

PROPULSIVE FORCE OF A HEAVING-PLUNGING RIGID AIRFOIL WITH THICKNESS

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ABSTRACT

Heaving-plunging airfoils, which have been popular because of MAV applications can overcome drag and create net propulsion depending on the relative values of two forces generated by the leading edge suction and the shear stress. The two forces are in opposite directions and their values are highly dependent on Reynolds number, amplitude and frequency of oscillation. In this study, flows over a heaving-plunging NACA 0012 airfoil are numerically solved using a developed MATLAB code. The code uses Blasius theorem and unsteady aerodynamics to predict leading edge suction and surface velocity distribution, respectively. The motions of the airfoil are modelled as a vertical oscillation of a rigid plate with a thickness correction for NACA 0012. Critical values of Reynolds number, amplitude (h) and reduced frequency (k) that give zero net propulsive force are determined for $0 \leq kh \leq 0.4$ and $0 \leq Re \leq 4.5 \times 10^4$. A curve is fitted to obtained zero net propulsive force data. For comparison, the flows are also solved using a commercial CFD solver, FLUENT. The results obtained from both solvers are in good agreement. Computational time requirement of the developed code is less than a minute and beyond comparison with the commercial solver.

Keywords: unsteady aerodynamics, heaving-plunging airfoil, low Reynolds number, NACA0012.

DÜŞEY EKSENDE SALINAN KALINLIKLI BİR RİGİD KANAT PROFİLİNİN İTKİ KUVVETİ

ÖZET

Mikro İnsansız Hava Aracı uygulamaları sebebiyle popüler olan düşey ekseninde harmonik olarak salınan kanat profilleri, hücum kenarındaki emme ve kayma gerilmesinin meydana getirdiği kuvvetlerin görece büyüklüklerine bağlı olarak sürüklemeyi yenebilir ve net bir itki meydana getirebilir. Bu iki kuvvet birbirine zıt yöndedir ve aldıkları değerler; Reynolds sayısı, titreşim genliği ve frekansla değişmektedir. Bu çalışmada, akışa dik doğrultuda harmonik salınım yapan bir NACA 0012 kanat profili etrafındaki akış, geliştirilen bir MATLAB kodu ile sayısal olarak çözülmüştür. Geliştirilen kod, hücum kenarı emmesi ve yüzey hız dağılımı için sırasıyla Blasius teoremi ve daimi olmayan aerodinamik ilkelerini kullanmaktadır. Reynolds sayısı, titreşim genliği (h) ve indirgenmiş frekans (k) büyüklükleri için sıfır itki meydana getiren kritik değerler $0 \leq kh \leq 0.4$ ve $0 \leq Re \leq 4.5 \times 10^4$ aralıkları için tespit edilmiştir. Elde edilen verilere bir eğri uydurulmuştur. Karşılaştırma yapmak için, modellenen akışlar ticari bir hesaplama akışkanlar dinamiği yazılımı olan FLUENT ile de çözülmüştür. Geliştirilen kod ve ticari programdan elde edilen sonuçlar iyi bir uyum içerisinde. Geliştirilen kod için gereken hesaplama zamanı bir dakikadan az olup ticari yazılımla kıyaslanamayacak ölçüde kısadır.

Anahtar Kelimeler:
NACA 0012.

daimi olmayan aerodinamik, düşeyde salınan kanat profili, düşük Reynolds sayısı,

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Nomenclature

b	= half chord
c	= chord
$C(k)$	= Theodorsen Function, $F(k)+iG(k)$
C_p	= pressure coefficient
C_d	= drag coefficient, $C_{d,f}+C_{d,p}$
$C_{d,f}$	= viscous drag coefficient
$C_{d,p}$	= pressure drag coefficient
C_f	= sectional skin friction coefficient
C_s	= suction force coefficient
C_t	= average propulsive force coefficient
h	= heaving-plunging amplitude
$\bar{h}^*$	= dimensionless amplitude
i	= index in the x direction
j	= index in the j direction
n	= index in time
Re	= Reynolds number
k	= reduced frequency, $\omega b/U$
S	= leading edge suction force
s	= reduced time, Ut/b
T	= period of airfoil motion
U	= freestream velocity
U_e	= edge velocity
u	= horizontal component of velocity in the viscous region
v	= vertical component of velocity in the viscous region
w	= downwash
α	= angle of attack
Δt	= time step
Δx	= step in the x direction
Δy	= step in the y direction
δ	= boundary-layer thickness
q	= edge velocity from thickness correction
ν	= kinematic viscosity
ρ	= density of the air
ω	= vorticity, angular frequency
ω_0	= surface vorticity

