

Aerodynamic Analysis of a Bioinspired Multilayer Flexible Wing

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Abstract - In this paper, aerodynamic characterization and performance analysis of a bioinspired multilayer flexible wing are discussed. Our membrane wing that consists of two separate layers can achieve better performance for applications utilizing flapping wing locomotion. This novel wing has two distinct features, the first, a passive shape deformation that is dependent on the direction of the aerodynamic loading on the wing surface, thus can reduce the negative lift of the upstroking wing without a complex mechanism required for active pitching. The other feature is the vortex trap mechanism realized by the separation of the layers at upstroke that results in a large scale vortex above the upstroking wing. This vortex can also generate additional lift by preserving a low pressure core. These features are inspired by the active wing shape control of birds, as well as an unsteady aerodynamic mechanism called clap and fling exhibited by several flying insect species. Such passive shape control on membrane wings could be utilized on micro air vehicles featuring a simple flapping mechanism design to achieve robustness and light weight.

Keywords: Micro Air Vehicle (MAV), Flapping flight, Passive shape control, Low Reynolds number aerodynamics.

1. Introduction

Flapping flight locomotion is seen to be feasible and superior for the design of Micro Aerial Vehicles (MAVs) conceptually limited to the size of less than 15 cm. In a low Reynolds number region, where MAVs and natural flyers operate, viscous forces and unsteady aerodynamics that account for a number of unique phenomena (wing attached vortices, clap and fling, wake capture, rapid pitching motions) must be considered. At such conditions, traditional designs are disadvantaged over a flexible flapping wing which can extract additional aerodynamic forces through unique unsteady flow mechanisms [1-5]. Bio inspired designs offer a viable solution to the design of MAVs. BionicOpter [6], a recently developed dragonfly like MAV uses a rather sophisticated flapping mechanism that controls each wing's flapping frequency, flapping amplitude and wing rotation throughout the stroke cycle. It has a wingspan of 630 mm and a body length of 440 mm. DeFly micro [7] another highly successful 4 winged MAV having a wingspan of only 100 mm uses a simpler wing flapping mechanism due to weight limitations, but is able to harvest additional aerodynamic force through the so called clap and fling mechanism [8] 3 times in a stroke cycle. Clap and fling is an unsteady lift generating mechanism showcased by wasps [8] and damselflies [9] for example. Robobee [10] a bee mimicking real insect size MAV, on the other hand, uses an even more simple flapping mechanism utilizing piezoelectric actuators and a passive pitching mechanism, but demonstrates high flight stability through sophisticated control of the individual wings. Another study evaluated the effect of outer wing separation on lift and thrust generation in a flapping wing system that closely mimics the feather separation of birds during slow forward flight and hovering, demonstrating improved lift and thrust force generation [11]. These examples show that weight constraints, energy efficiency and robustness of a MAV demands simplicity that can be achieved through creatively implementing techniques learnt from nature.

Hovering flight capability is of key importance for a number of intended MAV missions. In nature, two strategies of how flapping flyers generate lift force for hovering are observed. Quasi symmetric horizontal strokes can generate lift force based on the thrust force of the wings, as shown by hummingbirds [1-2]. Hovering with inclined stroke plane can generate lift force mainly based on the drag force of the wings. In this case the flapping is highly asymmetric; the projected area of the wings and the duration of the upstroke are often reduced at the upstroke to reduce drag. Evolution resulted in an excellent adaptation of the skeletal and muscular system of birds that makes it possible for them to extend their wings during downstroke, and flex them backwards during upstroke to reduce drag; a flapping behavior called "avian stroke" [12]. Birds are also capable of increasing the gap between their tip feathers during upstroke to further decrease drag

[1][13]. On the other hand, hovering insects move their wings solely by muscles attached at the wing root. Insects generally show more complex wing kinematics, involving passive shape deformation. Dragonflies are known to be one of the most acrobatic flying insects capable of hovering with inclined stroke planes while maintaining their body orientation horizontal [14][15]; a feature highly desired by future MAV designs. Dragonflies pose two key features in achieving stable hovering flight with an inclined stroke plane. The tandem wing arrangement allows energy extraction by the hindwing from the wake of the forewing [15][16]. In addition, phasing of the wings produces a more stable lift, benefitting stability and reduced vibration [17]. Another feature is the anisotropic wing structure of dragonflies that results in different wing deformation depending on the orientation of surface loading. This feature supposedly helps reduce drag on the upstroking wings by decreasing projected area of the wings [18][19]. There is ongoing research to study the passive wing deformation of dragonfly and other insects due to aerodynamic loading.

