Unsteady Aerodynamic Analysis of a 2D Flapping Airfoil Performing Lateral Motion

K.Vijayakumar[1], K.V Srinivasan[2]

[1]Assistant Project Manager, [2]Technical Advisor

[1,2]National Design and Research Foundation, The Institution of Engineers (India),Bangalore, India

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Abstract : *In the current scenario, Nano Air Vehicle (NAV) plays an indispensable role in both defence and civil applications significantly, such as earthquake, avalanche, low intensity conflict, spying, etc. The important features of NAV include low Reynolds Number, fluid- solid interaction, boundary layer separation and other parameters. This research work is the continuation of our previous work related to the aerodynamics of flexible flapper & passive stability (200 mm flying model) and fully unsteady aerodynamic analysis of 3D flapping wing MAV which executing translational motion. Based on the lessons learnt by the authors from their previous experience, this paper examines the relationship between the wake structures and the forces developed by a flapping airfoil, executes the lateral motion which is one of the fundamental researches towards the development of NAV. In the present paper, the unsteady aerodynamic analysis of 2D flapping airfoil (Lateral motion) is analysed by solving the 2D time-dependent incompressible Navier-Stokes equations for free stream velocity of 5 m/s which includes dynamic mesh techniques, user defined functions, low Reynolds number, flapping motion and geometry. Different methods for dealing with the moving boundary were evaluated using mesh deformation, re-meshing and optimization for unstructured grids. Additionally, the control parameters such as the flapping amplitude, reduced frequency and Strouhal number were also taken into the account. These studies are stepping stone towards the design and development of NAV (~ < 75 mm), flapping wing mechanism, 1D wavelet analysis and testing through NI systems.*

Keywords: *Dynamic mesh, User defined functions, Reynolds number, reduced frequency, Strouhal number, Computational fluid dynamics*

INTRODUCTION AND BACKGROUND

The concept of using flapping motion is drawn from Nature. Birds, flying beetles, insects, fish, etc., have used flapping wings or fins for thrust and lift production for millions of years. Insects and tiny birds, such as hummingbirds, are small airborne bodies which rely on the unsteady aerodynamics of flexible flapping wings to produce lift and thrust. The unsteadiness of the aerodynamics arises from the rapid complex motion of the wings which flap, rotate, twist, deform through large amplitudes, etc. NAV must have the ability to fly in urban settings, tunnels and caves, maintaining forward and hovering flight, manoeuvre in constrained environments, and perch when required. However, due to its small size and low flight speed, the NAV [1-3] design drastically deviates from that of traditional aircraft practices. In addition to this, there are different types of existing Nano drones which are Cyborg beetle, Samarai drone, Nano Quad-copters (voice recognition), suicide drones and sometime even like a tiny flying grenade (looks like a small NAV) which is remotely flown, Spy butterfly, Raven drone etc. In addition to this, flying beetle [4, 5] plays a major role; it can be remotely controlled and is equipped with a camera and a microphone.

For instance, it will be used in search-and-rescue missions and can get into small nooks and crevices in a collapsed building to locate injured survivors during earthquakes. Furthermore, mosquito drones become very popular because, it has the potential to take a DNA sample or leave RFID tracking nanotechnology on your skin. It acts like bio-camouflage vehicle. It is envisioned that such small NAV has a huge potential applications. A typical NAV is shown in Fig. 1.

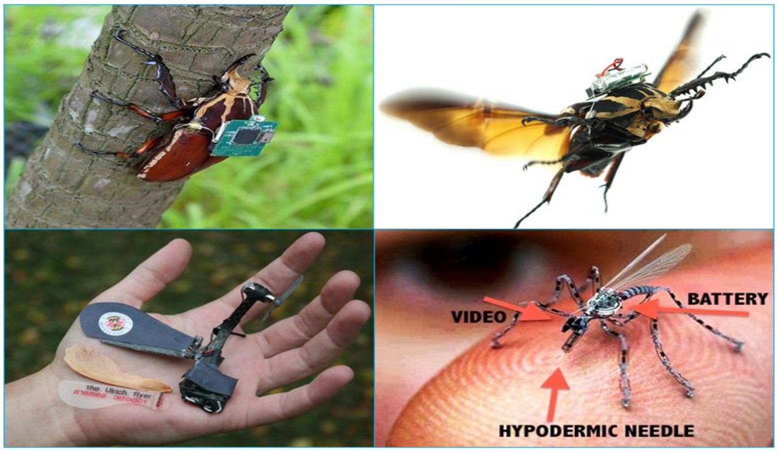


Fig -1: Typical flying beetle & NAV [5]

Furthermore, during the futuristic swarm operation (Large number of vehicles deployed from a UAV) and multi-role cooperative flying with other vehicles such as underwater vehicle and ground robots, will be one of the challenges and key aspects toward these developments. These types of vehicles have bio-mimicking concepts which have evolved from the nature. Compare to other miniaturized aerial vehicle, this vehicle has huge applications specifically during the war scenario such as an interesting option for a platoon or a squad in the middle of the fire-fight. Fig. 2 shows the comparison of unmanned air vehicles and other flyers with respect to Reynolds number and weight.

