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Numerical Analysis of Flapping Wing Pitching at Low Reynolds Number using CFD

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Abstract—*Flapping wing aerodynamics is fascinating field for design of MAV (Micro Aerial Vehicles). The flow over a NACA 0012, oscillated sinusoidally in pitch, is simulated numerically using two-dimensional Navier-Stokes solver at a Reynolds no of 20,000. The commercially available CFD code "FLUENT 16.2" has been used to carry out the numerical study. The flow field is assumed to be laminar and incompressible and it is shown in the validation of results that the laminar assumption provides good agreement with experiments for this Reynolds number. Pitching is studied along various positions on chord axis from -1c to 1c along chord where c is chord length. Results obtained are verified with experimental results of Heathcote et al [1]. Current study focuses on Reduced frequency k = 3 and 5 with Angle of pitch amplitude ±15, ± 30. As pitch location is moved from inside airfoil towards -1c coefficient of thrust C_t is increased. Reduced frequency k improves C_t for the same pitch amplitude at same location of pitch. C_t is obtained at various locations and maximum thrust obtained can be used by MAV for maneuver.*

Nomenclature

$C_{t\ mean}$ = *time averaged thrust coefficient*
C_d = *coefficient of drag*
C_t = *Coefficient of Thrust* = (- C_d)
c = chord, m
f = frequency of oscillation, Hz
h = non-dimensional plunge amplitude
k = Reduced frequency, $2\pi f c/U_0$

Keywords: *flapping wing, CFD, reduced frequency, coefficient of thrust, pitch amplitude*

1. INTRODUCTION

Inspiration from nature is a key element for research and scientific development. The field of flapping wing aerodynamics has been inspired by flying animals such as birds, bats, insects and efficient swimmers like fishes, which have extraordinary flying and swimming capabilities like forward flight, maneuver and hover. More recently the interest of researchers in this field has increased due to the possible application of flapping wing powered micro aerial vehicles (MAVs) and submerged vehicles. Several experimental and numerical investigations have been performed on flow over flapping wings to understand the unsteady mechanisms of aerodynamic forces generation and also to determine the effects of varying different flapping parameters such as flow Reynolds Number (Re), reduced frequency, plunge amplitude, mode of motion, and phase difference between pitching and plunging motion. There is therefore an increased need to understand the flapping wing mechanisms used in nature and to adopt or modify them for the design of flapping-wing vehicles. To this end, it is necessary to provide the vehicle designer with the aerodynamic knowledge and prediction tools required to select the flapping mechanism most suitable for the chosen mission objectives. The pitching and plunging motions of airfoils have received a lot of attention recently, due to the increased interest in the design of micro air vehicles. The use of combined pitch plunge motion with phase difference between them has often been used for the generation of thrust and lift. These aerodynamic forces could be significantly enhanced under similar operating conditions by using generalized pitch motion with variable center of wing rotation. The current study investigated the flowfield and aerodynamic forces for this generalized pitching motion. CFD uses numerical methods to solve the fundamental nonlinear differential equations like RANS (Reynold's Average Navier Stoke's) that describe fluid flow which will provide results without carrying out wind tunnel tests.CFD is cost effective and time saving tool for such type of experiments.

Researchers have studied plunging, pitching and combined pitching plunging motion of wing section NACA 0012 for Reynolds number effects pertaining to leading-edge separation, vortex shedding and aerodynamic performance by inviscid and viscous solvers. Knoller and Betz were the first to study effective force obtained which decomposes into lift and thrust. Heathcote et al. [1] studied a water tunnel study of the effect of spanwise flexibility on the thrust, lift and propulsive efficiency of a rectangular wing oscillating in pure heave has been performed The power extraction capability of the airfoil operating in the wingmill mode is studied by Tuncer et al. [2] computing the dynamic stall boundary for a combined pitch and plunge motion at the reduced frequency values of 0.1, 0.25 and 0.3. The flow over a NACA 0012 airfoil, oscillated sinusoidally in plunge, is simulated numerically using a compressible two-dimensional Navier–Stokes solver at a Reynolds number of 2×10^4 studied by J. Yong and J.C.S. Lai [3].