In this study a novel wing concept is proposed and its aerodynamic performance is evaluated. The wing consists of a rigid and a flexible layer, producing spanwise separation of the layers at upstroke, while forming a single flexible layer at downstroke. Force measurement was conducted on a scaled model with a comparable aspect ratio (AR) to dragonfly wings, to assess the performance of the wing, to provide a comparison with the rigid wing and single layer flexible wing. Flow measurement with digital particle image velocimetry (PIV), has been done on a larger model to explain the measured force data and quantify operation of the wings in downstroke and upstroke.

2. Experimental setup

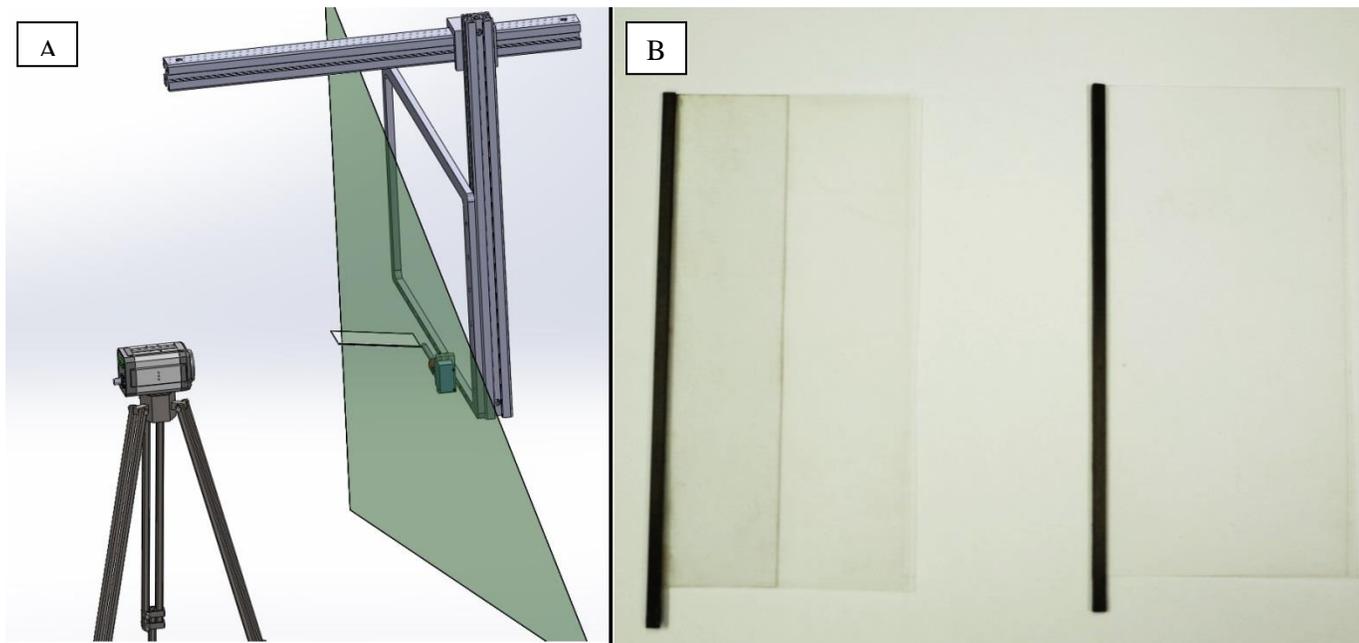


Fig. 1: The measurement arrangement and the tested AR 2 wings.

