NUMERICAL INVESTIGATION OF SINUSOIDALLY PLUNGING NACA0012 AIRFOIL AT RE=1000

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ABSTRACT

A NACA0012 airfoil undergoing sinusoidally plunging motion at Re=1000 is simulated by both analysing as laminar and also using the transitional shear-stress transport (SST) γ-Re_θ turbulence model. Depending on the key parameters of reduced frequency, plunge amplitude, plunge frequency and non-dimensional plunge velocity, complex flow fields might be experienced by a flapping airfoil, thereby their influence on the aerodynamic forces, propulsive efficiency and vortical structure are investigated. Moreover, the fully laminar and transitional-flow numerical results are compared to each other.

INTRODUCTION

Researchers have recently developed an interest in flapping-wing aerodynamics as a result of increased design efforts in the area of micro aerial vehicles (MAVs), since because the flapping wings are essentially small jet engines and can be more efficient than the conventional propeller-driven engines for them due to operating at low Reynolds numbers (Pornsin-Sirirak, 2001; Wood, 2008; Hsu et al., 2010; de Croon et al., 2016). Thereafter the understanding of unsteady phenomenon of flapping wing at low Reynolds number flow gains significant importance in order to achieve sufficient thrust and propulsive efficiency for the chosen mission objectives of MAVs.

The investigation of the thrust generation by means of flapping wing dates back to the independent studies of [Knoller, 1909] and [Betz, 1912]. They recognized that the flapping wing creates an effective angle of attack and generates a force towards the flight direction, hence decreasing drag. The Knoller-Betz effect was initially verified by the experiment of [Katzmayr, 1922] as the stationary airfoil in the oscillatory wind-stream by measuring the average thrust. The first theoretical explanation of drag or thrust production based on the observed location and orientation of the wake vortices was presented by [von Karman and Burgers, 1935]. They identified thrust producing wake pattern of reverse Karman vortex streets, and their observations were confirmed by the wind tunnel experiments of [Bratt, 1950]. In the literature, the wake characteristics produced by plunging airfoils have been extensively studied both

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experimentally by [Freymuth, 1988; Jones et al., 1998; Lai and Platzer, 1999; Lua et al., 2007; Kurtulus et al., 2006a and 2006b; Turhan et al., 2022], and numerically by [Jones et al., 1998; Lewin and Haj-Hariri, 2003; Young and Lai, 2004; Kurtulus et al., 2009; Camacho et al., 2021]. These characteristics are commonly classified as drag-indicative, neutral or thrust-indicative wakes, considering the plunging amplitude and frequency. The drag-indicative wake results in a momentum-deficit streamwise velocity profile, and the thrust-indicative wake results in a jet-like velocity profile, typically characterized by Karman and reverse Karman vortex streets, respectively.

The objective of the current paper is to numerically explore the aerodynamics of the single plunging NACA0012 airfoil at very low Reynolds number of 1000. To this end, the simulations using fully laminar assumption and the transitional unsteady Reynolds-averaged Navier–Stokes shear-stress transport (SST) γ-Re_θ model are compared to each other. Moreover, the influence of plunge amplitude and plunge frequency on the aerodynamic forces, propulsive efficiency and vortical structure are discussed in detail.

METHOD

The two-dimensional low-Reynolds-number incompressible flow over the single plunging NACA 0012 airfoil shown in Figure 1 is simulated numerically with the commercial finite volume solver of ANSYS Fluent v17.2 [ANSYS Inc., 2016] by solving the Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations. Since the motion of the oscillatory airfoil could result in a transitional flow, both the fully laminar simulations and simulations with the shear-stress transport (SST) γ-Re_θ turbulence model are employed. The numerical solution is obtained by evaluating the gradients using the Least Squares Cells-Based scheme. For simulations with SST γ-Re_θ turbulence model, the second-order upwind scheme is adopted as the method to discretize pressure, momentum, turbulent kinetic energy, specific dissipation rate, intermittency and the momentum thickness Re equations. The transient formulation uses the second-order implicit iterative time advancement scheme (ITA), and the advantage of the implicit scheme is that it is unconditionally stable with respect to time step size [ANSYS Inc., 2016]. Pressure-velocity coupling is done by a segregated type algorithm of semi-implicit method for pressure-linked equations (SIMPLE), which is based on the predictor-corrector approach, and the details of the algorithm can be found in [Ferziger et al., 2020]. For the pure plunging simulations of the single NACA0012 airfoil, the motion of the airfoil is introduced by a rigid-body motion of the whole domain.