Dolphins, sharks and bony fish, swim at $0.2<St<0.4$. Taylor et al [4] show that birds, bats and insects also converge on the same narrow range of St, but only when cruising. Tuning cruise kinematics to optimize St therefore seems to be a general principle of oscillatory lift-based propulsion. A preliminary CFD study to analyse the effects of the reduced frequency (k), amplitude of oscillation (h) and the maximum non-dimensional flapping velocity (kh) on the thrust generation and efficiency of a NACA0012 airfoil undergoing pure plunge motion at a Reynolds number of 20,000 is performed by Ashraf et al. [5]. Aerodynamic phenomena and benefits produced by the flapping-wing interactions on tandem wings like dragonfly or Bi-plane configurations are discussed by Platzer and Jones [6]. The dynamics of the vortex structures generated by a foil in steady forward motion, plus a combination of harmonic heaving and pitching oscillations, is determined by means of the numerical solution of the vorticity equation. The force and the torque acting on the foil are also computed by Laura Guglielmini, Paolo Blondeaux [7]. J. C. S. Lai and M. F. Platzer [8] studied water-tunnel tests of a NACA 0012 airfoil that was oscillated sinusoidally in plunge are described. The flowfield downstream of the airfoil was explored by dye flow visualization and single-component laser Doppler velocimetry (LDV) measurements for a range of freestream speeds, frequencies, and amplitudes of oscillation.

2. COMPUTIONAL MODELLING

The commercially available software package ANSYS-DESIGN MODELER, ANSYS-MESHING and ANSYS-FLUENT was used to complete this investigation of pitching motion of NACA 0012 airfoil at various location along chordline. Validation of the computational model was performed by modeling o-grid having tetrahedral mesh. The working fluid throughout this investigation was air. Therefore, a robust computational model capable of predicting the effects due to low Re no. speed, turbulent, viscous, incompressible, and time-dependent phenomena was utilized.

The 2-D Domain used in this analysis was created. The result was a solution domain that includes a 50m diameter domain with inlet and outlet as left and right periphery of o-grid as shown in Fig. 1. A velocity inlet boundary was initially applied to inlet of grid and an outlet pressure outlet boundary was applied to the entire outlet periphery. A model of the solution space along with the resulting mesh is provided in Fig. 1. An unstructured 2-D grid of triangular elements was applied to the domain producing a resolution of 53360 nodes to 52339 elements. y^+ value is maintained below 5. The grid was composed of a 1000 equal parts on airfoil surface. The Spallart-Allmaras (1 Equation) viscous model in combination with the SIMPLEC algorithm was specified in order to ensure accuracy and stability.

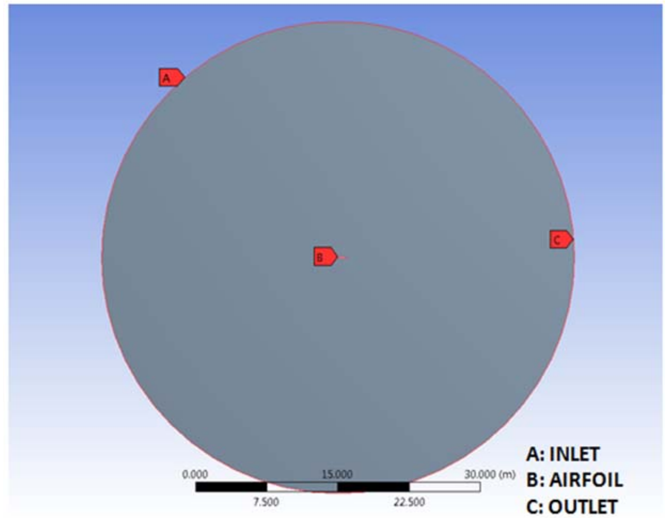

Fig. 1: Domain boundary conditions

The unsteady flow field around a NACA0012 airfoil undergoing pure pitching motion was simulated using the commercially available CFD package Fluent version 16.2, with an unsteady incompressible solver and second-order upwind spatial discretization. Solution ran on computer with Intel Xenon E5-1603 2.8 GHz, 4 Core processor with 8 Gb Ram took around 4.5 hours for each calculations of case.