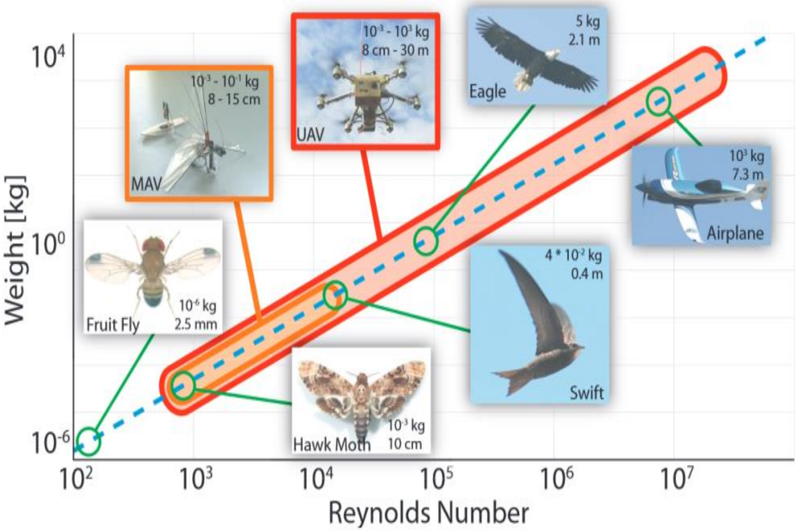


Fig -2: Comparison of unmanned air vehicles and other flyers [6]

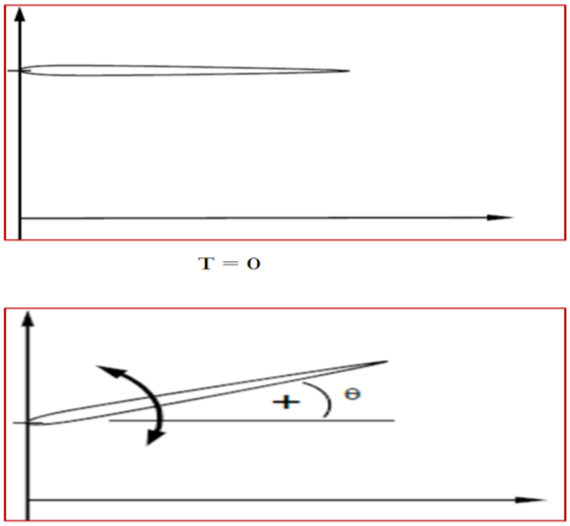
Nano Air Vehicles are considered limited by dimensions (< 75 mm) which places the corresponding aerodynamic flow in the range of low Reynolds number (10^2 - 10^4). The present work brings further insight into the aerodynamics of flapping lateral motion and provides interesting perspectives for the development of high efficiency Nano air vehicles for different applications [1-26], and makes recommendations on the future direction to advance the state of the art. With reference to our previous experience [7-10] and literature survey, it has long been accepted that steady-state aerodynamics does not precisely account for the forces produced by natural fliers. In this context, Flapping wing aerodynamics [11] has come into the attention after the evolution of requirements for NAV.

PROBLEM STATEMENT

Low Reynolds number [12] plays a major role in terms of enhancing aerodynamic performances (lift, efficiency), flight agility, and capability to hover coupled with a low noise generation. Further, it arises from the complex wing motion defined by translating (down stroke and upstroke) and rotating (supination and pronation) motions. Understanding these phenomena is challenging because it involves unsteady transitional flow, large deformation, and complex three dimensional motions.

Normal (or symmetric) flapping motions are characterized by strictly opposed down stroke and upstroke wing kinematics. As a consequence, the drag generated during down stroke counteracts the drag generated during upstroke [13]. The flow periodicity of pure flapping motion has not been previously explored. Our previous work [7- 9] on flapper (200 mm flapper by using NCBS wind tunnel) was mainly relying on the fundamental and applied research of the aerodynamics of flapping wings to evaluate the various parameters. After several attempts based on the quasi-steady approach, it was admitted that unsteady aerodynamic parameters / mechanisms are essential.

To start with the present, our research focus is on unsteady aerodynamics of a flapping airfoil performing lateral motion for better understanding of the fluid physics and the associated aerodynamics characteristics. Furthermore it is an attempt to determine the relation between the wake structure and the flapping parameters such as frequency, amplitude of motion and the relative importance of leading and trailing edge vortex [14]. The two dimensional numerical computations are used to evaluate the flow dynamics and the resulting aerodynamic loads experienced by a flapping airfoil. Fig. 3 shows the schematic view of the flapping airfoil under lateral motion (amplitude A and frequency f) while translating through a 2D fluid.



T = 0

T = 0 + ΔT

Fig -3: Schematic of the flapping airfoil: lateral motion

DYNAMIC MESH, USER DEFINED FUNCTIONS AND FLOW SIMULATION

A. Dynamic Mesh Generation and Movement

Dynamic-Mesh (DM) is currently being implemented in Ansys Fluent. Dynamic mesh has the ability to adjust, change, and modify its structure in response to any changes in geometry or other factors. With the help of these features, the mesh generation process never stops and continues throughout the entire simulation. Basically, the dynamic mesh model [13-15] in Fluent is used to model flows, where the shape of the domain changes with respect to time due to motion on the domain boundaries. The motion is determined by a user defined functions (UDF) and the update of the volume mesh is handled automatically by FLUENT at each time step. It allows customizing FLUENT to fit particular modelling needs such as customization of boundary conditions, new physical models, surface and volume reaction rates, material property definitions, customized post-processing, etc.

The results of the 2d flapping airfoil were highlighted here to demonstrate the capabilities and potential of the Dynamic Mesh method in Ansys package as well as providing some illustrative results for an interesting application. The meshes used in the present work were generated with very good refinement and grid quality control. The Navier-Stokes equations are solved with total tri-elements approximately 14-15 lakhs and forming a refined rectangular 2D domain (Fig.4) close to the profile and a fine mesh near the airfoil that is the flow domain meshed with high grid resolution near the airfoil surface.

