

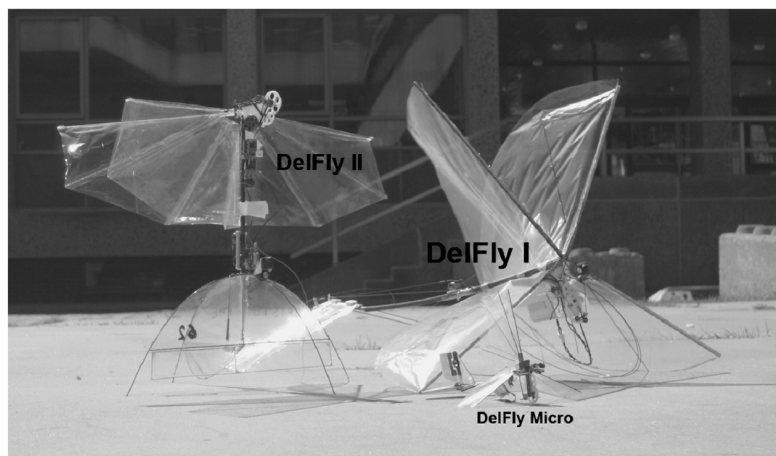
## Numerical simulation of “X-wing” type biplane flapping wings in 3D using the Immersed Boundary Method (IBM)

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### ABSTRACT

The numerical simulation of a “X-wing” type biplane flapping wings, has been performed in 3D using the Immersed Boundary Method (IBM). This “X-wing” type flapping configuration draws its inspiration from Delfly [1], a family of ornithopters developed by the Delft University of Technology, as shown in Figure 1. The unique “X-wing” design features a biplane flapping wings where two sets of wings were placed above each other moving in counter phase. On comparison with configurations using a single pair of wings or two sets of wings in tandem, experiments showed that the “X-wing” configuration gives lower power requirement and zero rocking amplitude, which is a beneficial property for a Flapping Micro Aerial Vehicle (FMAV) to be used as a camera platform.



**Figure 1:** Different versions of Delfly: I, II, Micro.

There are currently limited studies on “X-wing” type biplane flapping configuration, especially in 3D. One of the main reasons is due to the difficulty in simulating two independently moving wings in close proximity. Tuncer and Kaya [2] performed 2D simulations using the overset method and found that the biplane flapping configurations can give higher thrust compared to a single flapping airfoil. Nakata et al. [3] also used an overset method to simulate the “X-wing” flapping configuration in 3D and found improvement as a result of the clap and fling mechanism, which arises from the “X-wing” flapping configuration. Besides the overset method, another viable method to simulate the complex “X-wing” configuration is the IBM, which has been shown in many cases to simulate moving bodies successfully [4]. Tay et al. [5] used the IBM to investigate the interference effects of the flapping biplane airfoils and its tail in 2D. Results show that high lift or thrust can be generated depending on the relative distances of the airfoils/tail and the angle of attack of the tail.

The current study performs simulation on the “X-wing” type flapping configuration in 3D using the IBM. The current solver uses the IBM based on Yang [6] and Liao [7], which uses the discrete forcing approach. An external forcing term ( $f_c$ ) is explicitly added to the momentum equation, as shown in Eq. (1), which signifies the presence of the solid body. The forcing term is provisionally calculated explicitly using an Adam-Bashforth second order (AB2) scheme while the time integration scheme uses a semi-implicit AB2 scheme.

