

Actively bending flapping wings characterization

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Keywords: Unsteady flow, vortex-dominated flow, morphing wing, 3D3C PIV.

ABSTRACT

This study experimentally characterizes the flow generated by an actively deforming flapping wing. Active deformation is achieved using embedded piezoelectric actuators, which enable precise control of the wing bending. By phase-shifting the input electrical signal with respect to the flapping motion, the resulting bending motion is likewise phase-shifted relative to the flapping kinematics, allowing the influence of the bending phase lag, δ_θ , on the flow structures (and thus on the aerodynamic performance) to be characterized. This work focuses on two bending phase lags: $\delta_\theta = \pi/2$ and $\delta_\theta = 3\pi/2$. In both cases, the wing reaches its maximum bending at stroke reversal. The case $\delta_\theta = \pi/2$ corresponds to bending in the flapping direction (i.e. reduced effective flapping amplitude), whereas $\delta_\theta = 3\pi/2$ corresponds to bending in the opposite flapping direction (i.e. increased effective flapping amplitude). A scanning PIV technique is then employed to obtain volumetric velocity fields. The results show that the morphing wing with $\delta_\theta = \pi/2$ generates less intense vortical structures than the morphing wing with $\delta_\theta = 3\pi/2$, suggesting that active control of the flapping-wing shape could be used to tailor the instantaneous aerodynamic loads.

1. Introduction

The miniaturization of unmanned aerial vehicles (UAVs) down to extremely small sizes has intrinsic limitations in their propulsion due to increased fluid viscous forces relative to inertial forces. That is, at centimeter scales and below, conventional fixed and rotary wings suffer reduced aerodynamic performance. The remarkable agility and capability to hover of insects and small birds have thus fostered the interest of both aerodynamicists and zoologists on the role of flapping wings for the propulsion of UAVs.

The majority of previous studies have focused on the role of kinematics aiming at understanding the flow dynamics around flapping wings and resulting aerodynamic performance. The admitted conclusion is that unsteady vortex dynamics is the key element for lift generation. More specifically, the formation of a strong leading-edge vortex (LEV) on the suction side of the wing, synonym

of a low-pressure region, is the main mechanism responsible for lift production (see e.g. Eldredge & Jones, 2019).

Recently, structural flexibilities (as observed in nature) have been incorporated as a parameter of the problem. Contrary to their rigid counterparts, flexible wings deform as a response to various forces: aerodynamic, inertial and elastic. The deformations of the structures lead to substantial differences in flow structure, hence aerodynamic performance. Wing deformation in biological systems can generally be decomposed into three different mechanisms: spanwise bending, spanwise twisting, and chordwise cambering (Wootton, 1981).

The recent development of "smart material" (here piezoelectric actuators) paves the way for the active control of the deformation (see e.g. Abbaszadeh et al., 2022) rather than being a response of the wing kinematics and structural properties. This study focuses on the active control of spanwise bending only, as it has been found from a previous numerical study to be responsible for large differences in lift when compared to rigid wings (Bouard et al., 2024a). Specifically, the study highlighted that bending phase-shift with respect to the flapping motion induces even larger differences in terms of aerodynamic performance and thus flow structures.

The present communication aims at validating this conclusion by actively controlling bending motion of a flapping wing using embedded piezoelectric actuators. The paper is then composed of a description of the wing and kinematics considered in the present work. The experimental setup and data processing are presented before the results for two different kinematics (i.e. bending phase-shift with respect to flapping motion) being discussed.