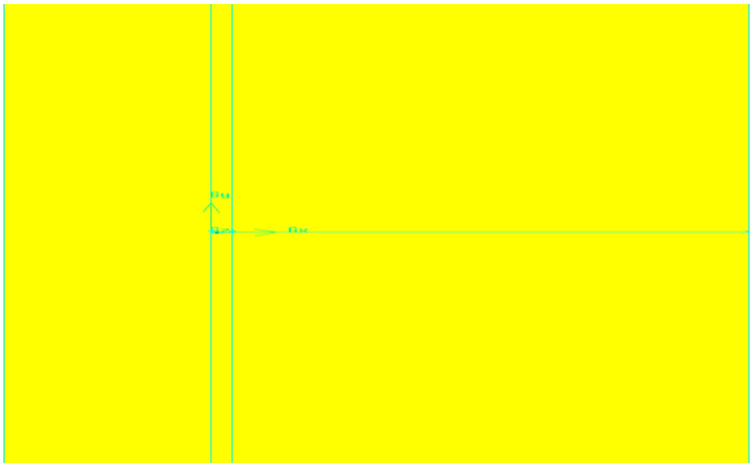


Fig -4: Rectangular 2D domain

In order to achieve the control of mesh deformation, fluent provides three different options. They are spring-based smoothing, dynamic layering and local re-meshing as shown in Fig. 5. In this context (unstructured mesh), a combination of the spring-based smoothing and the local re-meshing was used, which finally turned out to be a very good combination. The dynamic mesh technique was used here to solve mesh deformation and the User-Defined Function (UDF), which is provided by Fluent, was applied to set the lateral motion.

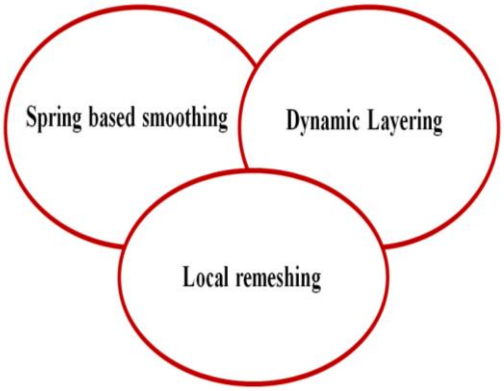


Fig -5: Mesh motion methods at Fluent [15]

The instantaneous airfoil velocity is computed by means of user-defined functions (subroutines) and applied through a no-slip boundary condition. The far field boundaries were located about 25 chords away from the airfoil [19]. Mesh was designed with a grid density increasing towards the wall. Fig. 6 shows the dynamic mesh with respect to upstroke and down stroke for various time intervals.

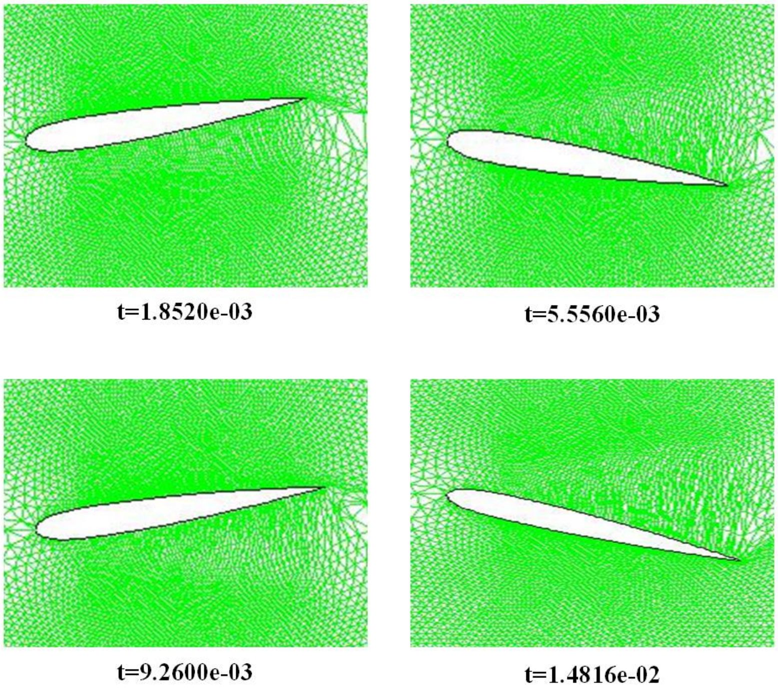

t=1.8520e-03
t=5.5560e-03
t=9.2600e-03
t=1.4816e-02

Fig -6: Dynamic mesh: upstroke and down stroke w.r.t time intervals

B. Reduced frequency, Strouhal number and Advance Ratio

Reduced frequency (k) is a dimensionless number and used in the case of unsteady aerodynamics and aero-elasticity. For 2d flapping airfoil (hovering) case,

$$\boxed{k = c/2*h_a = 0.14}$$

Strouhal number is widely used to describe the wing kinematics of flying birds and insects and characterize the dynamics of the wake and shedding behavior of vortex formation in biological propulsion [12, 16]. Also, it indicates the ratio between the flapping speed and reference velocity based on the peak to peak amplitude. In general for animal flights such as insects, birds, fish, the propulsive efficiency is high and approximately in the range of $0.2 < St < 0.4$. It is a dimensionless number describing oscillating flow mechanisms. The relation between reduced frequency and the Strouhal number is given as,

