_d = 0.124$ (Dergham et al., 2009), $c = 0.06$ m and $\alpha = 45^\circ$, and by estimating that an accurate time resolution can be obtained by discretizing this time scale in 10 instants, the acquisition time (25 ms) can effectively be considered negligible. The camera is equipped with a 50 mm focal length lens for a $370 \times 280$ mm$^2$ area imaging. Recall that these dimensions vary according to the direction $z$, $370 \times 280$ mm$^2$ being average values.

The volume dimensions ($370 \times 280 \times 83$ mm$^3$) and the acquisition time (8 s) not being sufficient to spatially and temporally describe the whole flapping period, measurements are reiterated at different instants and spanwise locations. Since the flapping motion is symmetric, measurements are limited to a half-period. Streamwise and spanwise spatial overlaps of respectively 20 and 5 mm are imposed between each volume. Similarly, a temporal overlap of 1 s is imposed. The measurement of the full three-dimensional velocity field around the flapping wing requires 4 instant-runs $\times$ 4 space-runs. Note that the position of the camera depends on the instant and spanwise location that is being measured (Figure 4).

The cross-correlation between two successive volumes is achieved using a C++ code. The data being time-resolved, a sequential process is applied. The relatively basic calculation involves a two-pass FFTW 3D correlation with 50% overlap and 3 points parabolic sub pixel approximation. Fixed $32 \times 32 \times 8$ voxels windows are used. Note that the correlation volume is isotropic in the real

---

Figure 4: Sketch of the different volumes. Evolution in time (from coloured to transparent) and space (from one colour to another).
reference.

Three-dimensional vector fields are post-processed using a 3×3×3 median filter. More specifically, vectors that stand without the 1.2 rms bounds (computed over the 3×3×3 neighbours) are suppressed and replaced by the median value.

Figure 5: Sketch of the volumetric correlation process

3. Results

Measuring the three-dimensional velocity fields using scanning PIV3D-3C is here particularly complex and challenging due to the dimensions of the investigation region (370×280×320 mm³) and to its application to a moving airfoil. Two main issues are encountered. First, velocity fields are subjected to a relatively strong noise that limits the accurate detection of vortical structures using λ₂ or Q criteria and implies the use of a spatial smoothing that tends to reduce the effective levels of characteristic quantities (e.g. velocity, vorticity). Second, besides the fact that the global behaviour of the flow is clearly put into evidence, the continuity between each volume (acquired at different runs) is not strictly ensured.

Despite these difficulties, a phenomenological description of the flow could be conducted, showing consistency with previous two-dimensional results (Jardin et al. 2009).

Figure 6 illustrates the main physical phenomena identified by superimposing velocity vectors and vorticity contours obtained by PIV3D-3C at instants t = T/20, 3T/20, 5T/20 et 7T/20. The spanwise planes are located 0.3 (p_tip) and 3.1 (p_root) chords away from the wing tip.

At the beginning of the stroke, it is shown from frame (a) that the airfoil in p_root interacts with the vortices shed during the previous stroke. The latter is responsible for the generation of a fluid jet oriented towards the lower surface of the airfoil and which strengthens the effective incident velocity. This feature adds momentum to the trailing edge shear layer from which develops a starting vortex (SV) whose formation is significantly accelerated. A similar trend is observed for the generation of the leading edge vortex (LEV). On the contrary, the airfoil in p_tip does not seem significantly affected by the wing/wake interactions. At this position, the flow is dominated by the advection of the tip vortex (TV) under the airfoil lower surface. Note that this downward advection is a result of the classical induced downwash associated with the formation of the TV.

