Original Article

Numerical Analysis of Fluid Flow Over Plunging NACA0012 Airfoil at Low Reynolds Number

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Abstract

The primary objective of this computational research is to investigate on the effects of Reynolds number, angle of attack, frequency, and amplitude of the plunging movement of NACA0012 airfoil on aerodynamic performance over time for a constant angle of attack. This paper deals with the laminar flow over the plunging NACA0012 airfoil at low Reynolds number 10000 with a plunging amplitude ratio of $0.2c$ and with three different frequency ratios of 0.9, 1.0, and 1.1. The influence of the angle of attack (constant over time) was studied in the range of 0° to 6°. OpenFOAM an open-source CFD software is used to simulate this problem computationally.

Keywords: Plunging Airfoil, Vortex Shedding, Boundary Layer, Strouhal Number.

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INTRODUCTION

Over the past years the flow over plunging airfoil has received comparatively less attention because it was thought that a pure plunge vibration has far fewer significance in practical applications. The pitching airfoil oscillates around the pivot, resulting in varying incidence angles at different stage of vibration. Plunge airfoil, on the other hand, are wings in which the airfoil move periodically along vertical direction (transverse to the flow), with a fixed orientation. However, it has been known that a flapping airfoil generates a thrust force. From the Water-tunnel flow-visualization experiments conducted by Jones et al[5] and Lai and Platzer[6], We gathered a significant quantity of data on the wake characteristics produced by flapping airfoils. The research work from Birnbaum[7] gave an analytical expression for the thrust generated by sinusoidal plunge oscillation of airfoil. Theodorsen[8] proposed a theory for the similar problem in the 1930s that is valid for all frequency within the constraints of small amplitude oscillations in inviscid incompressible flow. Dohring et al[9] demonstrated that when an airfoil is oscillated in plunge with the right combination of frequency and amplitude, a jet (rather than a wake) is formed downstream of the trailing edge, both experimentally and computationally. The phrase wake can be referred to as airfoil's net drag, whereas the term jet refers to the airfoil's net propulsion. They have particularly investigated the effects of plunge frequency and amplitude on the wake characteristics. It was found that at lower Strouhal numbers (~0.3)drag can be generated, due to viscous effect but at higher Strouhal numbers(~2), the deflection of wake was rather dominant.

The analysis of fluid flow over an oscillating airfoil have a wide range of applications like fluttering of aircraft wings, turbine machine blades, helicopters and even for aeroacoustic noise generation. Studies of unsteady transient aerodynamics of airfoil at low Reynolds numbers on an insect / bird flight scale meet the needs of Micro Aerial vehicle design which is required for Para armed forces, border patrol forces and other homeland service forces. Due to the very low Reynolds numbers found on such vehicles, flapping wing propulsion has recently been recognized as being more efficient than conventional propellers when applied to very small-scale vehicles, so-called microair vehicles.

Due to the flow properties in the low-Reynolds-number range, human-powered small-sized aero vehicles have shown significant aerodynamic performance issues due to laminar flow separation. In 2019, the study conducted by Sourav, Akhilesh and Ajith Kumar S[11], it is clearly shown that how the introduction of a delta-shaped surface protrusions influences the aerodynamic efficiency of NACA0012 airfoil. The main application of airfoil at low Reynolds number comes into picture when we consider resonance effect of a system and vortex shedding phenomenon.

The main objective of this numerical analysis is to study the laminar region of incompressible flow past purely plunging NACA0012 airfoil at low Reynolds number of 10000 for a range of angle of attack 0° to 6° and at three particular frequency ratios of 0.9, 1.0 and 1.1.

The effects of frequency and angle of attack on the aerodynamic coefficients C_l, C_d and Strouhal number have also been studied.