2. Experimental setup

2.1. Wing description and kinematics

We consider a wing with aspect ratio $AR = c/R = 4$ with $c = 0.06\text{m}$ and R the wing chord and span, respectively, obtained by radially extruding a NACA0012 profile with constant wing chord and pitch. The wing undergoes a flapping motion composed of combined sinusoidal revolving and pitching motions (Figure 1 (a) and (b)). The revolving amplitude covered by the wing during half a flapping period is set to $\phi_0 = 120^\circ$ during half a flapping period $T/2$ with $T \approx 51.4\text{s}$. That is, the Reynolds number Re based on the chord length c and mean velocity U at the wingtip over a stroke is $Re = 1173$. Experiments are conducted in water and kinematics are defined such that the Reynolds number and flapping amplitude-to-chord ratio are similar to those of previous numerical simulations from our group, performed in air (see e.g. Diaz-Arriba et al., 2022; Bouard et al., 2024b). The mid-downstroke (hence mid-upstroke since the kinematics is symmetric) pitch angle α_0 is set to 20° , beyond the (2D) stall limit of the wing section profile.

Active bending is performed using piezoelectric actuators embedded inside the wing, in a similar

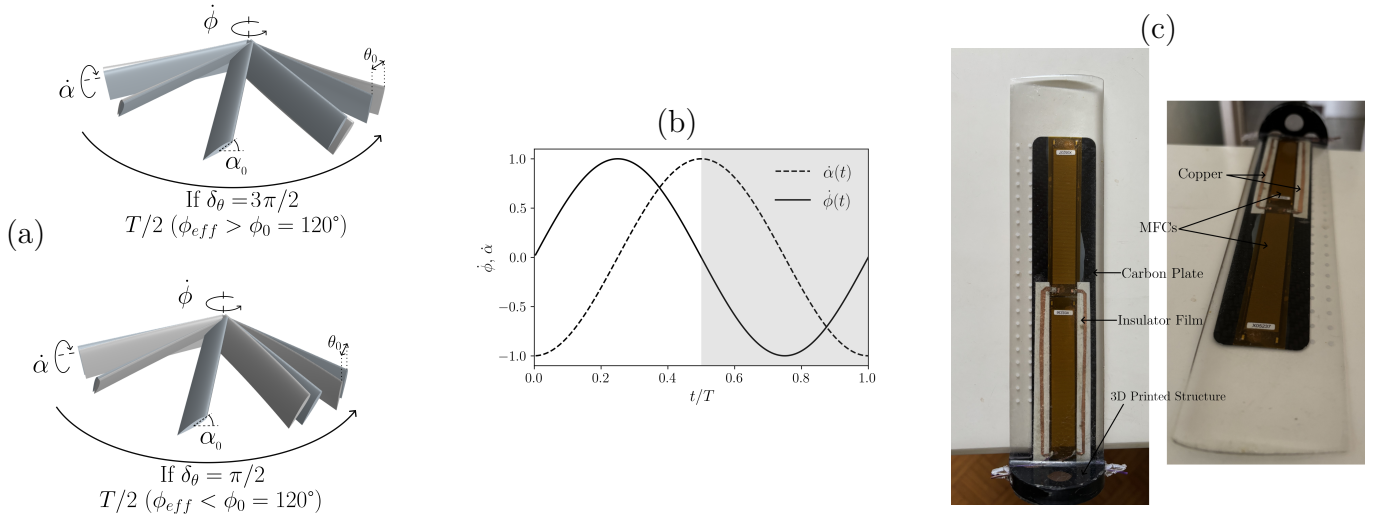


Figure 1. Flapping motion illustration during a downstroke phase (a) and top view of bending deformation at mid-downstroke (top and bottom, respectively). Rigid and actively bending wings are depicted in gray and lightgray. (b) Revolving $\dot{\phi}$ and pitching $\dot{\alpha}$ kinematics considered in the present work. (c) Example of a morphing flapping wing manufactured at Pprime Institute.

to fashion to Abbaszadeh et al. (2022), where piezoelectric actuators are embedded in a robot-fish, flexible structure. Piezoelectric actuators are Smart Material M8514-P1 actuators bonded to a carbon plate of thickness $h = 0.2\text{mm}$ (vendor: Alfa Carbon). The wing is made of AllRANE spheric 14747 with the following material properties: solid density $\rho_s = 1.14\text{kg.m}^{-3}$, Young modulus $E = 7.3\text{MPa}$ and Poisson ratio $\nu_p = 0.48$. Figure 1 (c) shows an example of a morphing flapping wing manufactured at Pprime Institute.