Figure 1A shows the experimental arrangement that was essentially the same for the force measurement and the flow measurement. The experiment was conducted in a water tank measuring $1.2 \times 0.8 \times 1$ m (L x W x H). The wing was placed around the middle of the tank and submerged 0.4 m in the water. The unsteady force on the flapping wing model is measured using a six-axis force/torque sensor (NANO17, ATI Industrial Automation, Inc.). The sensor is installed at the base of the rod holding the wing and rotated together with the wing to simultaneously measure the normal and tangential forces to the wing surface. The signals from the force/torque sensor are acquired at the sampling rate of 1000 Hz with an averaging of 16, resulting in an effective sampling rate of 62.5 Hz, using a data-acquisition board (NI USB-6210, National Instruments Co.). The force readings were low pass filtered. During the data acquisition, the effect of gravity (or buoyancy) is subtracted by biasing the force sensor. The effects of the added mass and inertial force are assumed to be negligible [20].

The measured forces can be conveniently transformed to the vertical axis resulting in the lift force; while in the axis of rotation the measured third force component directly gives the thrust force generated by the flapping wing.

The flow field was measured with a traditional phase locked PIV system. The flow was seeded with silver coated hollow glass spheres of 10 μm diameter. A signal was generated by the servo controller to trigger the camera and the laser pulse when the wing was at its mid upstroke and downstroke. The up and downstroke frames were recorded separately, one minute after the wing started flapping. At every second flapping cycle two frames were recorded by the high speed camera with 2 milliseconds time difference. 2D velocity field was calculated from each frame pair with a final interrogation window size of 32 x 32 pixels using an overlap of 50%. The vector field was subjected to median filtering. Finally 10 (for AR 4 wings) and 20 (for AR 2 wings) vector fields were averaged and smoothed.

The main focus of this study is to evaluate the feasibility of a novel multilayer wing design (Figure 1B) to be utilized on a flapping wing MAV. For simplicity the wings have a rectangular form, with the rigid layer having a chord length half that of the flexible layer. The layers are fixed together at the leading edge to a carbon fibre spar that is moderately flexible in the spanwise direction in the case of AR 4 wings, and rigid in the case of AR 2 wings. The wing is connected to the rotating shaft solely through the leading edge spar so the wing membrane can freely deform in the chordwise direction.

Conceptually, the multilayer membrane wing has two key features. Firstly its deformation is dependent on the load direction. In the downstroke phase, the two layers stick together resulting in higher rigidity that helps generate substantial vertical force by the larger drag of a wing flapping in an inclined stroke plane. In the upstroke phase the layers separate, thus the wing has a smaller projected area and the negative vertical force generated by drag decreases. This mimics the avian stroke as well as the asymmetric shape deformation of wings observed on dragonflies. This feature comes in a passive way that is easy to implement on a MAV.

Secondly, the separating layers at the upstroke phase form a lower pressure region, resulting in the formation of a new circulatory region. With the formation of an attached vortex on the wing's upper surface it is expected that additional lift force could be utilized to negate the upstroke drag's negative vertical force. This feature mimics, in some way, the clap and fling mechanism to facilitate a vortex trap. To anchor a large scale vortex by specifically designed airfoils to enhance lift generation is the focus of many studies since 1959 [21][22][23], however we have no knowledge of any similar designs for flapping thin membrane wings.

3. Results and Discussion

3.1. Force measurement

Force measurement was taken on rigid, flexible and flexible multilayer wings. The aspect ratio of the wings was 4 considering the chord and the length from the rotational axis. This is comparable to that of a dragonfly wing's aspect ratio. Note that the diameter of the rotating shaft holding the wing is 8 mm, and a gap of 1 mm was left between the shaft and the wing membrane to facilitate free shape deformation (there was no gap in the case of the rigid wing). Other properties of the wings are listed in Table 1.

The parameters of the flapping kinematics were set to be comparable to the conditions for a dragonfly's wings to operate. The flapping was set to be a simple sinusoidal motion with amplitude of 60 degrees. The flapping frequency was set for 0.5 Hz. This resulted in a Reynolds number of 6675, considering the average wingtip velocity as reference velocity and chord length as reference length. The reduced frequency was 0.375. In the following, we present the time histories of forces, relative to each other, of the tested wings to compare their performance. By presenting results relative to each other we eliminate any possible internal calibration error of the force sensor.