The single plunging NACA0012 airfoil and its position dynamics are depicted schematically in Figure 1. The chord length is prescribed as c=0.1m. The geometric angle of attack of the airfoil is set to 0° for all simulations. The fluid domain is prescribed as air at sea-level standard atmospheric conditions, and the operating Reynolds number is set to 1000. The details of the computational domain and the boundary conditions are shown in Figure 2. The domain is created by fully structured grid and the wake region is especially refined to capture the flow properties due to the motion of the airfoil.

The numerical simulations were conducted both with laminar conditions and also with the transitional turbulence model of SST $\boldsymbol{\gamma}$-$\boldsymbol{Re_\theta}$ model (also known as Transition SST model), which couples the $\boldsymbol{k}$-$\boldsymbol{\omega}$ SST model of [Menter, 1994] with two transport equations for intermittency ($\boldsymbol{\gamma}$) and momentum thickness Reynolds number ($\boldsymbol{Re_\theta}$) [Langtry and Menter, 2009]. This model has been used and validated against experimental or higher order numerical simulation of LES and DNS results at low Reynolds number external flow over an airfoil in the literature by [Counsil and Boulama, 2013; Chen et al., 2018; Carta et al., 2022; Ruiz and D’Ambrosio, 2022; Platzer et al., 2023; Anilir et al., 2023a and 2023b]. The fully laminar solutions are validated against the published data at Re=1000 by [Kurtulus, 2015, 2016, 2018, 2019, 2021 and 2022].

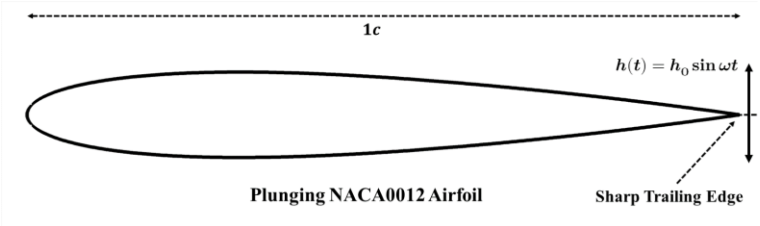


Figure 1*:* Schematic diagram of single plunging NACA0012 airfoil

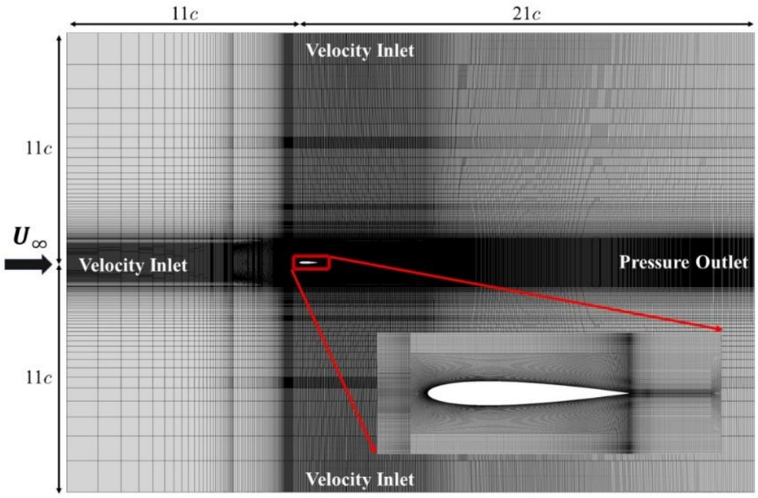


Figure 2*:* Computational Domain

The sinusoidal plunging position (h) and the angular frequency (ω) are defined by Eq. (1) and Eq. (2), respectively.

$$h(t)=h_0 \sin(\omega t) \quad (1)$$

$$\omega=2\pi f \quad (2)$$

where h_0 being the plunge amplitude, and f the plunge frequency in Hz. Other critical parameters for the plunging motion are the reduced frequency (k) (Eq.3) and non-dimensional plunge velocity (v_p) (Eq.4).