NUMERICAL ANALYSIS

A. Problem definition

The computational domain used for the present study of steady laminar flow past plunging airfoil is shown in Figure 1. A representative Reynolds number of 10,000 is selected for our study. The NACA0012 airfoil is made to plunge in tranverse flow direction with the fixed angle of attack. The range of angle of attack studied is from 0° to 6°. The distance between airfoil center and inlet is taken as $4.5c$. The chosen oscillation frequencies (f_e) for this study are 0.9, 1.0 and 1.1 and chosen plunge amplitude (Ae/w) is $0.25c$, where "w" is the width of the airfoil. The plunging amplitude and other lengths corresponding to the domain are non-dimensionalised with the chord length "c", of the airfoil. The oscillation frequency is also non-dimensionalised by considering a frequency ratio, f_r, where f_r is the ratio of oscillation frequency to that of the Strouhal frequency (vortex shedding frequency) of the stationary airfoil at the same Reynolds number of 10000.

Computations are carried out in OpenFOAM, an open-source CFD package. The numerical simulations were performed using pimpleFoam solver which is the combination of pisoFoam (Pressure Implicit with Splitting of Operator) and simpleFoam. The pimpleFoam is an incompressible turbulent transient solver for Newtonian fluids on a moving mesh. Here, the vortex shedding phenomenon is studied for a sinusoidally plunging airfoil.

The computational method involves the solving of the two-dimensional incompressible Navier-Stokes equation which is given by,

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

$$\nabla.\, u = 0 \quad (2)$$

where, u is the fluid velocity, w is the mesh velocity, t is time, p is the fluid pressure, Re is the Reynolds number and ∇ is the Laplacian operator.

The non–dimensional aerodynamic coefficients such as lift and drag coefficients are evaluated using the equations below

$$\text{Co-efficient of lift : } C_l = \frac{2F_l}{\rho U^2 A} \quad (3)$$

$$\text{Co-efficient of drag : } C_d = \frac{2F_d}{\rho U^2 A} \quad (4)$$

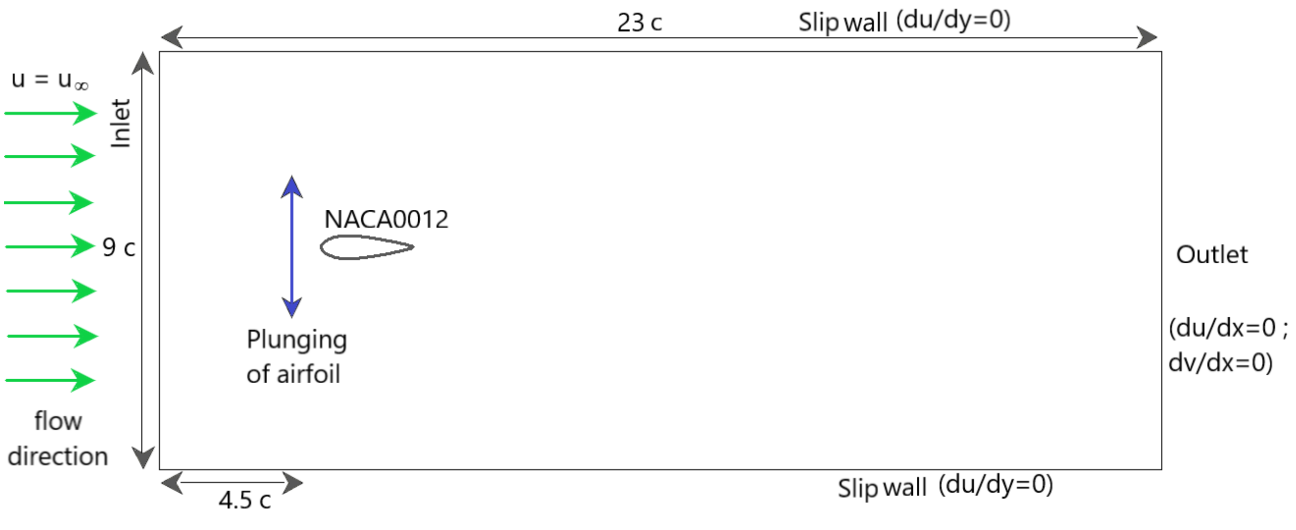

Fig. 1. Computational domain

To analyze the unsteadiness, due to flow over an oscillating airfoil we use Strouhal number equation to solve the system. In which the strouhal number is the non- dimensional representation of the shedding frequency, f_s.