$$\boxed{St = 2*k*h / \pi = 0.3}$$

Advance ratio (J) illustrates the breakpoint between quasi-steady and unsteady flow when J=1. If J>1 the flow can be considered quasi-steady While J < 1 corresponds to unsteady flow regimes [12, 17]. Most insects operate in this unsteady regime. For example, the bumblebee, black fly, and fruit fly have an advance ratio in free flight of 0.66, 0.50, and 0.33, respectively. The advance ratio is,

$$\boxed{J = U/2fbA = 0.47}$$

C. Flow Simulation

CFD plays a major role in recent studies of aerodynamics. However, obtaining more reliable numerical results for a growing number of problems such as unsteady aerodynamics, fluid solid interaction has been one of the major recent challenges. After selection of the model, it is vital to define the physical domain where the flow takes place, determining the boundary conditions. The unstructured meshes were used because it is extremely flexible when it comes to dynamic mesh, technique to solve the incompressible Navier-Stokes equation in two-dimensional domains with moving boundaries.

To facilitate the computation, it is important to choose the appropriate tools for an expedient and accurate definition of the lateral motion of the airfoil. The present work is based on the finite-volume formulation, where a CFD tool was applied to unstructured two-dimensional dynamic meshes around the flapping Airfoil performing lateral motion [13, 18] with the help of user defined functions in the pre-processor. The pressure-based solver was used in the unsteady incompressible laminar flow field around an airfoil undergoing kinematics.

In this work, flow solver was performed by the unsteady Navier-Stokes solver, which is provided by the fluent. Different boundary conditions were applied to different zones of the geometry. A velocity inlet condition was applied, while no-slip wall boundary condition was defined in the model. The Navier-Stokes equations were solved with the two dimensional double precision, SIMPLE & SIMPLEC pressure-velocity coupling, and second order upwind spatial discretization. The calculations were performed on moving grids.

RESULTS AND DISCUSSION

The authors proceeded with this effort and obtained the pressure coefficient [20, 21] at a particular time for the lateral flapping motion (airfoil). The reduced frequency is k = 0.14 and the peak to peak amplitude is 20. Fig.7 represents the pressure coefficient of the airfoil for a particular time period t=1.5001e-02.

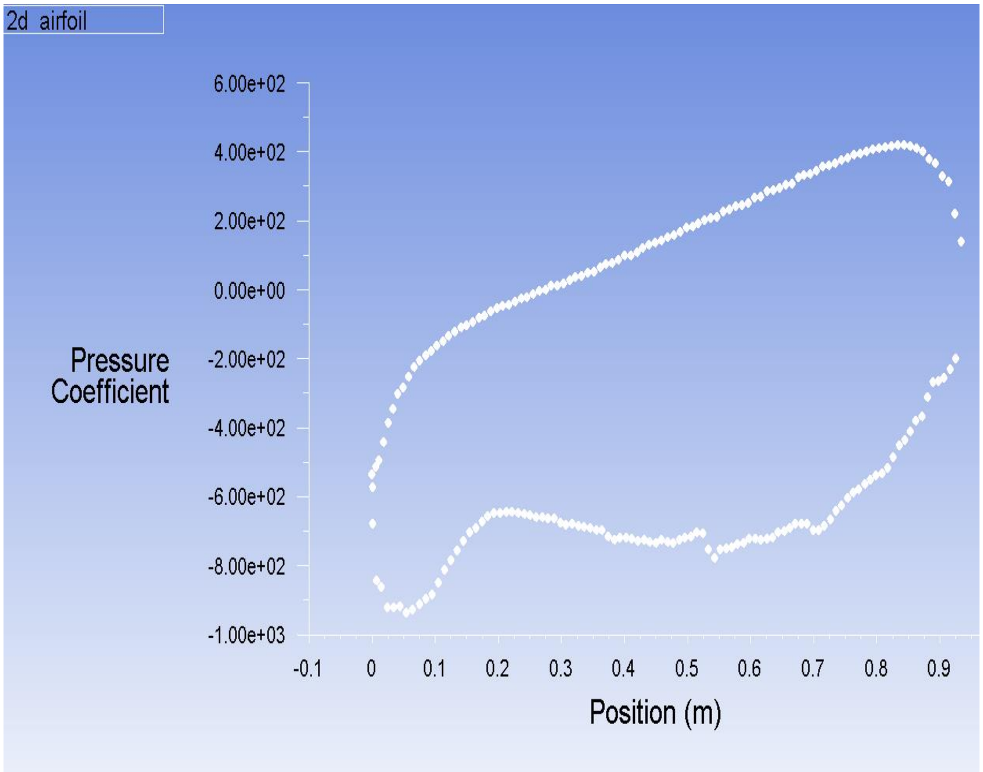
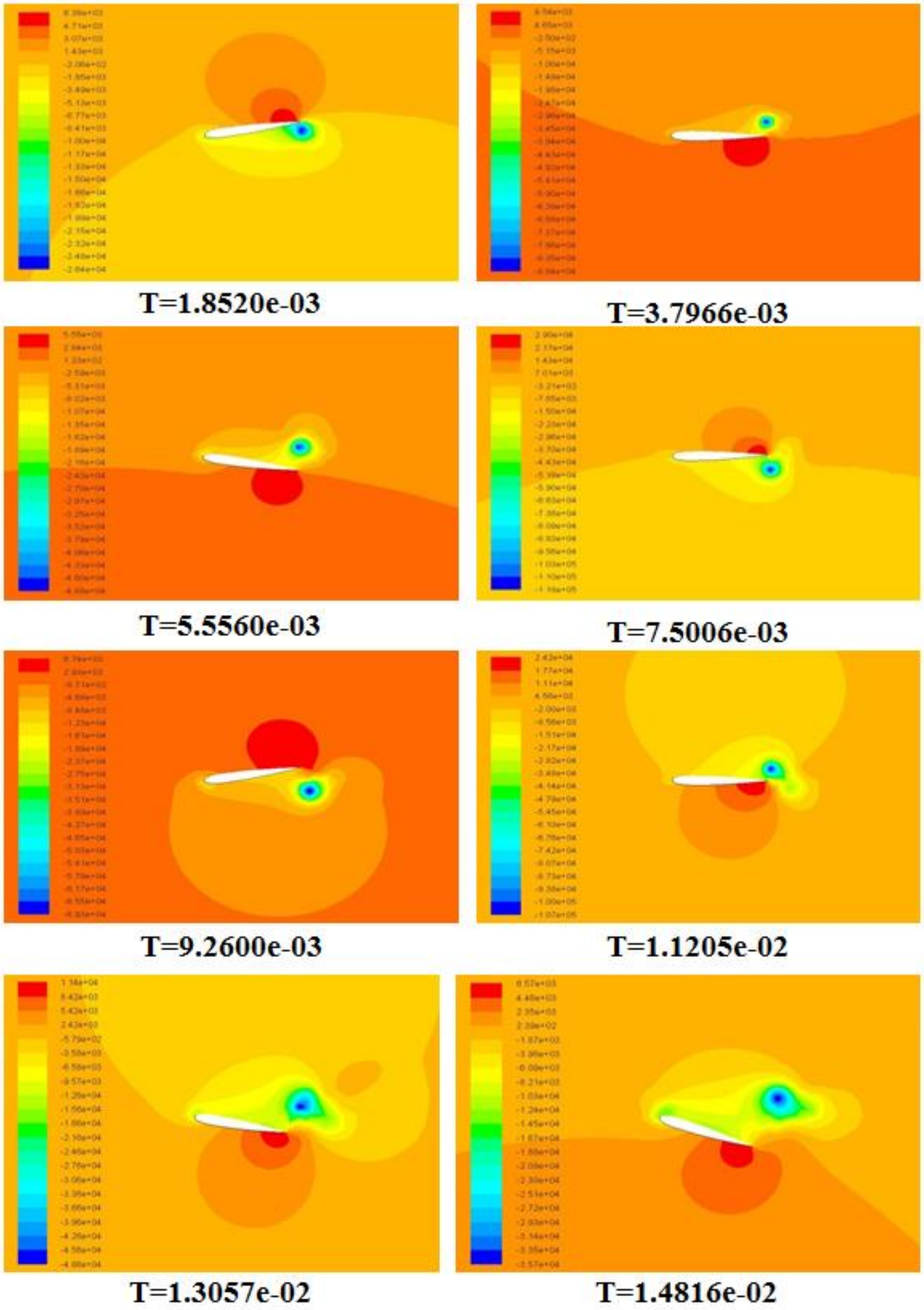