$$k=\omega c/U_\infty \quad (3)$$

$$v_p=k(h_0/c) \quad (4)$$

where c being the chord length, and U_∞ the freestream velocity. The propulsive efficiency (η) is then defined by the ratio between the mean thrust (C_t) and mean power (C_P) coefficients.

$$\eta = C_t / C_P \quad (5)$$

The mean power coefficient is computed by integrating the lift coefficient times the flapping velocity on the flapping airfoil as shown in Eq.6. Time-averaged data is obtained by taking the mean of 10 complete oscillations after periodic conditions are reached. The flapping velocity (v) is defined in Eq.7 and its variation in one period of plunge motion is shown in Figure 3.

$$C_P = \frac{1}{\Delta t}\int_{\Delta t}(C_l \dot{h}/U_\infty)\mathrm{d}t \quad (6)$$

$$v = \dot{h} = 2\pi f\,(h_0/c)\cos(2\pi ft) \quad (7)$$

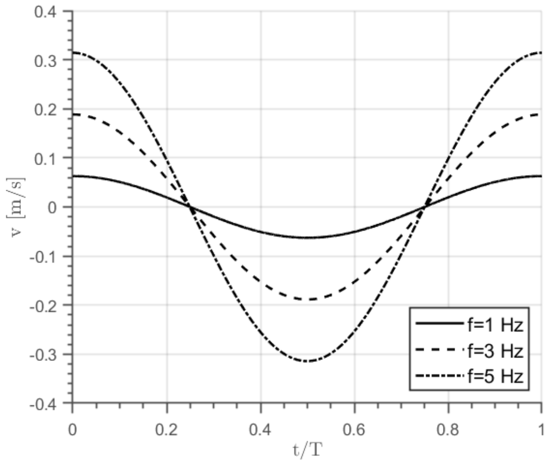
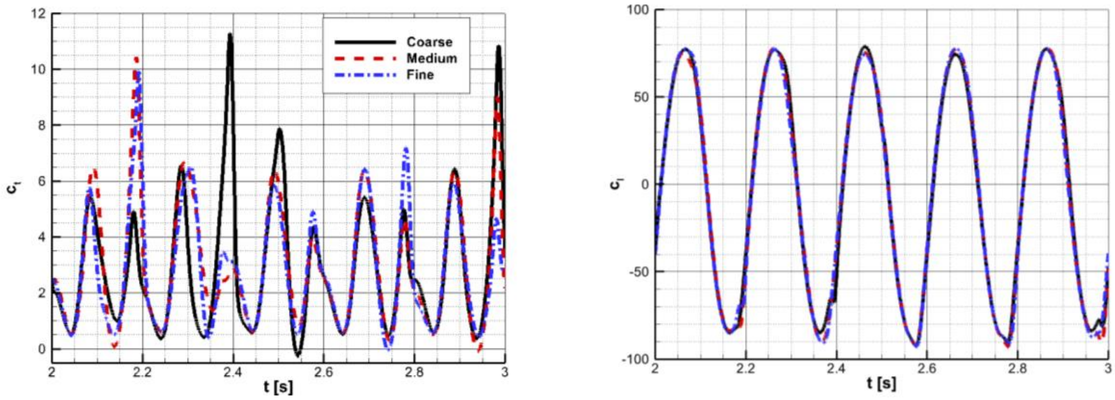


Figure 3: Variation of plunge velocity for different plunge frequencies in one period of the plunge motion