The plunging motion of the airfoil was modeled by using the 'dynamic mesh' feature and the whole grid and airfoil was moved as a rigid body. The use of the dynamic mesh feature limited the unsteady formulation to first order in time. The flow field is assumed to be laminar and it is shown in the validation of results that the laminar assumption provides good agreement with experiments for this Reynolds number range. The mesh used for the aifoil pure plunging and pitching is shown in Fig. 2.

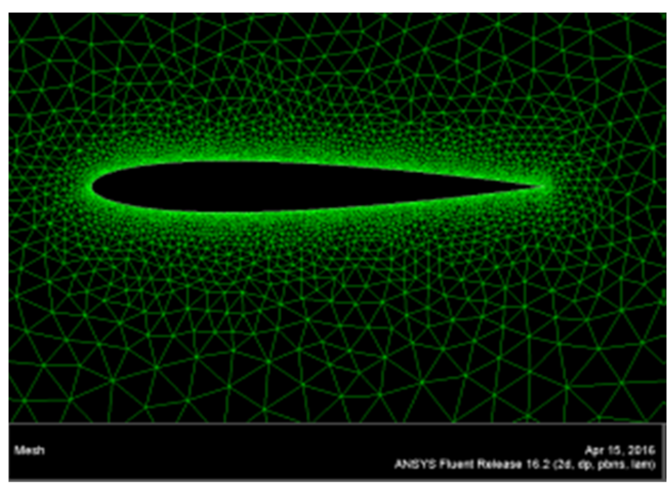

Fig. 2: Closer view of airfoil meshing

3. RESULTS AND DISCUSSION

An experimental data obtained from Heathcote et al. [1] for pure plunging motion obtained at different reduced frequency of NACA 0012 airfoil with equation y(t) = h cos(ωt). For different reduced frequency 2, 3, 4, 5, 6 at Reynolds no 20,000 $C_{t\ mean}$ obtained are compared with numerical obtained results and shown below in Figures 3 Same analogy for pure plunge motion is applied for pure pitching motion of airfoil at pitching point located from -1c to 1c. X velocity variation is captured at 2c distance from leading edge on a line perpendicular to chord line.

As shown, the CFD predictions agree quite well with the experimental data. The viscous model that provided the best agreement was found to be the S-A model. After a converged solution was obtained, the new grid was developed with increasing the resolution through decreasing face size to 0.0001 and dividing airfoil in 2000 points and y^+ value is maintained below 2 which resulted in mesh having 414000 nodes.

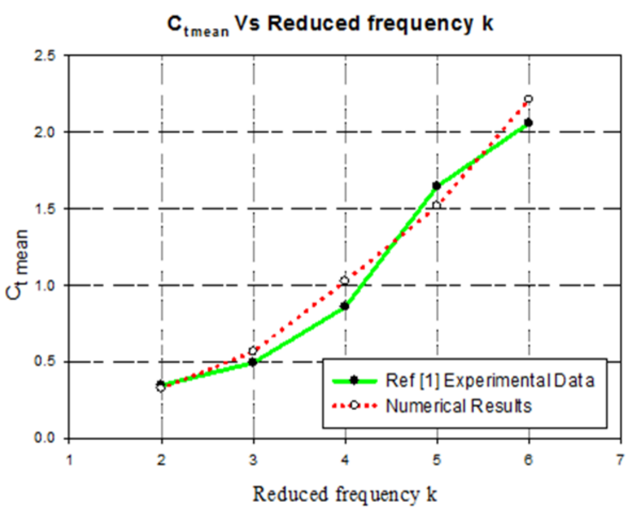

Fig. 3: Comparison of experimental and numerical data

3.1 Analysis for pitching amplitude of 15 Deg at location from -1c to 1c with reduced frequency 3 and 5.

As seen in graph in Fig. 4 below pitching at point 0.5 c location generates less thrust for both frequency 3 and 5 at 15 Deg of pitching amplitude but from this location as pitching point is moved towards -1c location increase in mean thrust value is observed. Towards 1c point airfoil starts producing drag.