The single layer flexible as well as the rigid wing operates symmetrically in downstroke and upstroke, thus we only consider the downstroke phase here. The lift coefficient is higher in the case of the rigid wing in the first half of the stroke, while in the second half the flexible wing performs better. By averaging 3 cycles we found a 7.51% gain in the cycle averaged lift force for the downstroke phase favouring the flexible wing. Thrust is also generated as the chordwise flexible wing passively pitches, making a relative angle of attack throughout the stroke.

Even though the multilayer flexible wing improves cycle averaged lift generation by 1.5%, it loses substantial thrust of 22.8% compared to the single layer flexible wing. Considering the lift force, the multilayer wing gains additional lift at the first half of both the up and down stroke, while outperformed by the single layer flexible wing at the second half. The multilayer wing loses substantial thrust at the down stroke phase.

Table 1: Summary of experimental conditions.

	AR 4 Rigid wing	AR 4 Flexible single layer wing	AR 4 Flexible multilayer wing
Dimensions of the wing	160 x 40 mm	160 x 40 mm	160 x 40 x 20 mm
Membrane thickness	1 mm	0.15 mm	0.15 x 0.5 mm
Dimensions of the LE spar	-	3 x 0.5 mm	3 x 0.5 mm
Flapping amplitude	60 degree	60 degree	60 degree
Reynolds number	6675	6675	6675
Reduced frequency	0.375	0.375	0.375

	AR 2 single layer wing 1	AR 2 multilayer wing 1	AR 2 single layer wing 2	AR 2 multilayer wing 2
Dimensions of the wing	120 x 60 mm	120 x 60 x 30 mm	120 x 60 mm	120 x 60 x 30 mm
Membrane thickness	0.14 mm	0.14 x 0.3 mm	0.2 mm	0.2 x 0.5 mm
Dimensions of the LE spar	3 x 1 mm	3 x 1 mm	3 x 1 mm	3 x 1 mm
Flapping amplitude	80	80	80	80
Reynolds number	10013	10013	10013	10013
Reduced frequency	0.56	0.56	0.56	0.56