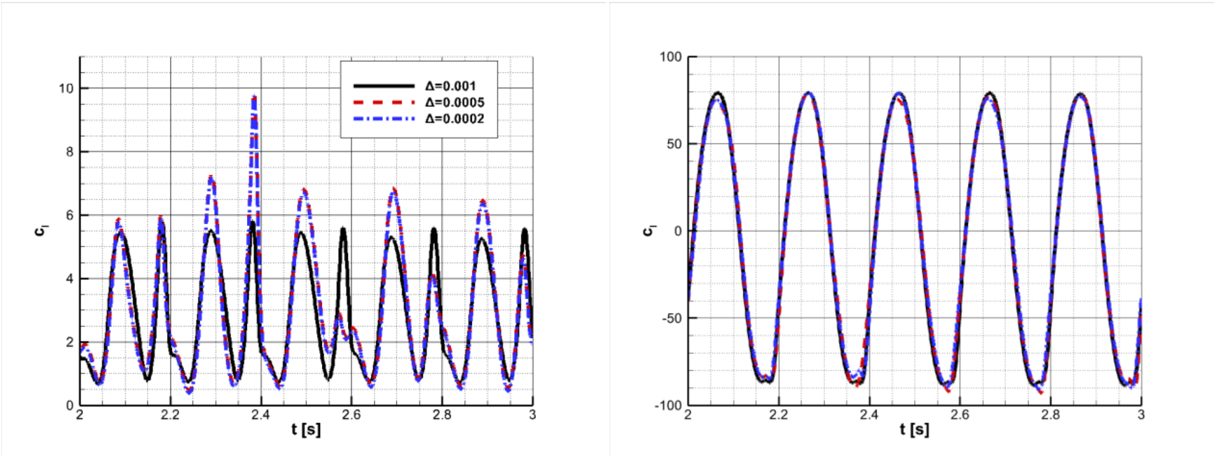
Grid and Time Refinement Studies

Grid and time refinement studies are carried out for U_∞=0.146 m/s, k=21.52, h_0=0.1c and f=5 Hz to obtain grid and time independent force coefficients and wake structures. For the grid refinement study, three different grids (coarse, medium, and fine grids) are employed with a refinement ratio of around 1.5 applied on both the number of points around NACA0012 airfoil and the whole domain. The coarse, medium, and fine grids contain 3.67×10^5 elements (500 points around airfoil), 5.12×10^5 elements (760 points around airfoil), and 7.89×10^5 elements (1000 points around airfoil), respectively. The time refinement study was also carried out with the medium grid at three different time step sizes of Δt=0.001s (200 time steps within a plunge cycle), Δt=0.0005s (400 time steps within a plunge cycle) and Δt=0.0002s (1000 time steps within a plunge cycle). Figure 4 and Figure 5 show the variation of the thrust and lift coefficients with respect to time for grid and time refinement studies, respectively. It can be clearly seen that the results obtained with the medium grid agree very well with the fine grid. Moreover, the results of Δt=0.0005s and Δt=0.0002s are very close to each other. Therefore, the rest of the studies were performed with the medium grid and the time step size of Δt=0.0005s.



(a) C_t vs time (b) C_l vs time

Figure 4: Time history of thrust and lift coefficients for grid refinement study at Re=1000



(a) C_t vs t (b) C_l vs t

Figure 5: Time history of thrust and lift coefficients for time refinement study at Re=1000