$$\text{Strouhal number : } St = \frac{f_s L}{U} \quad (5)$$

B. Domain Independence test

TABLE I: Summary of all the cases considered for domain independence test at Re = 10000 and α = 5°

Si. no	Domain size		Re	α (in deg)	Upstream	$\overline{C_l}$	$\overline{C_d}$	St
	Lx	Ly						
1	13	4	10000	5	2.0	0.2346	0.0649	1.8867
2	15	5	10000	5	2.5	0.2373	0.0633	2.0000
3	17	6	10000	5	3.0	0.2381	0.0637	2.0000
4	19	7	10000	5	3.5	0.2374	0.0618	2.0408
5	21	8	10000	5	4.0	0.2378	0.0626	2.0408
6	23	9	10000	5	4.5	0.2419	0.0628	2.0618
7	25	10	10000	5	5.0	0.2421	0.0628	2.0618

This test has been carried out to find the optimum domain size for the computations. It was found that the aerodynamics co-efficient and the Strouhal number are not getting affected by the changes in the domain size above a critical value. A total of nine domains as shown in Table 1, with the sizes starting from $13c \times 4c$ to $29c \times 12c$ and with corresponding upstream distance were meshed and simulated. Reynolds number 10000 and angle of attack 5° is kept as constant. After when the simulations were done the values of $\overline{C_l}$, $\overline{C_d}$ and St are noted and it has been found that after the critical domain size $23c \times 9c$ with upstream distance $4.5c$, the values of $\overline{C_l}$, $\overline{C_d}$ and St are not changing appreciably.

Hence the domain with size $23c \times 9c$ and upstream distance $4.5c$ is selected for the proceedings.

C. Grid Independence test

TABLE II: Summary of all the cases considered for grid independence test at Re = 10000 and α = 5°

Si.no	No. of cells	α	$\overline{C_l}$	$\overline{C_d}$	St
1	19400	5	0.2151475	0.0617805	1.290322
2	25650	5	0.2283812	0.0633350	1.886792
3	36450	5	0.2350255	0.0625617	2.000000
4	40678	5	0.2350255	0.0627075	2.020202
5	51650	5	0.2423285	0.0628534	2.061855
6	60148	5	0.2436600	0.0626030	2.061855

The grid independence test has been conducted to find the optimum grid that has to be used and the results are consolidated in Table 2, to find the optimum grid. A total of six different meshes are created with different number of grid cells ranging from 19400 to 97850 and keeping Reynolds number 10000 and angle of attack 5° as previous studies for the simulation. After the test, it has been found that the grid with 56400 number of cells is the optimum because after which the aerodynamic coefficients $\overline{C_l}$, $\overline{C_d}$ and St acquires no significant change.

D. Validation

TABLE III: Validation of $\overline{C_l}$ and $\overline{C_d}$ of simulated results with experimental results by Dong-Ha Kim et al[1] and Justin Winslow[2]

S.no	α (in deg)	Re	Results from literature	Simulated results	(%) deviation
$\overline{C_d}$, Dong-Ha Kim et al[1]					
1	1	10000	0.02040816	0.019801	2.973
2	2	10000	0.0495626	0.049069	0.99
$\overline{C_d}$, Dong-Ha Kim et al[1]					
1	5	10000	0.0626822	0.062322	0.574
2	5	20000	0.064481	0.0626	2.91
3	5	23000	0.055768	0.05535	0.749
$\overline{C_l}$ / $\overline{C_d}$, Justin Winslow[2]					
1	5	10000	2.7272727	2.74416	0.619

After the selection of optimum domain and grid, the code is validated based on experimental data which are available from the previous research works and is shown in Table 3. Each cases were validated through the time average coefficient of drag and time average coefficients of lift for a stationary airfoil at a fixed angle of attack and for a particular Reynolds number. The Reynolds number considered for the validation was from Re = 10000 to 23000. A maximum deviation of less than 3% was observed in validation which is quite acceptable.