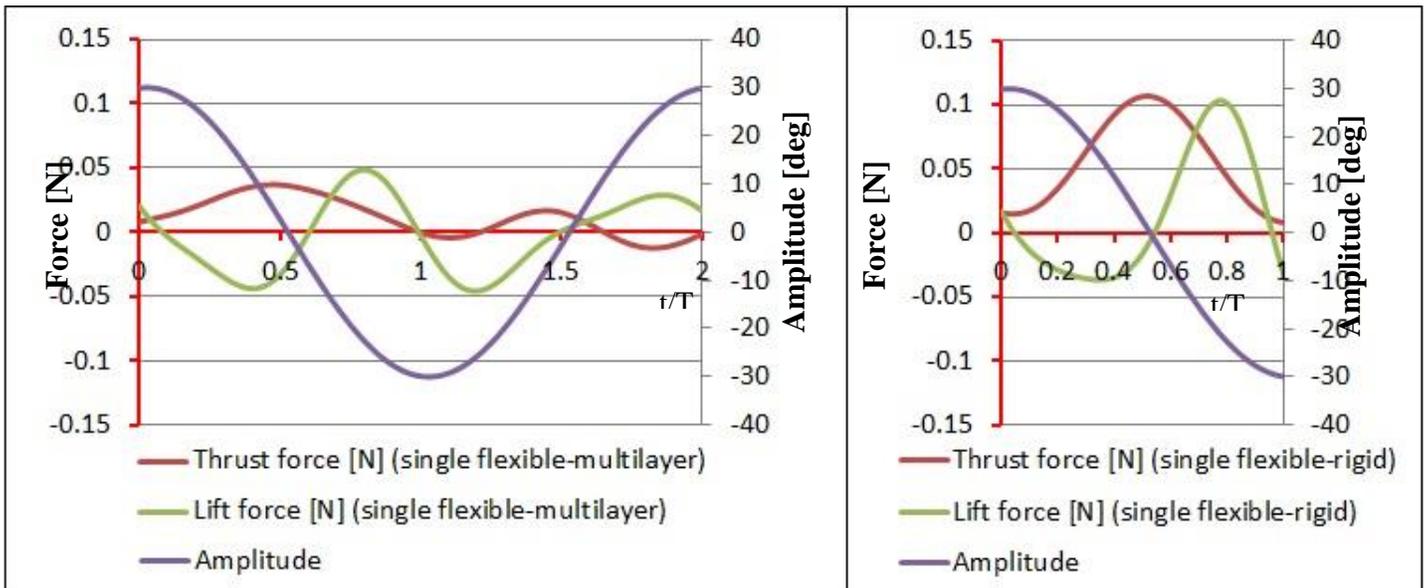


Fig. 2: Comparison of force gain between the three types of AR 4 wings tested.

For the single layer flexible wing to outperform the multilayer wing was unexpected. However, it can be explained. Observing the wing in operation we can see that the leading edge spar is bending, making the wing spanwise flexible. A spanwise twisting also could be observed. This results in a small separation between the layers at upstroke that can prevent the formation of an additional circulatory region. The limited lift improvement still encourages us to further study the multilayer wing. Improving the leading edge spar's rigidity, as well as using more flexible material for the lower layer of the wing, could result in higher gain on lift.

3.2. Flow visualization results

Seven wing models have been tested with traditional phase locked PIV measurement. One set of measurements were made on the same wings as the force measurement, to confirm the effect of the separating layers on the flow structures. In case of the second set of experiments, we set different conditions: lower aspect ratio, higher flapping amplitude, stiffer leading edge spar. Four wings have been tested initially, to confirm the effect of flexibility, and to achieve a better resolution on visualizing the flow between the separating layers. Experimental conditions are summarized in table 1.

Figure 3 shows vorticity contours in the case of the AR 4 wings used for the force measurement, at midspan at mid upstroke and at mid downstroke (in the case of the rigid and the single layer flexible wing the downstroke and the upstroke is essentially the same so we only present the upstroke for that wing).