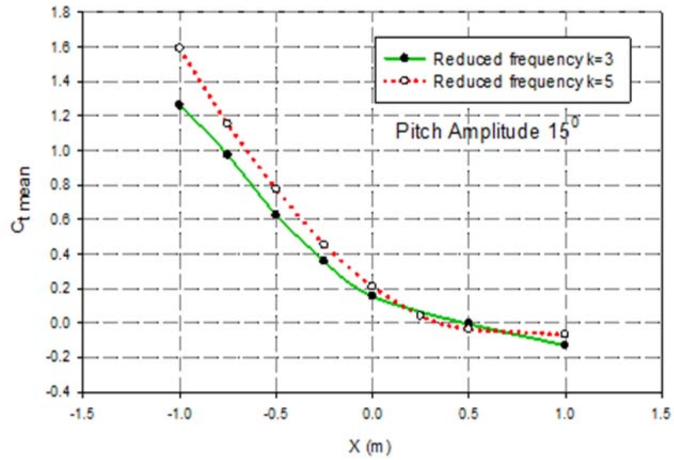

Fig. 4: Variation of mean thrust coefficient with pitch location for amplitude of 15 Deg at reduced frequency k=3 and k=5.

3.2 Analysis for pitching amplitude of 30 Deg at location from -1c to 1c with reduced frequency 3 and 5.

As seen in graph in Fig. 5 below pitching at point 0.5 c location generates drag for both frequency 3 and 5 at 30 Deg of pitching amplitude but from this location as pitching point is moved towards -1c location increase in mean thrust value is observed for reduced frequency of 5. Towards 1c point airfoil starts producing drag for both frequency.

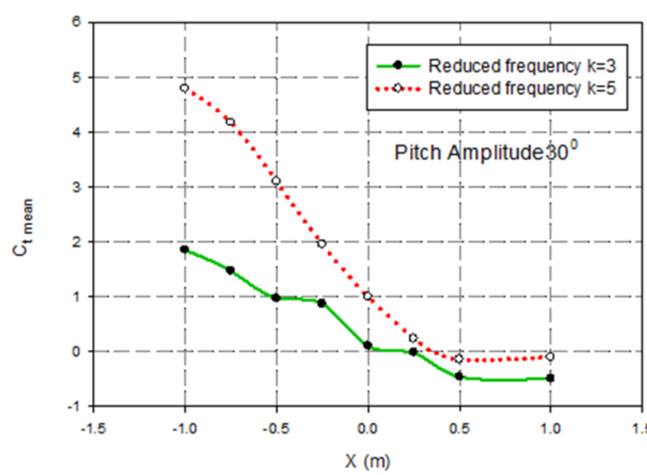

Fig. 5 :Variation of mean thrust coefficient with pitch location for amplitude of 30 Deg at reduced frequency k=3 and k=5.

3.3 Pitching at -1c (chord length) location

Pitch amplitude 15 and 30 deg with reduced frequency 3 and 5 producing variation in X velocity vs Y is shown in Fig. 6. This type of variation towards positive x direction is called jet velocity profile which results in thrust producing. Higher pitch amplitude with higher reduced frequency producing more thrust is justified with large variation in 30 deg k=5 case.

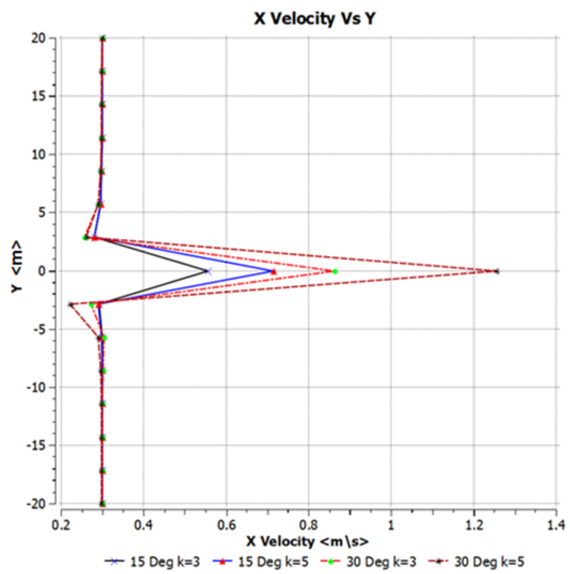

Fig. 6 Variation of X Velocity Vs Y at 2c location from leading edge for pitch at -1c.

3.4 Pitching at 0c (chord length)

Pitch amplitude 30 deg with reduced frequency of 5 is producing mean thrust 4.78 is producing change in inlet velocity 0.3 to 0.62 is in well agreement with Fig. 5 graph.