Frame (b) gives further evidence of the formation of the LEV. In p_root, a broad region of strong vorticity levels extends beyond the airfoil upper surface, analogous to the presence of a low
pressure suction region which greatly contributes to lift production. In \( p_{\text{tip}} \), this region is considerably reduced. At this position, the development of the LEV is not forced by the wing/wake interactions, i.e. by the action of the impacting fluid jet identified earlier. Furthermore, the tip downwash decreases the effective angle of attack, hence reducing the production of local vorticity at the leading edge. Both features contribute to the smooth formation of the LEV near the wing tip. Besides, one can notice the shedding of SV in \( p_{\text{root}} \) and the formation of a tip vortex (TV) in \( p_{\text{tip}} \). The relative positions of SV and TV suggest that both vortices are connected to each other, ensuring a continuity between streamwise and spanwise vorticity.

The most prominent phenomenon is observed in frame (c). In \( p_{\text{root}} \), the LEV is shed into the wake, leading to the formation of a second LEV. The flow reaches a von Karman shedding state characterized by steep variations in aerodynamic loads. Its behaviour is dominated by the two-dimensional instability, akin to that observed in strictly two-dimensional cases. In \( p_{\text{tip}} \), the LEV is confined at the wing upper surface. More specifically, it grows with the wing translation until it reaches a quasi-steady state. This behaviour indicates that the production of spanwise vorticity at the leading edge is balanced by a three-dimensional mechanism arising from the free end condition. At this spanwise location, the flow is dominated by a three-dimensional stability. This particularity is associated with a smooth time evolution of aerodynamic loads. Frame (c) also denotes the concomitant development of the TV whose vorticity levels increase with the translation.

Frame (d) exhibits the wake of the flapping wing near the end of the half-stroke. A complex vortical activity is identified in \( p_{\text{root}} \) whereas a rather simple organization is observed in \( p_{\text{tip}} \). Such pattern suggests that the near root region will be subjected to strong wing/wake interactions during the subsequent half-stroke whereas the flow around the wing tip will develop naturally.

The analysis of the three-dimensional flow that develops around a flapping wing whose translation phase is rectilinear (as opposed to revolving wings) demonstrates that the free end condition induces a stabilization of the leading edge vortex near the wing tip. In this region, the tip downwash that originates from the formation of the tip vortex reduces the effective angle of attack, hence the spanwise vorticity production at the leading edge. In addition, the tip vortex might balance the production of spanwise vorticity by promoting the reorientation of spanwise vorticity into streamwise vorticity and advecting it downstream. However, three-dimensional effects only affect the near tip region such that most of the wingspan is still dominated by two-dimensional instabilities and, as a consequence, by severe wing/wake interactions. Since three-dimensional effects grow with the formation of the tip vortex, i.e. with the airfoil translation, the frontier between predominantly two-dimensional and three-dimensional regions evolves from the wing tip to the wing root. The region swept by this unstable frontier may be qualified as a transition region. It is characterized by both significant wing/wake interactions and three-dimensional stability.

4. Conclusion

In conclusion, the measurement of the three velocity components in a volume has been developed to investigate the complex low speed flow that develops around a flapping wing. The high speed parallel scanning of a LASER sheet synchronized with a high speed camera allowed particles mapping over a deep volume (83 mm). Feasibility has been verified by controlling the displacement linearity and the position of the LASER sheet in the volume. An adaptive volumetric correlation was employed to extract velocity vectors from the particle recordings. Despite issues related to the fact that volume acquisitions were conducted during different runs, a phenomenological description of the flow was achieved. In particular, the interplay between the tip vortex and the leading edge vortex was characterized. The flow appears to be dominated by two-dimensional instabilities along most of the span and strongly affected by three-dimensional effects near the wing tip.
Figure 6: Illustration of the flow that develops around a finite span flapping wing. Non-dimensional velocity vectors and vorticity contours/surfaces: (a) wing/wake interactions at $t=T/20$, (b) development of LEV, SV and TV at $t=3T/20$, (c-d) evidence of three-dimensional stable, two-dimensional unstable and transition regions at $t=5T/20$ and $t=7T/20$.

Acknowledgements
This work is funded partially by the 13th CPER and the ANR VIVE3D. Their supports are greatly acknowledged.
References