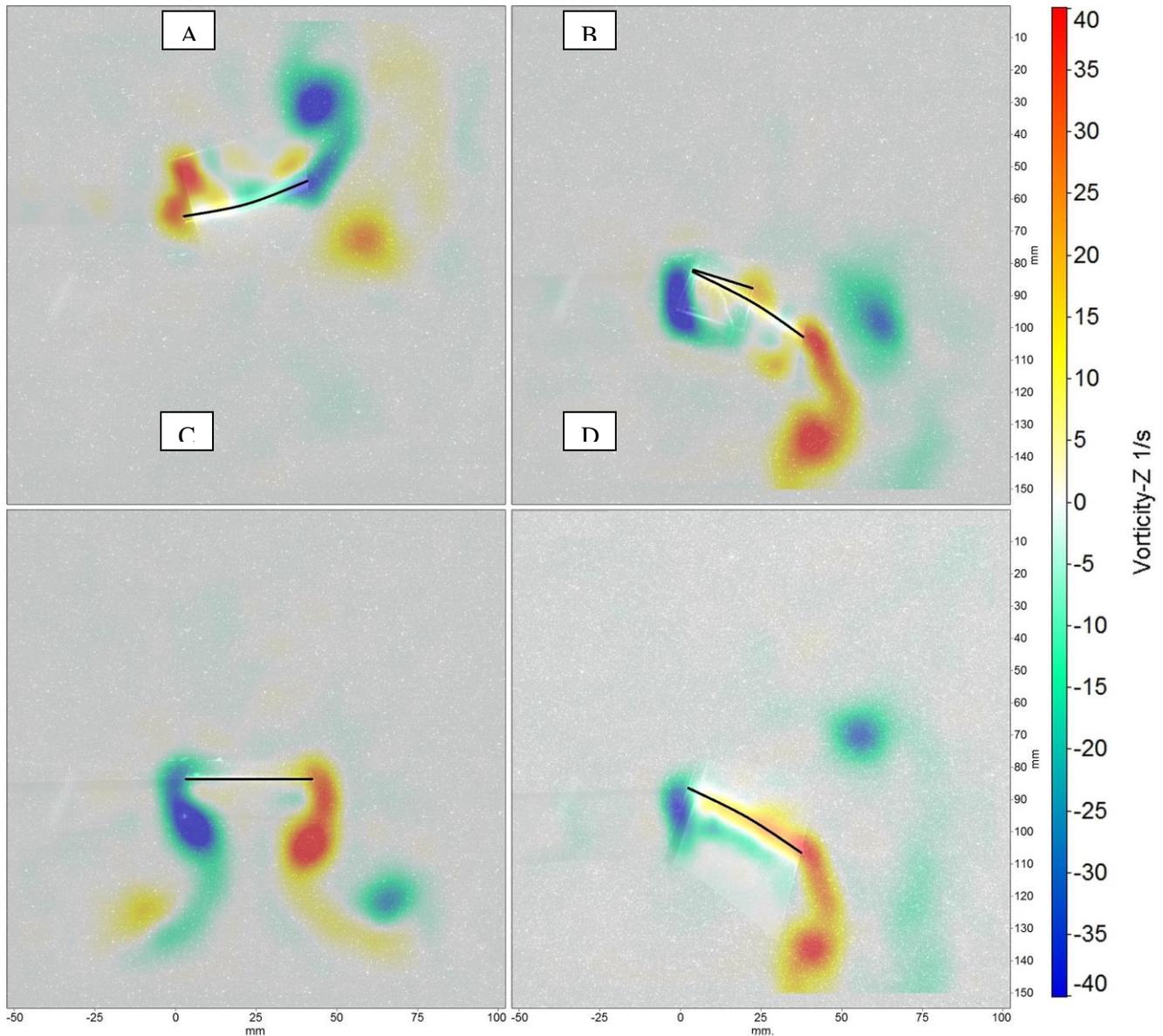


Fig. 3: Vorticity contours of the studied AR 4 wings: A, flexible multilayer wing downstroke; B, flexible multilayer wing upstroke; C, rigid wing upstroke; D, flexible single layer wing upstroke. (The leading edge of all the wings is on the left.).

From the images we can see that the flexibility of the membrane affects the shedding of the trailing edge vortex (TEV). Accordingly, the multilayer wing shows an earlier TEV shedding in its upstroke, quantitatively the same as the flexible single layer wing, however in its downstroke as the two layers together result in an effectively more rigid

membrane, the TEV sheds later (that is similar to the case we observe at the rigid wing, when the distance between the wing edges and the shed vortices are the smallest). The different TEV shedding results in the two counter rotating shed trailing edge vortices being closer to each other in the upstroke phase of the multilayer flexible wing, generating a jet between the vortices that results in higher thrust generation in the upstroke phase. This explains why no substantial thrust force difference has been measured between the multilayer and the single layer flexible wings at upstroke (Figure 2). The separating layers produce a clockwise rotation of the flow at upstroke; however from the resolution of our measurement on AR 4 wings it is not clear if a vortex is formed in the gap.

For the second set of wings we used different scaling to gain higher resolution, which helps us observe how the gap between the separating layers affects the flow. Two wings with different flexibility have been tested, both multilayer and single layer, to test the effect of flexibility on the flow. Results are shown in Figure 4-5. When we compare the multilayer and the single layer wings, we can see that the multilayer wing generates stronger leading edge vortices, which can be the result of reinforced torsional rigidity because of the thicker membrane layers at the overlapping region of the two membranes (Figure 5 B-E and D-F). This results in a larger effective angle of attack at the leading edge as the wing cannot twist as much as the single layer wing. Similarly the shed TEV is stronger in the case of the multilayer wings. In the multilayer wing we can clearly identify a circulatory region between the gap of the separating layers, and it is stronger in the case of the more flexible wing where the gap is larger (Figure 5 B-D). The results show that a more flexible separating membrane enhances the vortex strength in the gap, while the leading edge vortex is not affected substantially by this change.