The input voltage signal of piezoelectric actuators is sinusoidal resulting in approximately sinusoidal bending motion (not reported here for the sake of conciseness). The bending amplitude resulting from the actuation of piezoelectric devices is about 33% of the chord length ($\approx 2\text{cm}$) which corresponds to a bending amplitude $\theta_0 \approx 4^\circ$ (Figure 1 (b), bottom). Using a phase-shift of the input signal with respect to the flapping motion, we introduce bending phase-lag δ_θ corresponding to the phase-shift of the bending motion with respect to the flapping motion. Two phase lags are considered in the present work : $\delta_\theta = \pi/2$ and $3\pi/2$ corresponding to maximum negative bending (i.e. forward bending) and maximum positive bending (i.e. backward bending) of the flapping wing at stroke reversals, respectively. In other words, if $\delta_\theta = \pi/2$, the flapping wing wing bends in the direction of the revolving motion at $t/T = 0$ while $\delta_\theta = 3\pi/2$ corresponds to the wing bending in the opposite direction at $t/T = 0$. Therefore, the wing with $\delta_\theta = \pi/2$ flaps over a lower effective amplitude (as bending induces a forward displacement of the wingtip) with respect to a rigid wing while the wing with $\delta_\theta = 3\pi/2$ flaps over a larger effective amplitude.

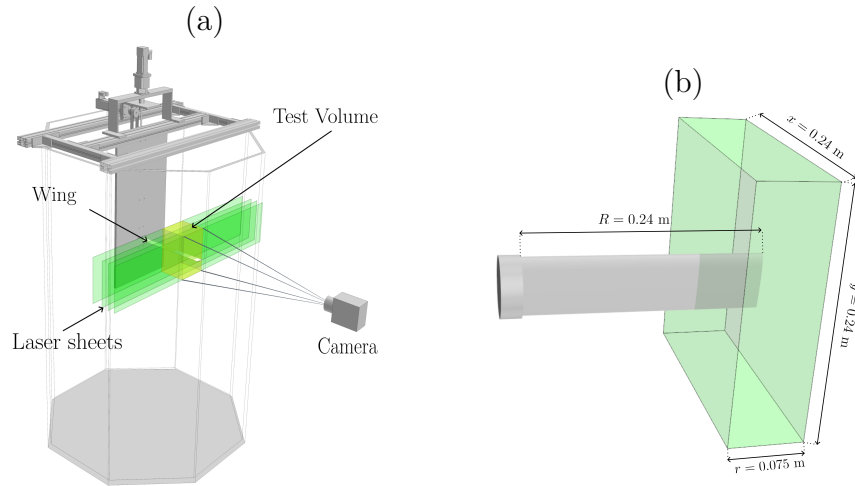


Figure 2. Illustration of the experimental setup (a) and dimensions of the test volume around the flapping wing (b).

2.2. 3D3C scanning TR-PIV

Experiments are conducted in a water tank made of Altuglas, with dimensions $1 \times 1 \times 1.5 \text{ m}^3$, as shown in Figure 2 (a). The wing is connected at its root to a vertical axis through a pivot joint. The vertical axis is rotated thanks to a step-by-step motor and a worm gear screw. The pivot joint allows for the pitching motion to be driven by a second step-by-step motor through a transmission belt and two pulleys. A fixed end plate separates the motion system and the wing to limit hydrodynamic perturbations from the system. One motor rotation is discretized into 65536 encoder points. Taking into account the reduction ratio of gear boxes (associated with each motor) and the step of the worm gear screw, one encoder point represents a 2.5×10^{-6} and 0.001 degree displacement for the revolving and pitching motions, respectively. Thus, the discretization of motion laws up to the hundredth of second induces an error of the order of 300 and 10 encoder points along a flapping cycle, corresponding to 7.5×10^{-4} and 0.01 degree displacements for the revolving and pitching motions, respectively. However, larger uncertainties in the wing position may arise from looseness and clearance in the pulleys and transmission belt system.