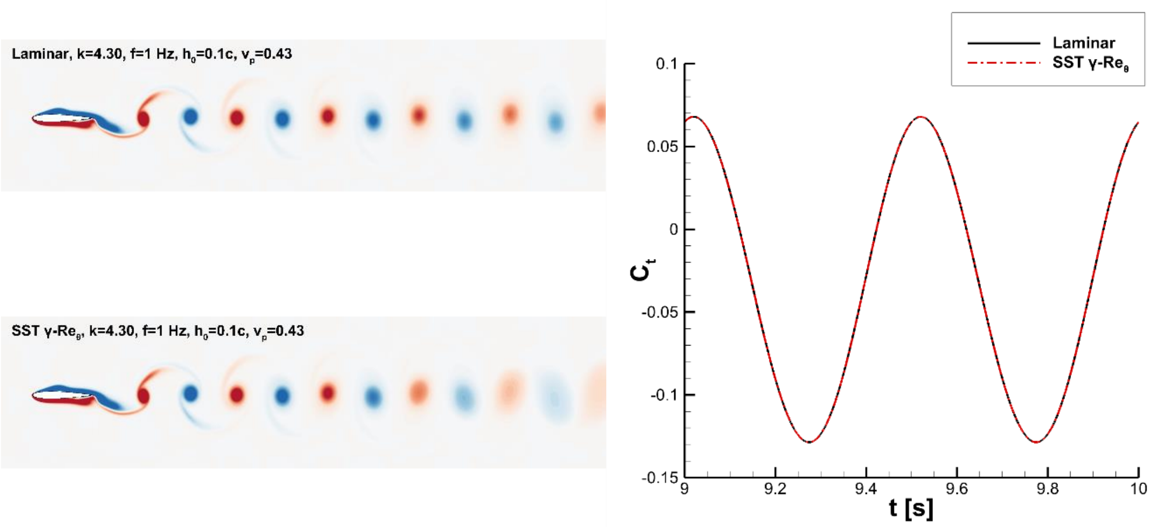
RESULTS

Flow Visualization

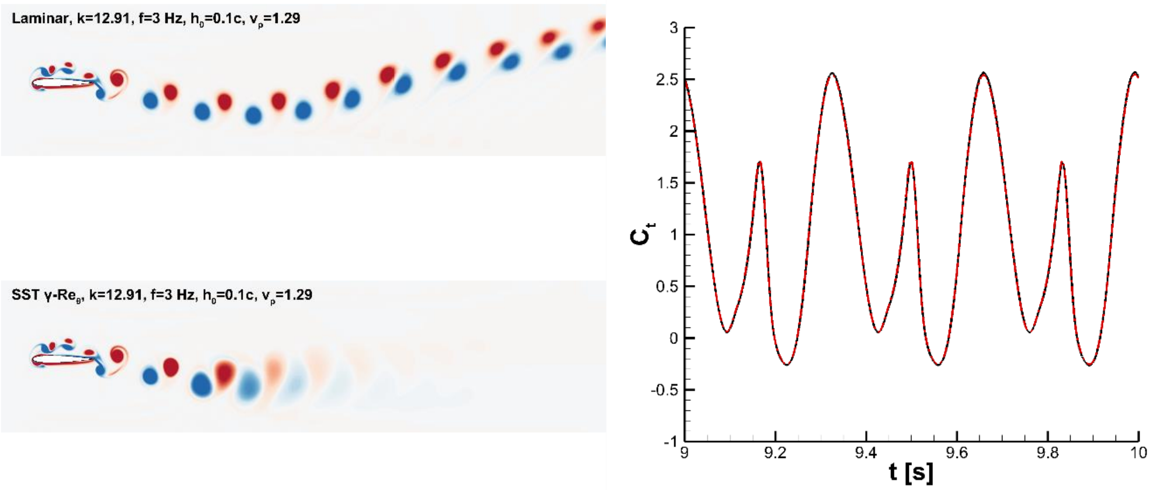
The instantaneous vortical structure around the single plunging airfoil are presented in Figure 6 by inspecting the z-vorticity contours for different conditions. Figure 6 also shows the comparison of the laminar and turbulent transitional-flow simulations that are found to be alike. At the lowest non-dimensional plunge amplitude, v_p, of 0.43, almost neutral wake structure produces very small amount of drag demonstrated by both simulations (see Figure 6a). The flow structure is actually very familiar to experimental flow visualization of [Jones et al., 1996] at v_p=0.56 that enhance the confidence on our simulations (see Figure 6e). [Lai and Platzer, 1998] found in the water tunnel experiments at Reynolds number of 20,000 that the thrust is produced as soon as the non-dimensional plunge velocity v_p exceeds values greater than approximately 0.2. Moreover, the numerical simulations of [Anilir et al., 2023a] shows that the neutral wake formation is obtained at around v_p value of 0.2 for Reynolds number of 30,000 and 60,000. Considering the current study, the drag is produced at almost doubled v_p value most likely due to the much smaller operating Reynolds number, more viscous dominant flow.

Figure 6b shows the deflected wake phenomenon at v_p value of 1.29. The near flowfield the wake structure until the 4th vortex shedding are almost identical for both simulations. The deflection in far wake region is upward for the laminar results, whereas the transitional-flow simulations demonstrate the horizontally aligned wake. On the other hand, this difference in the wake structure does not influence the aerodynamic coefficients (see Figure 6b). [Wei and Zheng, 2014] observed a very similar deflected wake formation with the laminar results (first downward after 4th shedding upward) at k=20, v_p=1.3 for Re=500. The deflected wake phenomenon was observed and discussed in the literature in various numerical [Jones et al., 1998; Lewin and Haj-Hariri, 2003; Lagopoulos et al., 2020] and experimental [Jones et al., 1998; Lai and Platzer, 1999; Cleaver et al., 2012; Anilir et al., 2023a and 2023b] investigations of single plunging airfoils for similar v_p values.