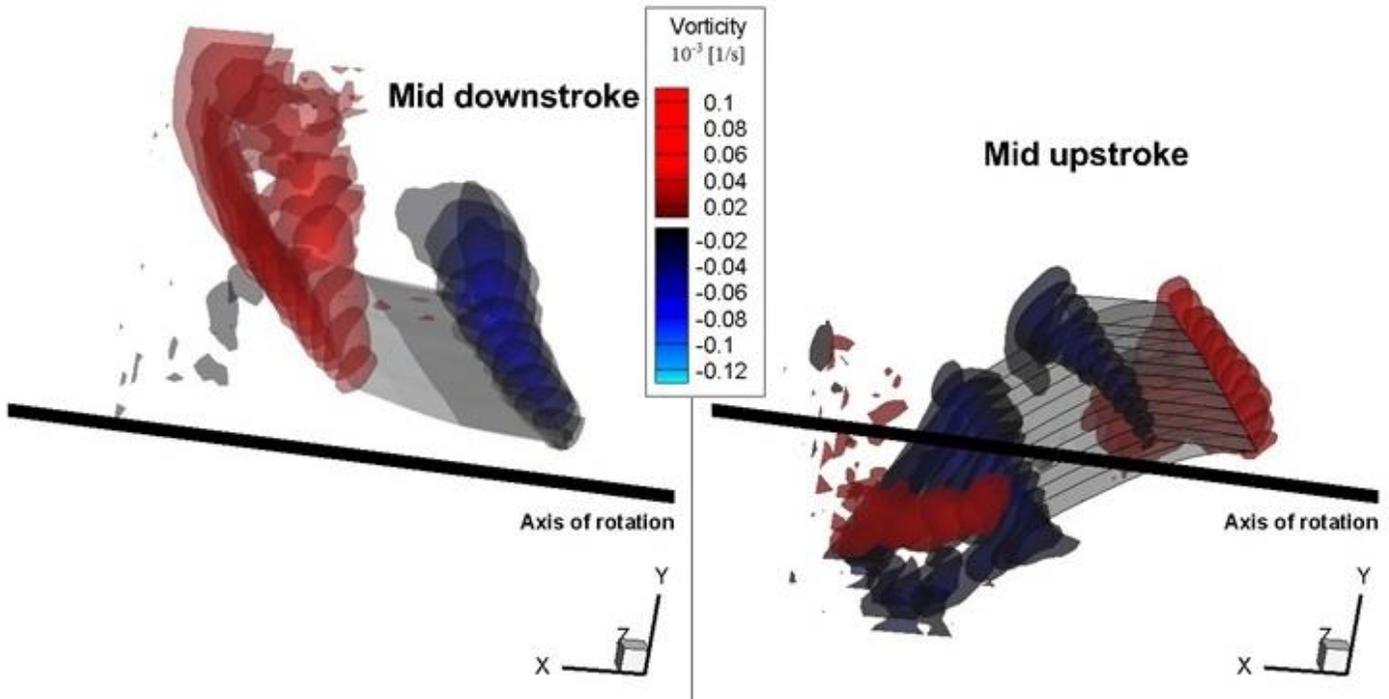


Fig. 4: Vorticity contours along the span of the AR 2 multilayer wing 2 (more rigid).

To represent the overall flow structure of the multilayer wing, we have measured the flow field at every 10 mm from the wingroot to the wingtip of the AR 2 multilayer wing 2, which was the more rigid one. The results show that the vortex strength in the gap between the separating layers gradually increases along the span (Figure 4). This gradual increase of vortex strength is observable for both trailing and leading edge vortices, however less pronounced as those vortices can detach from the wing surface after reaching a critical value; on the other hand the vortex between the separating layers is more confined in space thus its shedding behaviour is different.

