Analysis And Optimization of Dragonfly Wing

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Abstract: The dragonfly's wings are flexible dynamic structures. In order to study them, the fluid structure interaction of the wing has to be well understood. In the current study, interaction of dragonfly's wing with air is modelled using Navier Stokes equation for the fluid motion and a set of algebraic path functions for the motion of the wing

In this work, a 2-D model of a NACA-2415 airfoil is taken as a wing first and then two airfoils moving out of phase with each other are tested in COMSOL MULTIPHYSICS 5.2 software using Fluid-Structure Interaction (FSI) module. The motion of the wings is shown in the figures and the plots of lift and drag are plotted. This study explores the thrust and lift generation mechanism of flapping wing which can further be exploited for optimal design of flapping MAVs.

Keywords: Dragonfly, Wings, FSI, Moving mesh, COMSOL

1. Introduction

Dragonflies are nature's wonderful creature. In general, large dragonflies have a maximum speed of 10–15 meters per second (22–34 mph) with average cruising speed of about 4.5 meters per second (10 mph).

Dragonfly flight, as with general insect flight, is a rich field of research. Dragonflies unlike conventional aircrafts can twist their wings, therefore eternizing the desired aerodynamic forces. Their wings are mainly composed of veins and membranes. Due to these veins and membranes, dragonflies are able to perform maneuvers. Their excellent flying characteristics inspire researchers to create biomimetic design for MAVs [2]. Now the question is, why only study dragonfly's motion when there are other insects too that can fly? The reason is dragonfly wings generate substantial lift in a steady flight than any other insect.

Weis Fogh [3] first proposed the clap and fling mechanism to understand the lift generation in dragonflies. The details of this mechanism are explained in the work of Lighthill [4].

The lift is generated by four mechanisms, namely

- Classical lift
- Supercritical lift
- Vortices
- Vortex shedding

Thrust is generated both by movement of the wing through the air and by the twisting of the wing (supination/pronation) at the ends of each stroke [5]. Dragonflies take advantage of dynamic stall and large angle of attack for high maneuverability.
Studies show that the wake structure of the wing is significantly distorted due to wing-wing interaction during dorsal reverse stroke; where at certain motion a new vortex ring is formed and slowly develops through the entire second half-stroke [6].

This paper presents the motion visualization, pressure distribution and forces acting on the wings of the dragonfly.

2. Theory

Considering the flow around the wings to be compressible, the equations used by the solver are Navier Stokes equations as stated below:

$$\rho\frac{\partial u_{fluid}}{\partial t} + \rho(u_{fluid}.\nabla)u_{fluid} = \nabla.[-p\boldsymbol{I} + \mu\left(\nabla u_{fluid} + \left(\nabla u_{fluid}\right)^T\right) - \frac{2}{3}\mu(\nabla.u_{fluid})\boldsymbol{I}] + \boldsymbol{F}$$

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u_{fluid}) = 0$$

$$\frac{\rho \partial^2 u_{solid}}{\partial t^2} - \nabla.\sigma = \boldsymbol{F}v$$

Here, $u_{bd} = u_s$

u_{fluid} = fluid velocity

u_{solid} = solid's velocity

p = pressure

ρ = density of the fluid

F = volume force vector

T = absolute temperature

μ = dynamic viscosity

u_{bd} = velocity at the boundary

u_s = velocity of the solid.

The Navier–Stokes equations have no known general analytical solution, but local solutions can be derived in the vicinity of critical points in the flow [1].

The flow is also characterised by low Reynolds number which is given by:

$$R_e = \frac{\rho u L}{\mu}$$

Where, L= representative length of wing

The Navier-Stokes interface automatically calculates the local cell Reynolds number $\mathbf{u}_{fluid}$

$$R_e{}' = \frac{\rho u h}{2\mu}$$

Using the element length *h* for *L* and the magnitude of the velocity vector *u* for the velocity scale *U*.

In low Reynolds number flow, the viscous effects dominate which are considered in Navier Stokes equation and the flow is laminar.

3. Wing Motion

3.1 Single Wing

The wing of a dragonfly follows path "8" which may or may not be inclined to horizontal. In this study, it is perpendicular to the horizontal direction. The dragonfly uses rowing motion along an inclined stroke plane. During hovering, the body lies almost horizontal. The wing push backward and downward and at the end of the stroke, feather and slice upward and forward [7]. In contrast many other hovering insects use a symmetrical back and forth stroke near a horizontal stroke plane which generates lift in both half strokes [7].