3D3C scanning PIV measurements are performed. A high-speed single frame $1024 \times 1024 \text{ px}^2$ camera is placed perpendicularly to the wing span and acquires images of particles in a volume enclosing the outboard portion of the wing tip (about 1/3 of the wing span, see Figure 2 (b)). The camera is synchronized with a high-speed laser that scans the volume at a frequency of 20kHz. Specifically, the laser consecutively illuminates adjacent slices of the volume and the camera acquires images of particles in each slice. The experimental measurement technique is illustrated on Figure 1 (a). The volume is discretized into 100 slices and is hence scanned in 5ms, which is fast enough to consider the flow as ‘frozen’ in time. Planar images in adjacent slices are then stacked to reconstruct a volume of particles. The scale difference due to the depth of the measurement planes

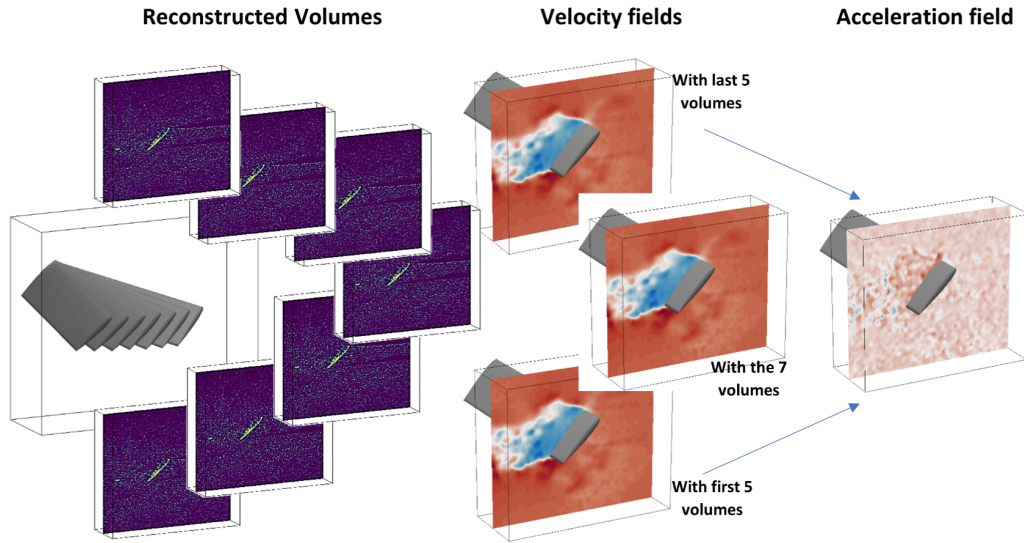


Figure 3. Illustration of the volumetric images (left) used to compute the velocity field (center). Extracted from Diaz-Arriba (2021).

is considered using B-spline interpolation computed from a calibration procedure. Seven consecutive volumes are scanned at 20Hz which allows for the computation of velocity fields through particle volume correlation, as well as for the computation of acceleration fields (Figure 3). The sub-pixel cross-correlation is performed using an in-house code based on the FTEE (Fluid Trajectory Evaluation based on Ensemble-averaged cross-correlation) method (Jeon et al., 2014), whose implementation relies on the SLIP library (Tremblais et al., 2010). The interrogation volume in the initial pass consists of $64 \times 64 \times 24$ voxels and is reduced to $48 \times 48 \times 12$ voxels in the second pass, both with a 50% overlap. The final three passes are then performed using interrogation volumes of $32 \times 32 \times 12$ voxels with a 75% overlap. The selected interrogation volume dimensions yield an approximately isotropic spatial resolution in physical space. It is similar to that used in previous flapping flight investigation from our group (David et al., 2012; Tronchin et al., 2015) and the reader is referred to these works for further details on the 3D3C scanning PIV measurements. We note that the camera and laser are fixed in space and the whole wing motion setup is rotated for measurements at each wing position (i.e. instant t/T considered in the flapping period). Eleven positions, corresponding to instants $t/T = 2.04, 2.06, 2.11, 2.13, 2.19, 2.25, 2.30, 2.36, 2.39, 2.43$ and 2.46 are acquired for both kinematics. Acquisitions at a given position are performed after 5 periods for initial transients to sufficiently decay.