Fig -7: Pressure coefficient at t =1.5001e-02

Vortex Characterization / Flow Unsteadiness

LEV and TEV plays a crucial role when considering the symmetric motion because it dominates the vortical flow field during the down and upstroke phase [21, 22]. The numerical flow solver preceded the velocity and the pressure flow fields in the whole computational domain at each time step. The aerodynamic force resulting from the flapping motion primarily seems to arise from the accelerating inertial effect, leading to the presence of a strong pressure region. The flapping frequency, pressure distribution, LEV and TEV of the airflow were examined.



T=1.8520e-03 T=3.7966e-03

T=5.5560e-03 T=7.5006e-03

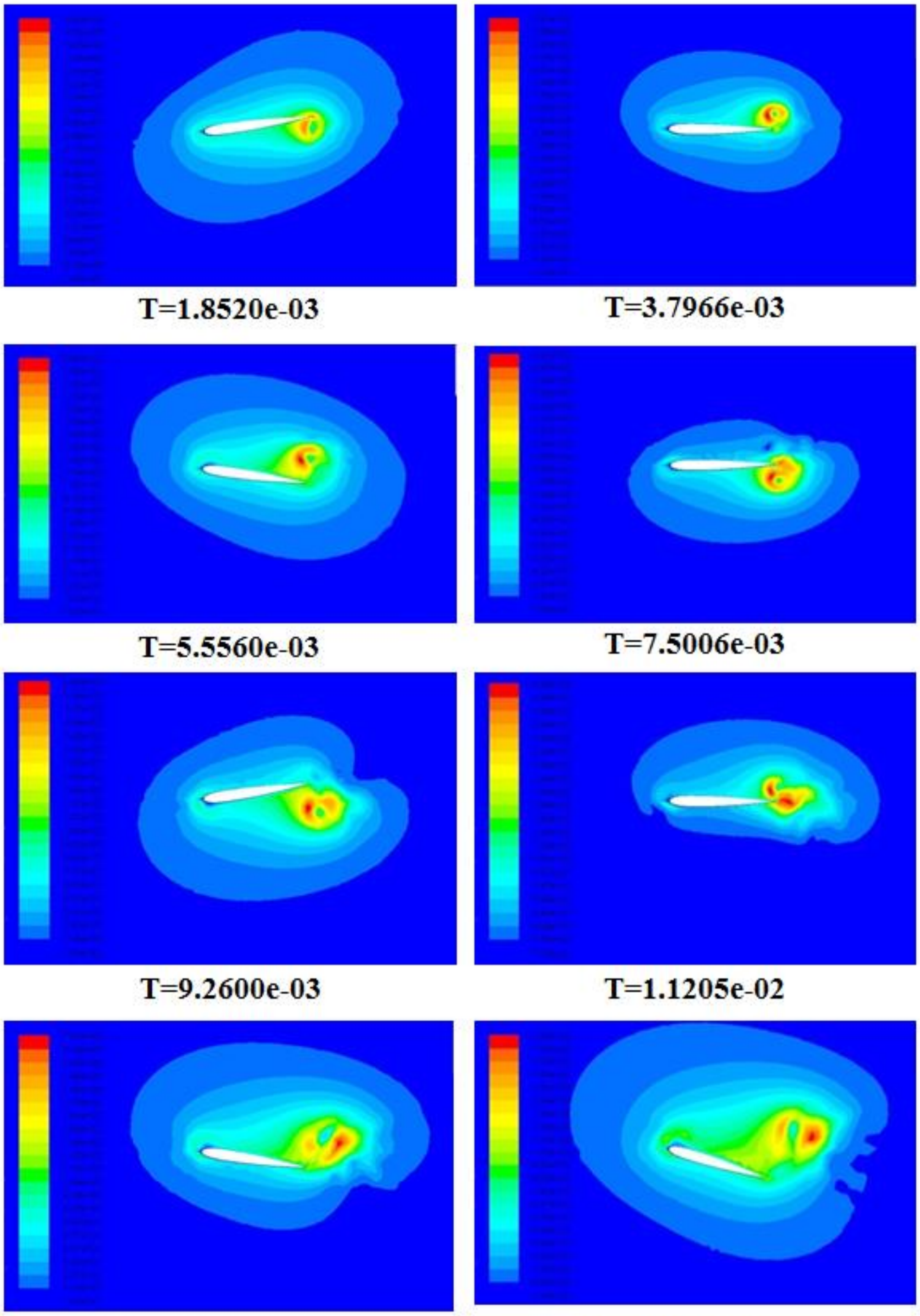
T=9.2600e-03 T=1.1205e-02

T=1.3057e-02 T=1.4816e-02

Fig -8: shows the down stroke & upstroke of the pressure contours:

2D flapping airfoil with respect to various time steps

From the Fig. 8 and Fig. 9 it is observed that the aerodynamic forces relied more on the dynamic behaviours of LEVs while the wake structures were mainly controlled by the TEV. It is well understood that, 2D flapping flight can be aerodynamically more efficient than the optimal steady motion. Furthermore, the wake pattern can be controlled by adjusting amplitude, shape of wave form, and frequency. The smaller and weaker wake vortex structures were found to be dissipated rapidly and finally extinct at further downstream [22]. This process (down stroke and upstroke) would repeat in cycles. Finally, the vortices were shed alternatively in the wake of the flapping wing.