The dragonfly's asymmetric rowing motion generates lift mainly during the downstroke [8] and allows it to support much of its weight by the upward drag created during the downstroke; for the more common symmetric motion, the drag roughly cancels [7].

In this work, the overall path has been divided into four segments and each segment has been simulated for 10 seconds.

The first segment is the downward stroke inclined at a 145^o to positive x direction while the wing is inclined at an angle of attack of -45^o. The second segment is an inverted semicircular transition phase taken at 0^o angle of attack to the next segment. The third segment is the upward motion inclined at 45^o to positive x direction while the wing is at an angle of attack of 90^o. The fourth segment is a semicircular transition phase taken at 0^o angle of attack back to the first segment.

3.2 Two Wing

In the two-wing motion, the wings of dragonfly move downward and backward and then upward and forward. The asymmetrical flapping of its wings causes the downstroke to create drag which supports the weight of the dragonfly. This motion also helps the dragonfly to conserve energy. When the wings move out of phase, an induced flow is created by the hind-wing which reduces drag on the fore-wing.

In this work, the second wing follows the same path as the first except they are at a phase difference of 180^o. That is when the first wing is in first segment of the path, the second wing is in the third segment of the path.

4. Use of COMSOL Multiphysics® Software

Our approach to simulate wing motion requires the use of FSI physics along with advanced features of COMSOL in which structural mechanics is used to move the solid geometry with large distortions in surrounding fluid domain and fluid mechanics to simulate the motion. The most important aspect is to use moving mesh setting to solve the FSI and remeshing to track the motion of the wing.

As specified earlier, the wing of the dragonfly is modelled as an airfoil undergoing displacement in fluid (air). Several properties such as incoming velocity (10m/s), prescribed velocity of the wing (as path functions in the xy plane as a function of time) have been specified. With the time varying study, the motion of the wing is analysed. As the wing displaces in the fluid, continued remeshing is required because due to large displacements, the mesh distorts. So to obtain an accurate result and solve the model, automatic remeshing is used.

6. Results

The plot (Figure 1) shows that for a single wing most of the lift is generated in the first 10s of the motion which is the downward inclined stroke.

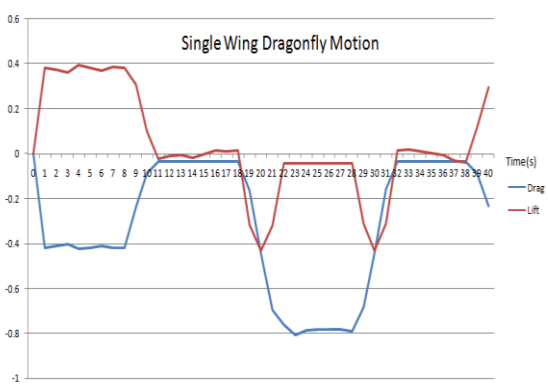

Figure 1: Shows the lift and drag on the airfoil (2D wing) with time. The airfoil changes its angle of attack from -45^{o} (0-10s), 0^{o} (10-20s), 90^{o} (20-30s), 0^{o} (30-40s).

The plot (Figure 2) shows that for two wings, most of the lift is generated in the first (0-10s) and the third (20-30s) segments of the motion which are the downward inclined strokes of the fore and the hind wings respectively. The dip in the lift curve is due to the flow disturbance when they cross each other.

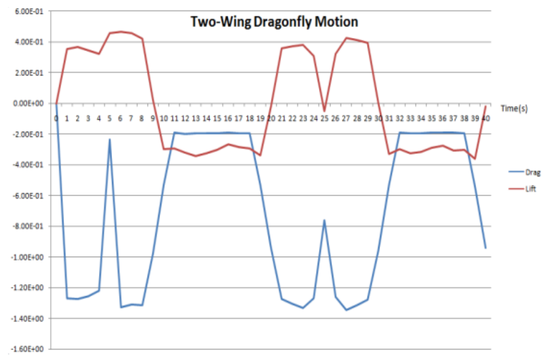

Figure 2: Shows the lift and drag vs time on two airfoils (2D wings) at a phase difference of 180deg in the motion. The airfoils changes its angle of attack from -45^{o} (0-10s), 0^{o} (10-20s), 90^{o} (20-30s), 0^{o} (30-40s).