RESULTS AND DISCUSSION

The present research is carried out to investigate the influence of plunging amplitude, frequency ratio and Reynolds number on the effects of vortex shedding. Here, the plunge amplitude $0.25c$ is selected for the plunging motion of airfoil. For this study, the Reynold's number 10000 and the frequency ratios, f_r = 0.0, 1.0 and 1.1 have been chosen.

A. Coefficient of Lift ($\overline{C_l}$)

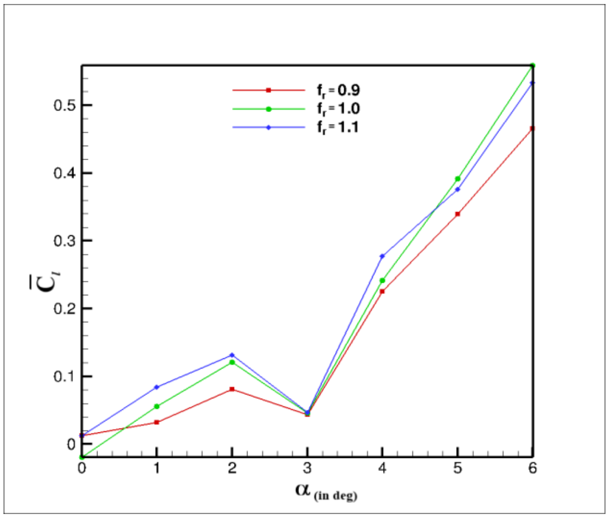

Fig. 2. Variation of $\overline{C_l}$ with respect to angle of attack, α at Re = 10000

The figure 2, introduce variations of $\overline{C_l}$ with α for various f_r. It can observed that $\overline{C_l}$ increases for all the frequency ratios from angle of attack α = 0° to α = 6°. However, it can also be noticed that there is a dip in $\overline{C_l}$ at angle of attack, α = 3°, this is due to the boundary layer separation phenomenon that arises at the airfoil surface. Jacobs and Sherman [4] also observed a substantial variation of lift coefficient in their study. The increase in $\overline{C_d}$ reaches a maximum at angle of attack 2°, then it readily stalls at angle of attack 3°. This is the point where this airfoil will drastically stop producing lift. When angle of attack is 2°, the boundary layer along the top surface of the airfoil separates. This flow separation is responsible for the sudden decrease in lift that occurs once the critical angle of attack has been exceeded. The flow reversal happens due to boundary layer separation, and vortical flow is observed above the back of the wing.

B. Coefficient of Drag ($\overline{C_d}$)

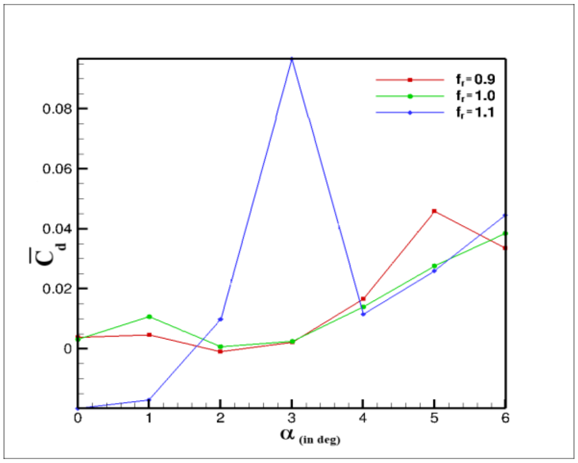

Fig. 3. Variation of $\overline{C_d}$ with respect to angle of attack, α at Re = 10000