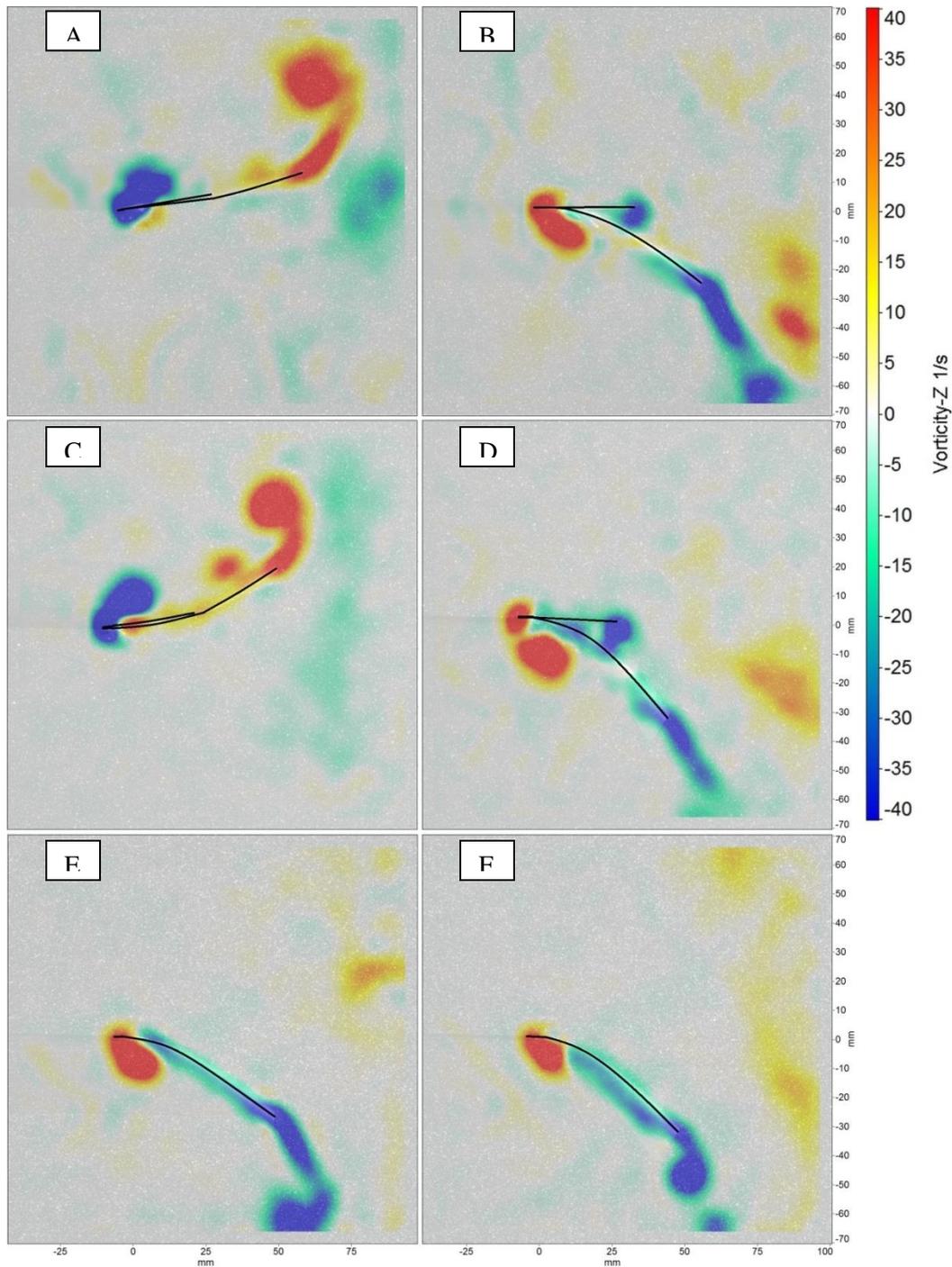


Fig. 5: Vorticity contours of the studied AR 2 wings: A-B, downstroke and upstroke of the multilayer wing 2 (more rigid); C-D, downstroke and upstroke of the multilayer wing 1; E, upstroke of the single layer wing 2 (more rigid); F, upstroke of the single layer wing 2. (The leading edge of all the wings is on the left.)

4. Conclusion

A novel membrane wing design has been studied by force and flow measurement. The multilayer wing deforms differently in the upstroke and the downstroke phase. Lift force generated by the wing is improved however thrust output of the wing is less compared to a single layer membrane wing of the same flexibility. Flow measurement on a larger scale

model proves the existence of an attached vortex on the upper surface of the wing between the separating layers at upstroke. This vortex can theoretically generate a useful aerodynamic force. The strength of this vortex depends on the flexibility of the wings and can be tuned for a more optimal performance.

We plan to test a wider range of wing materials to achieve optimal performance. This passively deforming wing could be utilized for MAV designs using simpler flapping mechanisms; generating lift, based on drag force.

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