Figures 3 and 4 depict the flow visualization of a single airfoil and two airfoils. The disturbances in the flow field are shown by the variation in colors.

It is important to keep in mind that the frequency of the periodic motion of the wings is very high. The first and third segments constitute most of the time period, while second and forth segments are just the transitionary phases.

7. Conclusion

In this study, it is shown that the application of the second wing increases the total lift generated in one cycle as compared to single wing. The complex wing motion of the dragonfly is successfully simulated using COMSOL.

Future studies may include the inclination of the path with the horizontal axis, and/or changing the angle of attack of the wing in the various segments.

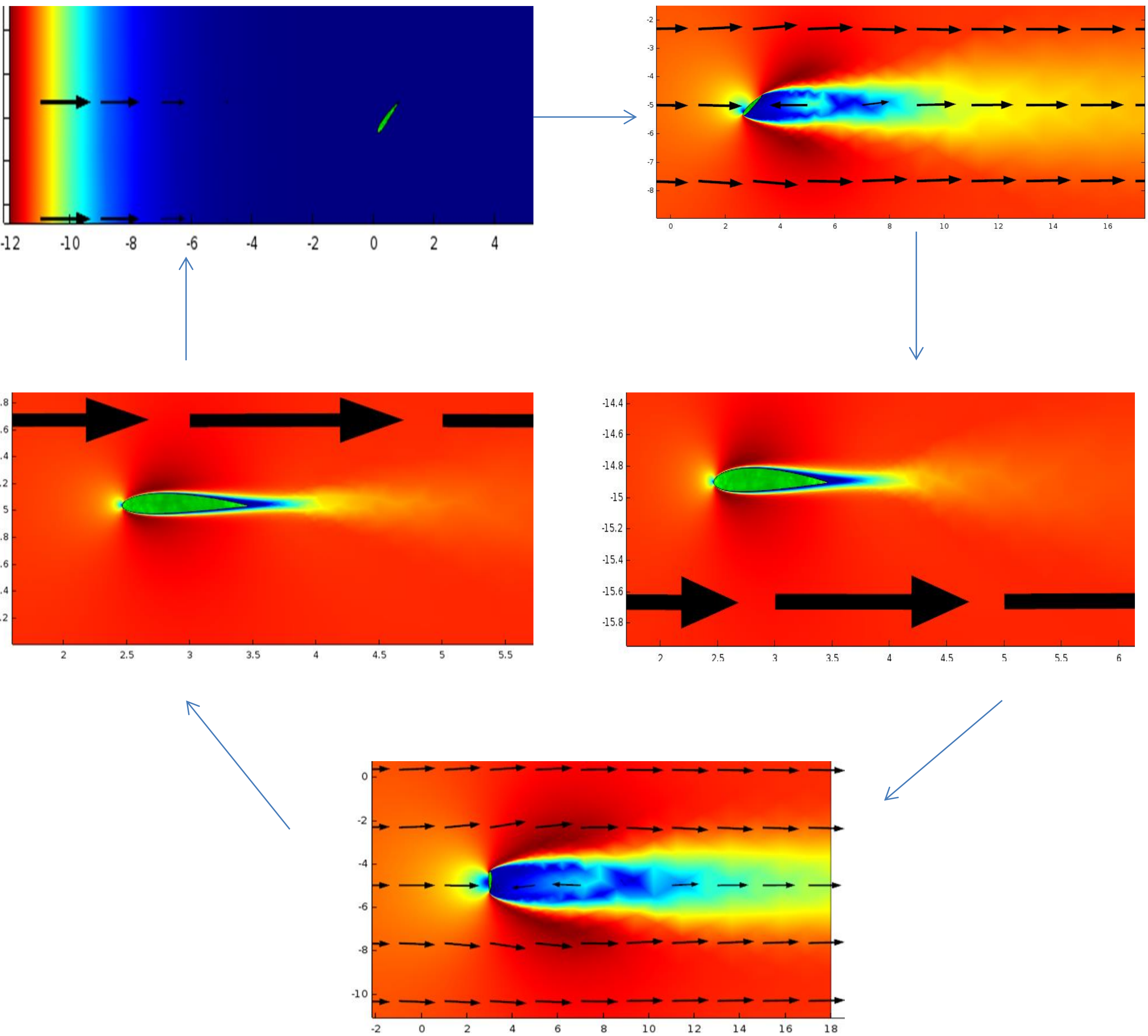

Figure 3: Shows position of the single airfoil at t= 0,5,15,25,35s in clockwise sense