3. Results

3.1. Velocity fields

The results are primarily compared through the velocity fields obtained for both the $\delta_\theta = 3\pi/2$ and $\delta_\theta = \pi/2$ motions. Figure 4 shows velocity vectors and non-dimensional spanwise vorticity contours, $\omega_z c/U$, at the spanwise location $r/R = 0.80$ during the first half of the downstroke for $\delta_\theta = 3\pi/2$ (left column) and $\delta_\theta = \pi/2$ (right column). At the beginning of the downstroke ($t/T = 2.04$), both wings interact with the wake generated during the previous upstroke. The primary difference arises from bending, which allows the $\delta_\theta = 3\pi/2$ motion to pass over the wake, whereas the $\delta_\theta = \pi/2$ case interacts strongly with its previous wake, as evidenced by the large clockwise vorticity region (blue spot) located near the wing leading edge. Later in the stroke, at $t/T = 2.06$, both motions exhibit the development of a leading-edge vortex (LEV), although in the $\delta_\theta = \pi/2$ case the LEV already appears to start shedding into the wake. This behavior is also reflected in the trailing-edge vortex (TEV), which has

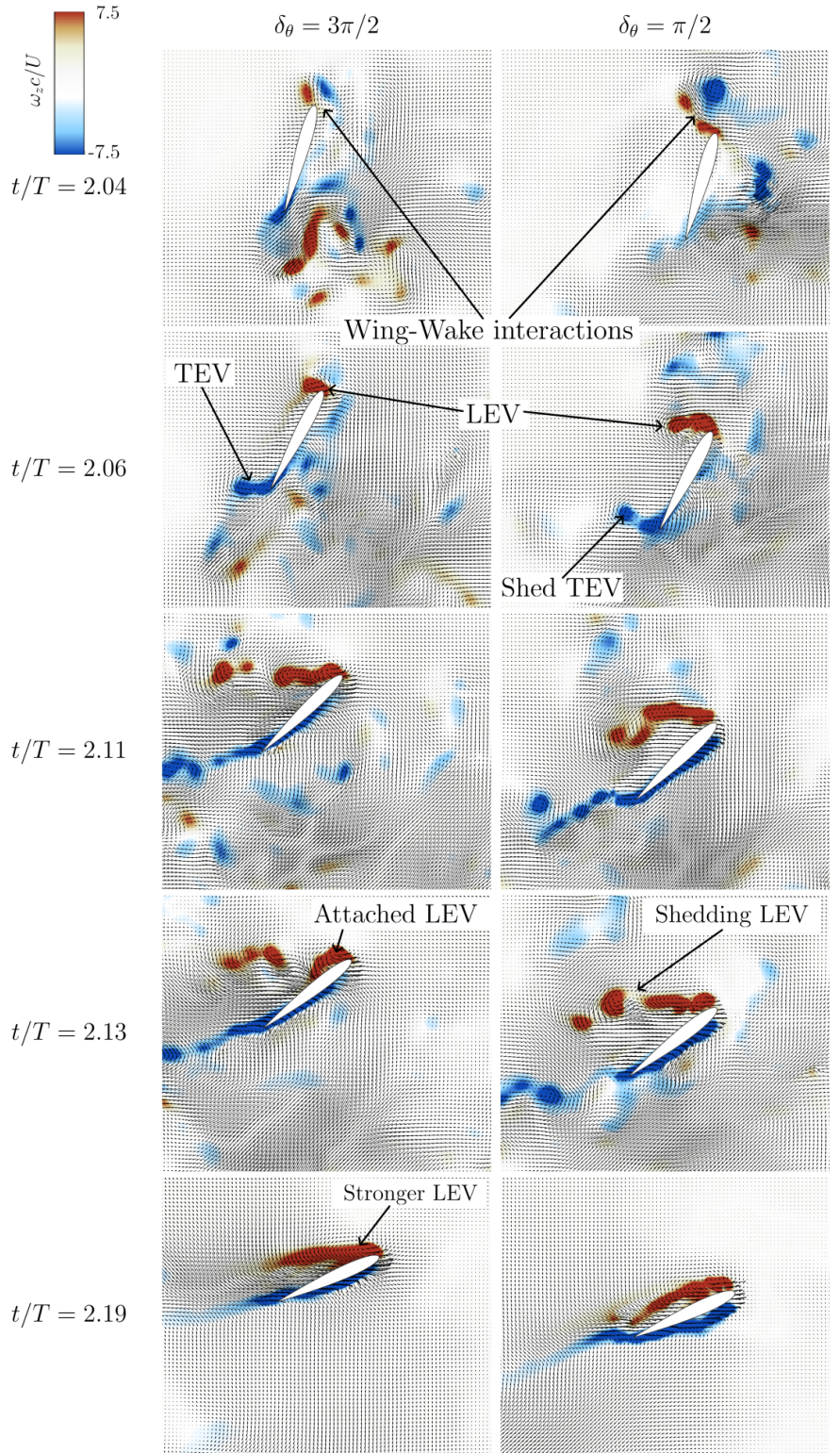


Figure 4. Velocity and vorticity fields obtained from 3D3C TR-PIV for both $\delta_\theta = 3\pi/2$ and $\delta_\theta = \pi/2$ kinematics in the spanwise section $r/R = 0.80$.

already been shed in the $\delta_\theta = \pi/2$ case, while it only begins to shed in the $\delta_\theta = 3\pi/2$ configuration. The TEV is then shed in both cases ($t/T = 2.11$), before the LEV destabilizes in the $\delta_\theta = \pi/2$ motion, whereas it continues to grow without significant interference in the $\delta_\theta = 3\pi/2$ case at $t/T = 2.13$. Slightly before mid-downstroke, at $t/T = 2.19$, it can be appreciated that the $\delta_\theta = 3\pi/2$ case presents a stronger, attached, LEV than the $\delta_\theta = \pi/2$ configuration. This can be explained by the wing velocity, influenced by the bending motion, which in one hand ($\delta_\theta = 3\pi/2$) is larger with respect to a rigid wing while in the other hand ($\delta_\theta = \pi/2$) is lower. The wing's velocity directly influences the development and attachment of the LEV and thus explains the differences in flow topology. The three-dimensional geometry implies the development of a tip vortex (TV) which is known to influence drastically the flow past flapping wings (Medina & Jones, 2016). The next subsection thus focuses on the analysis of 3D flow structures.

3.2. 3D flow structures

3D flow topology is studied using Q -criterion isosurfaces, $Qc^2/U^2 = 10$, colored by the non-dimensional spanwise vorticity $\omega_z c/U$ displayed in Figure 5 during the second half of the downstroke phase for both $\delta_\theta = 3\pi/2$ (left column) and $\delta_\theta = \pi/2$ (right column) motions.

First of all, clear differences can be observed between the two kinematics. Specifically, $\delta_\theta = 3\pi/2$ motion exhibits more intense vortical dynamics than that of the $\delta_\theta = \pi/2$ motion. At mid-downstroke ($t/T = 2.25$), while the $\delta_\theta = 3\pi/2$ kinematics shows strong vortex shedding and a developed LEV on the wing's upper surface, the $\delta_\theta = \pi/2$ case is characterized by a TV that is shed in the wake. Later on, at $t/T = 2.30$, the TV merges with the LEV and the TV induced flow interacts with the LEV core flow resulting in small scale structures indicating LEV burst for both motions. At $t/T = 2.36$, the wing pitches up which strengthens the LEV as seen on Figure 5 where vortical structures appear to be more intense with respect to previous instants. This instant also highlights the influence of bending phase-lag on vortical structures development as the wing with $\delta_\theta = 3\pi/2$ has a larger velocity with respect to a rigid flapping wing while the $\delta_\theta = \pi/2$ wing has a lower velocity resulting in stronger dynamics in the first case. This is further visible at the next instant $t/T = 2.43$ where the $\delta_\theta = \pi/2$ configuration exhibits distinct vortices (LEV and TV) while the $\delta_\theta = 3\pi/2$ motion presents a more complex flow with the merging of LEV and TV.