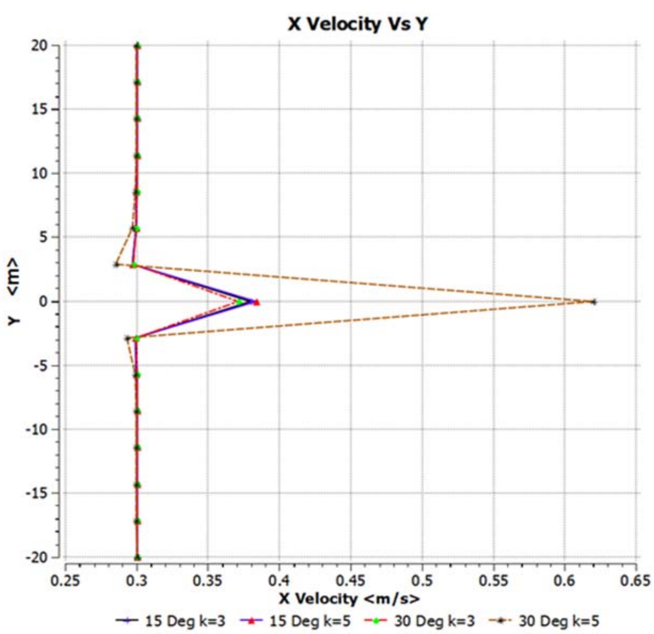

Fig. 7: Variation of X Velocity Vs Y at 2c location from leading edge for pitching at 0c.

3.5 Pitching at 1c (chord length)

Pitch amplitude 15 and 30 deg with reduced frequency 3 and 5 producing variation in X velocity vs Y is shown in Fig. 7. This type of variation towards positive x direction is called negative jet velocity profile which results in drag producing. Most drag producing combination is of 30 deg with reduced frequency k=3 is deduced from below graph.

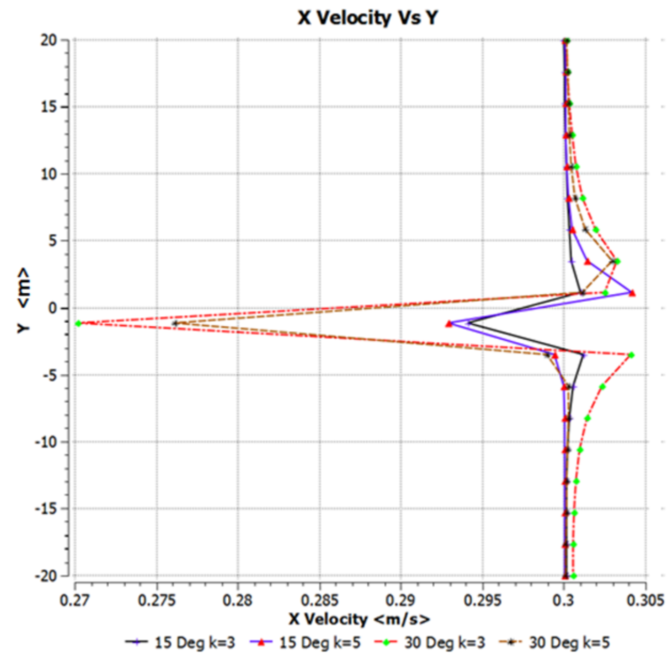

Fig. 8: Variation of X Velocity Vs Y at 2c location from leading edge for pitch at -1c.

4. CONCLUSION

ANSYS-FLUENT model was designed to study pitching motion at various pitch location along chord line. Variation in X velocity is obtained by CFD-POST 16.2 software of Ansys Inc. Accuracy of the results checked with mesh independent study. Mesh with more than 4lakhs nodes have been deployed to carry out simulation results but it was so CPU intensive that took around 27 hours for same machine but numerical results obtained were in agreement with one obtained with 56K node mesh. The main reason for error is value's obtained from published material extraction from graphs provided.

a) Though pitching motion at chord length 1/3 or ¼ location gives lesser value of $C_{t\ mean}$ considerable change can be obtained for the same as pitching point is shifted from inside airfoil body to outside towards leading edge.

b) $C_{t\ mean}$ value obtained at -1c location is enough for maneuver for birds. This value also depends on direct proportionate to pitch amplitude and reduced frequency.

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