The $\overline{C_d}$ graph show a variation of drag against the increase in angle of attack (α = 0° to 6°) for the frequency ratios 0.9 and 1.0. At f_r = 1.0 (Resonance frequency), the excitation frequency of oscillating cylinder is equal to that of the natural shedding frequency of the stationary NACA0012 airfoil. But a total different behaviour was observed for the frequency ratio 1.1. The slight increase in frequency ratio, f_r at 1.1 we can notice a negative drag (thrust producing condition) from angle of attack 0° to 2°. After the critical angle of attack α = 2°, there is a sudden rise of coefficient of drag and attaining its peak value at angle of attack 3°.

C. Strouhal number (St)

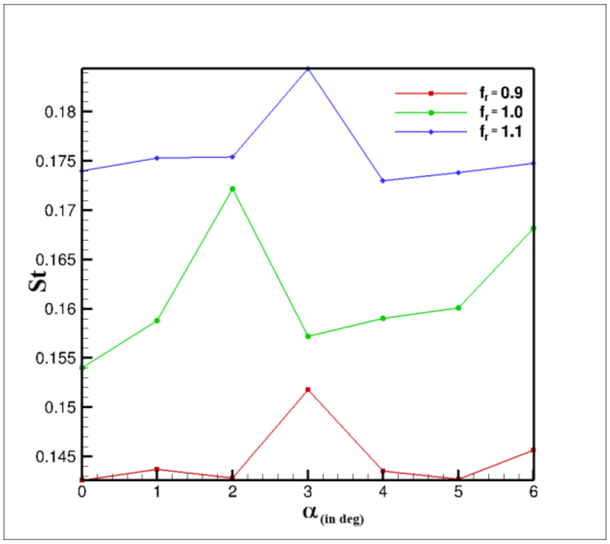

Fig. 4. Variation of St with respect to angle of attack, α at Re = 10000

The results shown in figure 4, shows the variation of Strouhal number with increase in angle of attack from α = 0° to 6° for three different frequency ratio values 0.9, 1.0, and 1.1. It is noticed that Strouhal number increases with frequency ratios. A sudden jump in Strouhal values is observed for the frequency values 0.9 and 1.1 at angle of attack 3°. But for the frequency value 1.0, the jump arises earlier at angle of attack 2°.

CONCLUSION

The aerodynamic characteristics and vortex shedding phenomenon for the transversely oscillating (plunging) NACA0012 airfoil were investigated at lower Reynolds number (Re = 10000) and at low angles of attack (0° to 6°). The frequency ratios, $f_r = f_e/f_o$ considered for the study are 0.9, 1.0 and 1.1 and with the constant plunging amplitude 0.25c for all the cases.

We have observed an interesting results for the aerodynamic characteristics of plunging NACA0012 airfoil. For the variation of $\overline{C_l}$ vs α, we have seen a dip for all three frequency ratios at angle of attack 3°. The sudden decrease in lift coefficient after angle of attack 2° is due to boundary layer separation at the surface. After the dip at $\alpha = 3°$, the flow gets reattached and C_l begins to increase with angle of attack.

In the $\overline{C_d}$ vs α plot, particularly for the frequency ratio 1.1 (just after the resonance frequency), it has been noticed that till $\alpha = 2°$, the plunging airfoil produces thrust (negative drag) and just after angle of attack 2°, the $\overline{C_d}$ rises to its peak at $\alpha = 3°$. In the Strouhal number vs α plot, a normal trend of St has been seen. The Strouhal number increase with the increase in frequency ratio. But, the frequency ratios 0.9 and 1.1 have their peak value of Strouhal number at $\alpha = 3°$, while for the resonance frequency 1.0, the Strouhal number attains the peak even before at $\alpha = 2°$.

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