1. INTRODUCTION

The concept of flying with flapping wings is not a rare practice for nature, and the idea of designing and manufacturing devices flying with that method is undeniably comes from nature itself. Winged insects has been living in our world for million years [1], but the aerodynamics behind the flight with flapping wing were understood recently [2]. Number of experimental and computational studies report that flapping wings generate higher lift than the wing in steady motion under the same conditions [3]. The lift generated by a flapping wing can reach several times higher values than the case with fixed wing [1,4].

In recent years, many researchers are attracted to the concept of flapping wing, simply due to the increased interest in Micro Aerial Vehicles (MAV). MAV's are small autonomous flying vehicles, largely motivated by the need for aerial reconnaissance robots inside buildings and confined spaces for industry, commerce and military [4]. The main attributes of MAV's are their ability to fly at low Reynolds numbers and their small sizes.

Gaining thrust from a such miniaturized vehicle with traditional methods is inefficient. Therefore, flapping wing aerodynamics might be inevitable for successful MAVs design. Unlike conventional aircrafts, flapping wing aircrafts generate thrust with the help of leading-edge vortex (LEV) [5]. LEV is the vortex that is

attached to the leading edge of an airfoil. LEV generates a lower pressure area, which results in a large suction on the upper surface of a flapping airfoil. LEV's main characteristics and the implications on lift generation change as the Reynolds number varies [6].

Estimation of propulsive force via conventional CFD solvers for a flapping wing is quite expensive in terms of time and computational power needs. Gulcat [7] has proposed an alternative method for propulsive force estimation of a flapping airfoil. In his method, unsteady boundary layer equations are solved numerically to predict the viscous effects on an oscillating thin airfoil. Both the leading edge suction force and the edge velocities are obtained from unsteady potential theory. Gulcat has studied different types of flapping motions for both rigid and flexible thin airfoils and obtained satisfactory results [7].

Percin [8] has studied both numerically and experimentally the flow around a flapping NACA 0012 airfoil. He calculated trust and pressure coefficients for different reduced frequency values. Tuncer et al. performed computational studies for optimization of flapping airfoils in terms of maximum thrust and propulsive efficiency. They considered flapping motion of the airfoil as a combination of pitching and sinusoidal plunge [9]. Flapping airfoil is an active research subject, where great number of experimental and numerical studies along with review articles has been published recently [10-17].

In present study, by adding a thickness correction for NACA0012 to the method proposed by Gulcat, we manage to model the flows over a heaving-plunging NACA 0012 airfoil. We estimate the critical values that give zero net propulsive force for pairs of Reynolds number and the oscillation amplitude (h) times the reduced frequency (k), kh . In order to assess the efficiency and the accuracy of the method, we also obtained solutions using a commercial finite volume based Navier-Stokes solver [18], and then compared them with those that we obtained from our MATLAB code [19].

The main objective of this study is to estimate critical values of Reynolds number and kh pairs that give zero net propulsive force for a heaving-plunging NACA 0012 airfoil. In the following sections, theoretical and numerical formulation of the velocity-vorticity formulation based model are given. Besides presentation and comparison of the obtained results, an expression that represents the zero net propulsive force curve for the NACA 0012 is presented in Results and Discussion. General assessments about method are given in Conclusion.

2. FORMULATION

Using quasi-unsteady aerodynamics approach given in Reference [20], the leading-edge suction force and the boundary layer edge velocities can be obtained. The formulas for the theoretical evaluation of edge and extended edge velocities as well as the thickness corrections are given in the following sections.