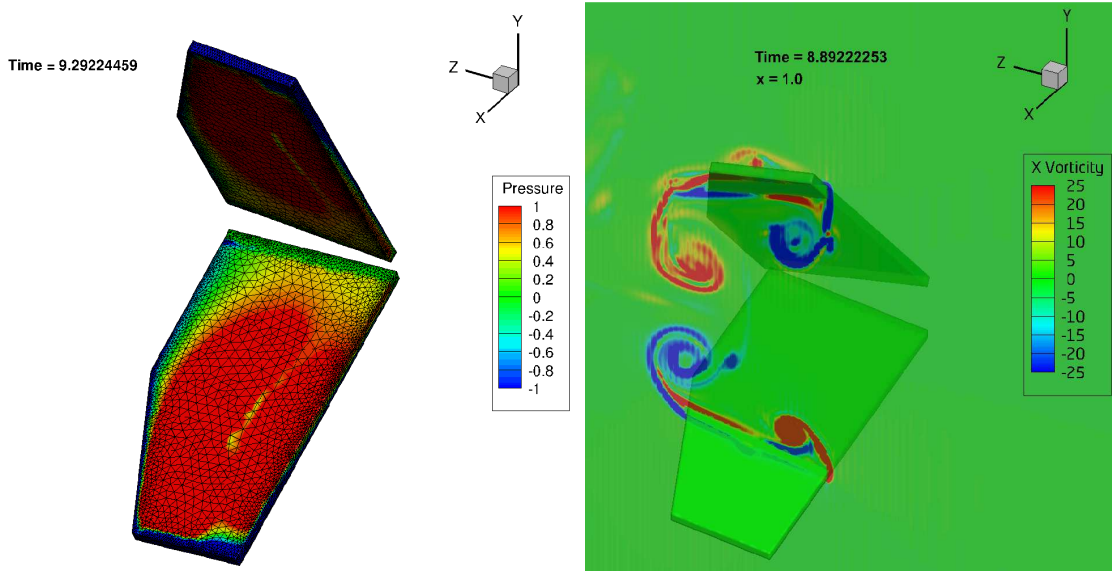
$$\frac{\partial u}{\partial t} = -u \cdot \nabla u + \frac{1}{\text{Re}} \nabla^2 u - \nabla p + fc \quad (1)$$

A fractional step method, which is based on an improved projection method [8], is used to solve the modified non-dimensionalized incompressible Navier-Stokes equations. Due to the complexity in the design of Delfly, some simplifications have been used in the simulation. The wings are simulated using rigid thin plates with and without prescribed flexibility, as opposed to using thin membranes which flexes according to fluid structure interaction. At the root of the wings, a small amount of clearance (equivalent to 0.3 chord length) is added between the two wings to prevent the wings from intersecting one another. The actual Re of Delfly in forward flight is around 9k. At this Re, the 3D flow structures are significantly more complex due to the smaller scales vortices associated with transition. This can hinder a systematic analysis of the results. Hence, the simulations are run at a lower Re of 1k and 5k. Despite the simplifications, valuable insights can still be obtained from the simulation.

There are four objectives to be achieved in this study:

1. Evaluate and compare the effects of Re at 1k and 5k.
2. Compare the performance of the “X-wing” type flapping configuration with the more common single wing flapping configuration.
3. In the forward flight of Delfly, its body inclination angle is always non-zero. Hence, we would like to evaluate the effect of simulating at a body inclination angle of 30 degrees.
4. Prescribed deformation of the wings are applied to compare their differences with rigid non-deforming wings.

The simulation results are analyzed in terms of thrust, lift, efficiency, vorticity and wing surface pressure, as shown in Figure 2. The simulation and analysis of results are still ongoing. Preliminary results show that there is a conclusive advantage to using the “X-wing” type flapping configuration, which gives higher thrust compared to the single wing configuration. In the comparison of 0 and 30 degrees inclination angles, the drag variation over one period is very different from one another. It is not simply a projection of forces. It is also found that changing the Re from 1k to 5k resulted in the breakup of vortices into smaller scales. However, the force outputs for the two Re cases are very similar. These results provide a deeper understanding in the underlying aerodynamics of the “X-wing” type flapping configuration, which will help to improve the performance of FMAV using this unique configuration.



**Figure 2:** Instantaneous wing surface pressure (left) and X vorticity contours at  $x = 1.0$  (right)

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