T=1.8520e-03 T=3.7966e-03

T=5.5560e-03 T=7.5006e-03

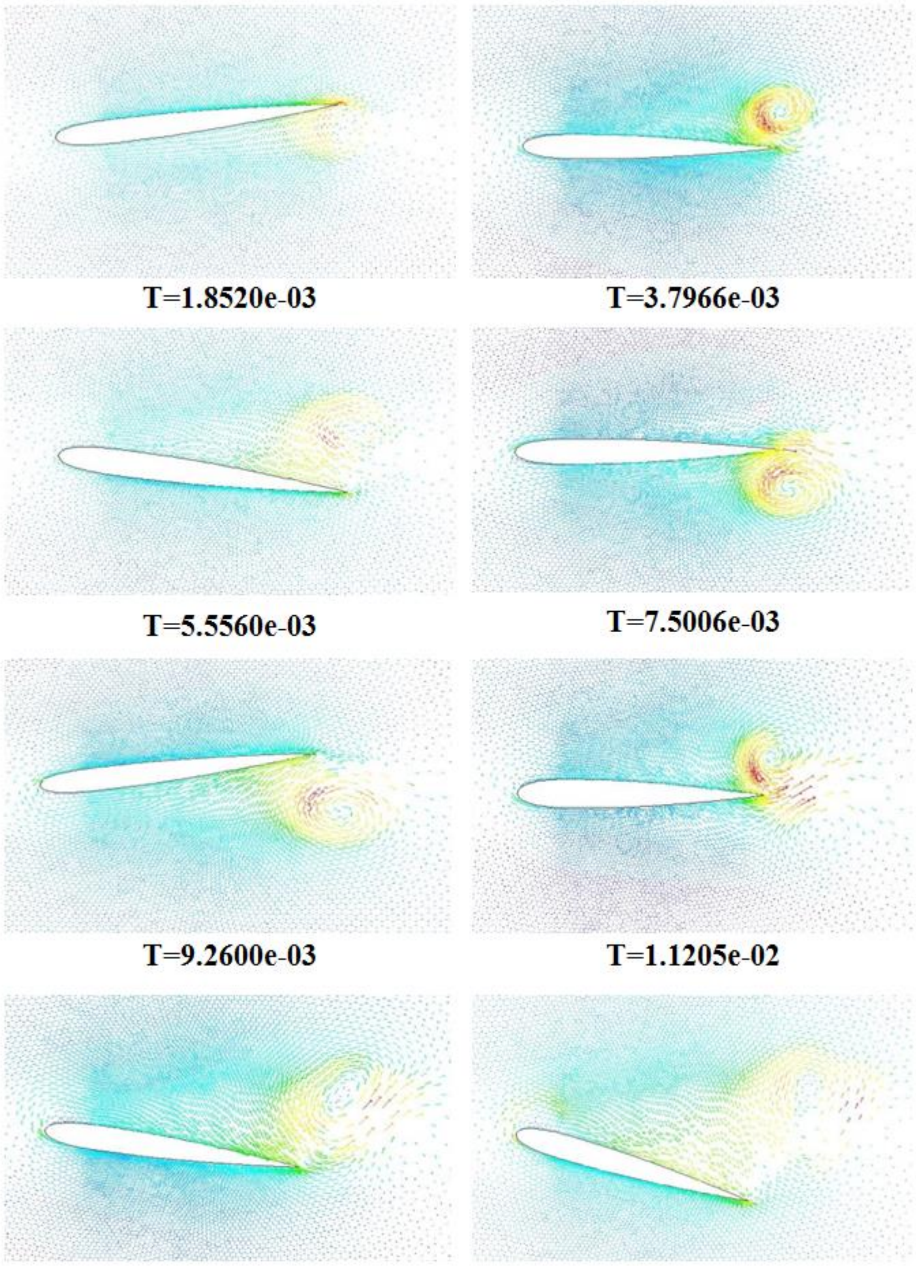
T=9.2600e-03 T=1.1205e-02

T=1.3057e-02 T=1.4816e-02

Fig -9: shows the down stroke & upstroke of the contours of velocity magnitude:

2D flapping airfoil with respect to various time steps

Based on our research, the direction of the wake deflection not only depends upon the position of the airfoil but also on the contributing factors such as initial acceleration, flapping frequency and amplitude.



T=1.8520e-03 T=3.7966e-03

T=5.5560e-03 T=7.5006e-03

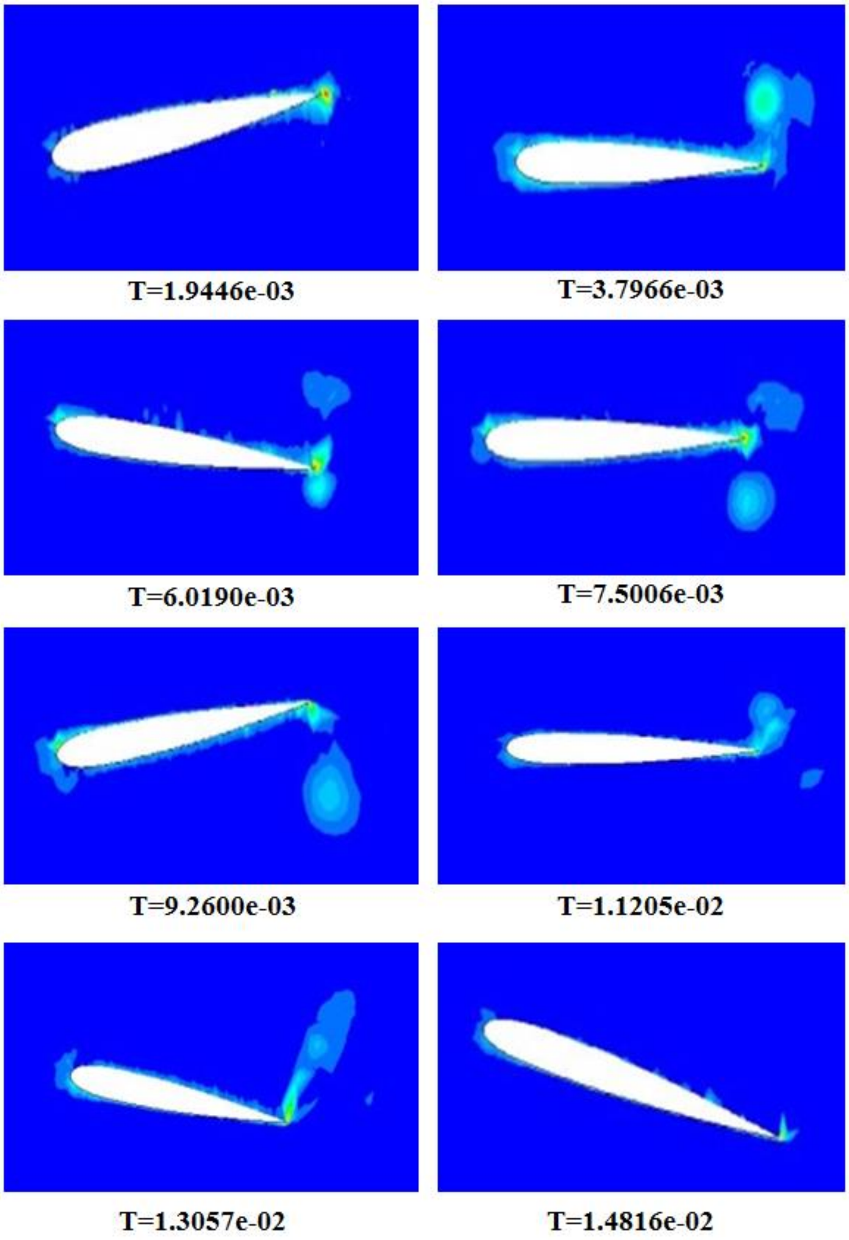
T=9.2600e-03 T=1.1205e-02

T=1.3057e-02 T=1.4816e-02

Fig -10: shows the down stroke & upstroke of the velocity vectors:

2D flapping airfoil with respect to various time steps

From the Fig.10 and Fig.11 shows the velocity vectors and contours of vorticity of magnitude of flapping airfoil and it is pragmatic that vortices are generated during the flapping cycle and reach the maximum strength during the flapping motion (up and down stroke). The leading edge vortices are weaker during the Upstroke than during the down stroke and shed into the wake region. Similarly the TEV and shear layer vortices were also observed. Furthermore, there were some destructive vortex interactions and vortices remain close to the airfoil.