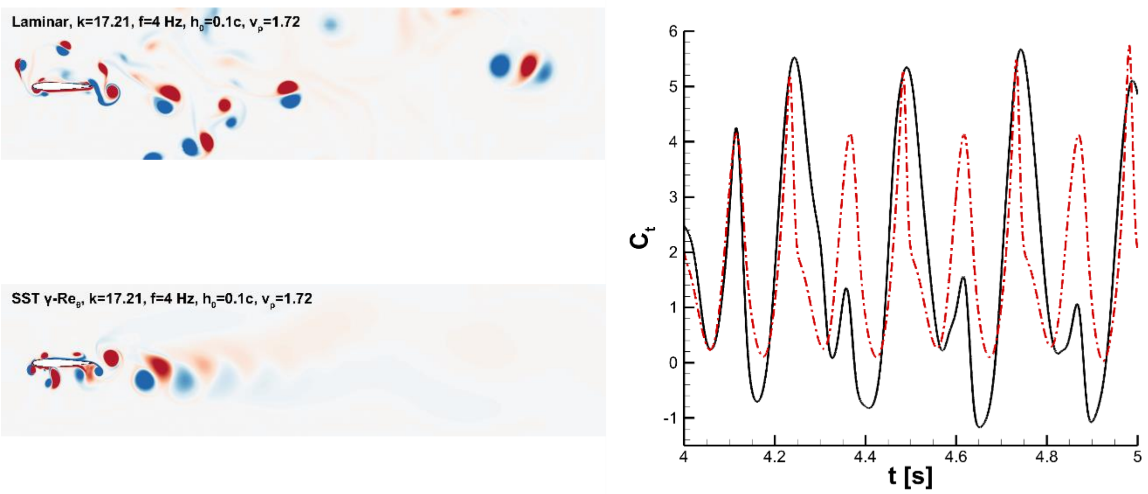
It is found that at a higher plungle frequency of 5 Hz, the laminar and transitional-flow results deviate (see Figure 6d). The maximum plunge velocity for this case becomes more than 0.30 m/s which is a double of freestream velocity. Also, the velocity magnitude near the airfoil could increase up to 1.8 m/s. As shown in the figure 7, the intermittency factor, ranging from 0 to 1, determine the transition between the laminar (0) and turbulent (1) regions. A value within the 0 to 1 range signifies the transitional region. For the case of f=5 Hz, most of the region is solved by fully turbulent flow assumption. However, since the vortex street and near the airfoil is solved by admission of the laminar flow for the case of f=1 Hz, the laminar and turbulent transitional-flow simulations are in quite good agreement.


Laminar, k=4.30, f=1 Hz, h_0=0.1c, v_p=0.43
SST γ-$Re_θ$, k=4.30, f=1 Hz, h_0=0.1c, v_p=0.43
Laminar
SST γ-$Re_θ$
C_t
t [s]

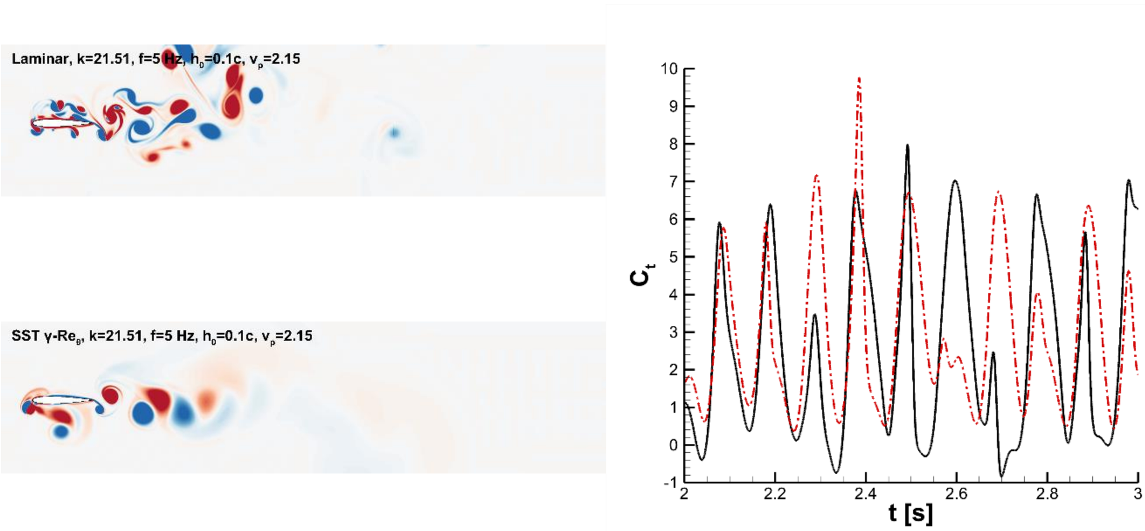
(a)