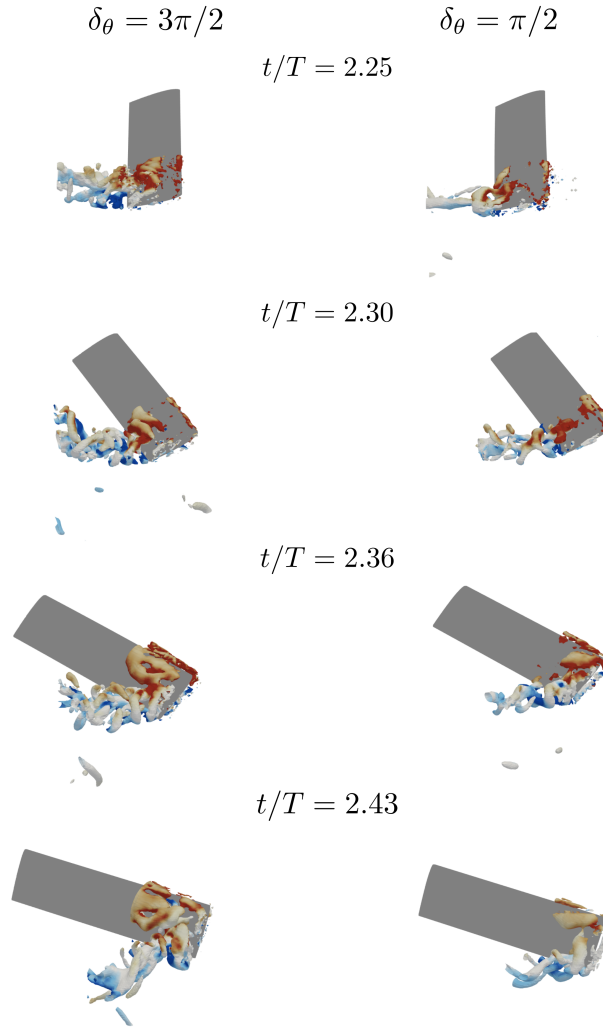


Figure 5. Q -criterion isosurfaces, $Qc^2/U^2 = 10$, colored by non-dimensional spanwise vorticity $\omega_z c/U$ during the second half of a downstroke phase for both $\delta_\theta = 3\pi/2$ (left column) and $\delta_\theta = \pi/2$ (right column) motions.

4. Conclusions

The influence of active bending of a three-dimensional hovering flapping wing on flow structures has been studied experimentally using 3D3C TR-PIV. The latter is based on a scanning technique consisting in illuminating consecutive adjacent planes with thin laser sheets. The active bending is realized using piezoelectric actuators that are embedded inside the flapping wings. Using such actuators, we are able to phase-shift the bending motion with respect to the flapping motion. We thus studied two configurations where bending phase-shift results in either the wing covering a larger or a smaller amplitude than that of the rigid wing. Configurations exhibit substantial differences in terms of flow structures. Specifically, vortical structures are more intense and more prone to unsteady behavior in the large-amplitude configuration with respect to the low-amplitude

kinematics.

Acknowledgements

This work was supported by the French government program “Investissements d’Avenir” (EUR INTREE, Reference No. ANR-18-EURE-0010). The experiments were carried out on the Plateforme Hydrodynamique Environnementale (pHE). Authors greatly acknowledge R. Bellanger, B. Robert and Y. Salinesi without whom this study would not have been possible.

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