T=1.9446e-03 T=3.7966e-03

T=6.0190e-03 T=7.5006e-03

T=9.2600e-03 T=1.1205e-02

T=1.3057e-02 T=1.4816e-02

Fig -11: shows the down stroke & upstroke of the contours of vorticity of magnitude:

2D flapping airfoil with respect to various time steps

From the flow visualization and flow patterns depicted in figures [8-11], it is observed that at the wall, the airfoil drove the fluid toward the upstream and slows down the incoming flow and the pressure is relatively higher at the lower surface than that without wall. As the flapping frequency increases, the measured forces will be increasingly affected by the size of the test section size (computational domain). In this context, the domain size plays an important role in determining the aerodynamic forces [23, 24]. The airfoil generates larger thrust in a larger domain. Similarly, at high frequency, the aerodynamic forces are largely determined by the wing motion instead of the free stream flow.

LIFT AND DRAG FORCES

The unsteady aerodynamic simulation for 2d flapping airfoil executing lateral motion is analyzed. Interestingly, the lift forces at the upstroke and the down stroke are slightly different [25, 26]. The transient aerodynamic forces of lift and drag on a 2d flapping airfoil were observed. The lift coefficient (C_L) was calculated from the convergence results and area of the wing (A), Density (ρ) were known.

$$\boxed{L = \tfrac{1}{2} * \rho * V^2 * C_L * A}$$

V is assumed to be forward velocity in Hover Condition. Similarly, the drag coefficient (C_D) was calculated from the convergence results and the area of the wing (A), Density (ρ) were known.

$$\boxed{D = \tfrac{1}{2} * \rho * V^2 * C_D * A}$$

The lift and drag were estimated. The graph between lift and drag with respect to time is shown in the Graph.1 and it shows the variation of lift and drag in y-axis according to time in x-axis.

Graph -1: Lift, Drag vs. Time

Improving aerodynamic performances

The upstroke phase being harmful, the relative importance of the upstroke and down stroke phases should be profoundly considered. The most important unsteady aerodynamics effects are leading edge vortex, clap and fling mechanism, Rotational lift, wing-wake interactions. When the airfoil moves downwards to its lowest extreme, it sheds the positive vortices which enhance the lift. Likewise the lift is reduced as the airfoil moves upwards to its extreme upper position. So, the lateral motion is recognized as being of primary importance in the generation of lift and thrust and also high frequency regime remains relatively unexplored.

In summary, the present simulation results suggest that the development of aerodynamic loading is driven mainly by the kinematics of the airfoil, not its cross-sectional profile. Flapper would generate all necessary lift and control forces with the help of only two moving aerodynamic parts i.e. Flapping wings. It is well known that, the NAV will push the limits of aerodynamic and power conversion efficiency, endurance, and maneuverability for very small, flapping wing air vehicle systems in which to improve the efficiency and stability in hovering and forward flight during the deployment for indoor and outdoor environments.

CONCLUSION

A comprehensive numerical simulation of the lateral motion of flapping airfoil has been achieved successfully with the help of dynamic mesh techniques for free stream velocity of 5 m/s using the finite volume method. The aerodynamic characteristics caused by the time ratio between the down stroke and up stroke duration have been studied. The corresponding wake structures of the airfoil also have been analyzed. The flow dynamics through UDF, dynamic meshing techniques were well studied along with different post-processing techniques. Furthermore, the relative importance of leading and trailing edge separation on the frequency dependences of the aerodynamic forces were assessed. The frequency dependence is found to be a result of vortex shedding from the airfoil for various factors. First of all, the impact of the vortex of the pressures at the nose of the airfoil is dependent on the flapping frequency. Afterwards, the vortex separates and it is moving downstream over the surface of the airfoil. The present works emphasized the fundamentals of unsteady aerodynamic effects and provide the required capabilities such as moving mesh, moving boundaries, UDF implementation, and mesh refinement. The current findings will be helpful towards the design and development of modern NAV inspired by insect & bird flight.

FUTURE WORK

The futuristic work and studies will extend into the third dimension of the flapping wing kinematics and flapping mechanism. It is well known that, the majority of lift, thrust, stability, control and agility are produced mainly by the wing kinematics and related parameters. For instance, birds, insects or cyborg flying beetles will never flap their wing like translational motion. It encompasses different wing kinematics such as folding and unfolding mechanism, Figure-of-Eight, etc. These parameters are still not well understood because of limitation in the computation as well as experimental. So far, many unmanned air vehicles (Mini, Micro, Nano) are developed by only translational motion, and few of them tried with different wing kinematics to replicate the nature flight. In order to develop a suitable NAV, the authors are trying to achieve an unsteady aerodynamic mechanism for different wing kinematics such as,

- The dynamic mesh adaptation functions and techniques will be executed (combined translational & rotational motion of 3D flapping wing)
- Execute and replicate the 3D motion (Figure-of-Eight) of 3D flapping wing
- To compute a dynamic and an aero-elastic case with flapping motion, and this is can be achieved by upgrading the Fluent UDF code to attain the desired parameters

Moreover, the authors are planning to do the experimental investigation through MART tunnel facility available at National Aerospace Laboratories, Bangalore for further verification and validation.

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