Laminar, k=12.91, f=3 Hz, h_0=0.1c, v_p=1.29
SST γ-$Re_θ$, k=12.91, f=3 Hz, h_0=0.1c, v_p=1.29
C_t
t [s]

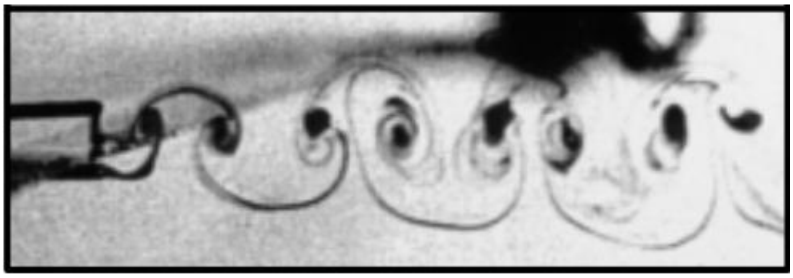
(c)


Laminar, k=17.21, f=4 Hz, h_0=0.1c, v_p=1.72
SST γ-$Re_θ$, k=17.21, f=4 Hz, h_0=0.1c, v_p=1.72
C_t
t [s]

(d)

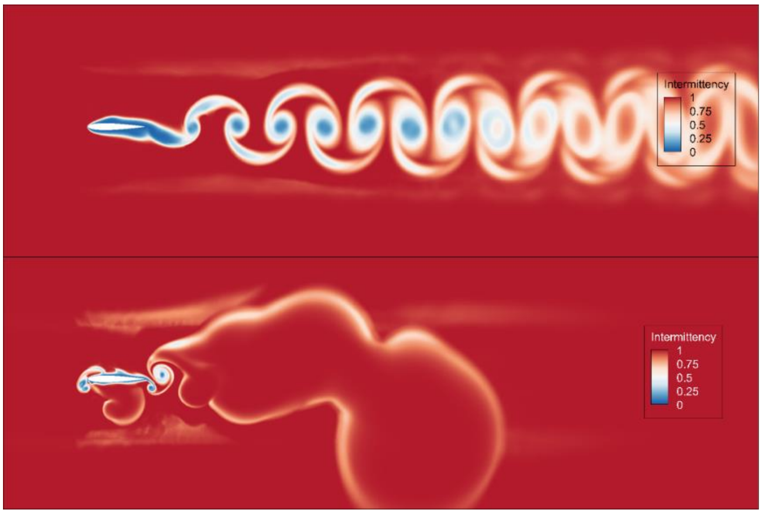


(b)



(e)

Figure 6: Instantaneous vortical structures around the single plunging airfoil and time history of the thrust coefficient computed using Laminar and SST γ-Re_θ models for (a) k=4.30, f=1 Hz, h_0=0.1c, v_p=0.43, (b) k=12.91, f=3 Hz, h_0=0.1c, v_p=1.29, (c) k=17.21, f=4 Hz, h_0=0.1c, v_p=1.72, (d) k=21.52, f=5 Hz, h_0=0.1c, v_p=2.15 at Re=1000, and (e) water tunnel experiment of [Jones et al., 1996] at v_p=0.56



(a)

(b)