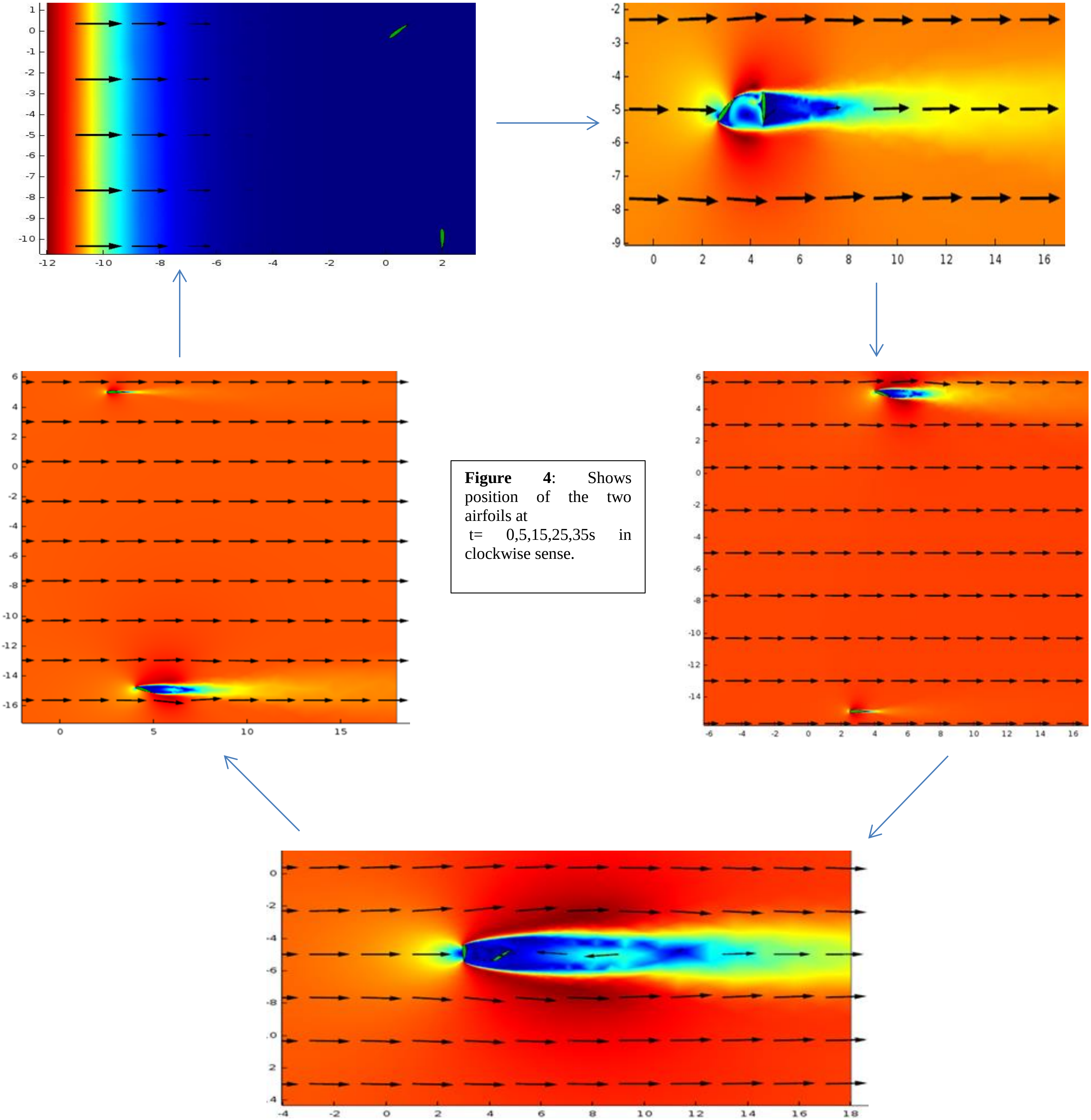

Figure 4: Shows position of the two airfoils at t= 0,5,15,25,35s in clockwise sense.

8. References

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