Figure 7: Intermittency contours for (a) k=4.30, f=1 Hz, h_0=0.1c, v_p=0.43, and (b) k=21.52, f=5 Hz, h_0=0.1c, v_p=2.15 at Re=1000

Mean Aerodynamic Coefficients

Figure 8 depicts the variation of aerodynamic coefficients and propulsive efficiency with respect to nondimensional plunge velocity. It is noticed that the thrust coefficient exponentially increases as v_p enhances similar to those literature results [Lai and Platzer, 1999; Heathcote and Gursul, 2007; Anilir et al., 2023a and 2023b]. On the other hand, the lift coefficient decreases as v_p increases. The laminar solution predicts much greater lift production than the transitional solution due to stronger vortex field at v_p=2.15.

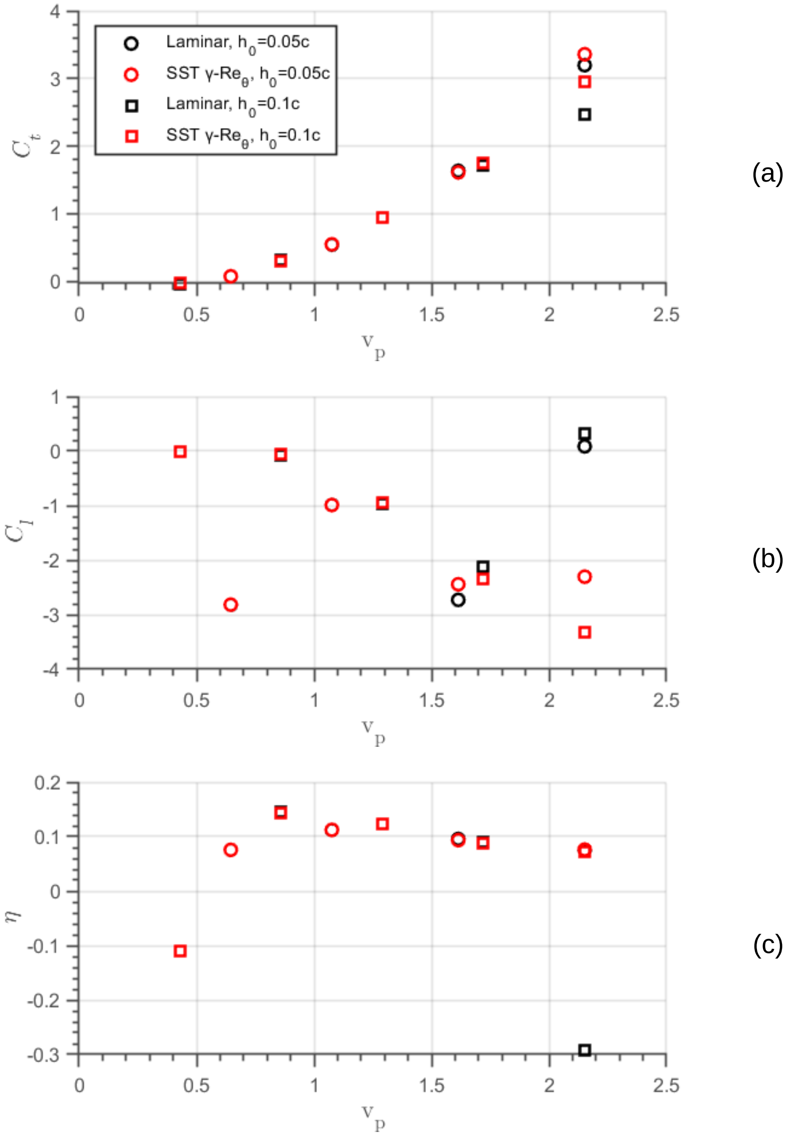


Figure 8: Variation of (a) thrust coefficient, (b) lift coefficient, and (c) propulsive efficiency with respect to nondimensional plunge velocity

CONCLUSION

The current study aims to investigate the sinusoidally plunging NACA 0012 airfoil at Re=1000 for different frequencies ranging between 1 Hz - 10 Hz. The results are presented for both laminar and SST γ-Re_θ model. It is found that above f=4 Hz and v_p=1.72 the results deviate however at f=1Hz the vortical patterns and aerodynamic coefficients are found to be similar.

Acknowledgments

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