Heaving-Plunging Airfoil with thickness

For a vertically oscillating airfoil, the sectional propulsive force created by the leading edge suction, S is written as follows [7]:

$$S = -2\rho\pi[\dot{h}C(k)]^2 \quad (1)$$

,where $h = -h^* \cos(\omega t)$ is the time variation of the height due to the vertical oscillation and $\dot{h}$ denotes the derivative of it with respect to time. In Eq. (1), $C(k)$ is the Theodorsen function, which has real and imaginary parts of $F(k)$ and $G(k)$, respectively. Here, $k = \omega b/U$ is the reduced frequency [21], where b is the half chord, ω is the angular frequency, and U is the free stream velocity. Derivation of Eq. (1) is shown in Reference [7]. If $s = Ut/b$ denotes the reduced time, the sectional propulsive force coefficient can be written as follows:

$$\begin{aligned} c_s &= S/(\rho U^2 b) \\ &= -2\pi k^2 [G(k) \cos(ks) + F(k) \sin(ks)]^2 \bar{h}^{*2} \end{aligned} \quad (2)$$

Here, $\bar{h}^* = h^*/b$ is the nondimensional oscillation amplitude. Using the downwash expression for harmonic motion and reduced frequency, k , time dependent normalized edge velocity can be written as below [7]:

$$\begin{aligned} U_e(s)/U &= 1 \pm [F(k) \sin(ks) \\ &+ G(k) \cos(ks)] k \bar{h}^* \sqrt{(1-x)/(1+x)} \end{aligned} \quad (3)$$

,where U_e is the edge velocity. The x indicates the location in x -direction and it is equal to -1 and 1 at the leading and trailing edges, respectively. Eq. (3) with + and - signs after the term “1” on the right-hand side corresponds to the normalized edge velocities for upper and the lower surfaces, respectively.

Extended Edge Velocity Approach

Perturbation velocity component in the flow direction, $\dot{u}/U$ and the lifting pressure coefficient, c_{pa} are linearly related for quasi-unsteady analysis. In the previous section apparent mass effect is ignored [22] in edge velocity calculation. For an airfoil in simple harmonic motion, extended edge perturbation velocity can be written in terms of amplitude of the lifting pressure coefficient, $\bar{c}_{pa}$ as follows:

$$\frac{u'}{U} = \frac{1}{4} \left(\bar{c}_{pa} - i k e^{-ikx^*} \int_{-1}^{x^*} \bar{c}_{pa} e^{ik\xi^*} d\xi^* \right) \quad (4)$$

The additional integral term requires integration of $\bar{c}_{pa}$ over x coordinate. The pressure coefficient, $\bar{c}_{pa}$ can be written in terms of real and imaginary parts of Theodorsen function as follows [20];

$$c_{pa} = \left[(F \sin(\omega t) \sqrt{\frac{1-x}{1+x}} + \left(Gk \sqrt{\frac{1-x}{1+x}} + 2k^2 \sqrt{1-x^2} \right) \cos(\omega t) \right] k h^* \quad (5)$$

The second term on the right-hand side of Eq. (4) can be transformed and written in terms of real and imaginary parts as below:

$$-i k e^{-ikx^*} \int_{-1}^{x^*} c_{pa} e^{ik\xi^*} d\xi^* = -R - iI \quad 6$$

Combining apparent mass and pressure term and rearranging the equation, the extended edge formulation takes the following form:

$$u'/U = \frac{1}{4} (\bar{c}_{pa} - R \cos(\omega t) + I \sin(\omega t)) \quad (7)$$

The perturbation velocity and vortex sheet strength are related as $\gamma_a = 2\dot{u}$

The Thickness Correction

Up to this point the calculations are based on the flow over a thin flat plate. However, with a correction term that is specific to airfoil, the flow around a flapping airfoil can be modelled. The method was developed by Van Dyke [23] and the details can be found in Reference [24].

To calculate the thickness correction, a new coordinate, s is introduced as follows:

$$s = x + c/2 \quad (8)$$

, where x is the distance from the midpoint of the chord that has a length of c . The thickness correction term, q is calculated as an edge velocity using the equation below.

$$\frac{q}{U} = \sqrt{\frac{s}{s + r/2}} \quad (9)$$

In Eq. (9), the edge velocity q and r represent the edge velocity and the radius of the curvature at the leading edge. In this study, the thickness correction is considered for NACA 0012. For 4 digit NACA profiles, radius of the curvature at the leading edge is calculated with the expression below.

$$r = 1.1019t^2 \quad (10)$$

,where t is the maximum thickness of the airfoil, which is the last 2 digits for 4 digit NACA profiles.

3. BOUNDARY-LAYER EQUATIONS

The vorticity transport equation for an oscillating rigid airfoil and its numerical solution with finite difference method are given in the following sections.

Velocity–Vorticity Formulation

Continuity and momentum equations for a two dimensional, unsteady, viscous flow can be written in terms of velocity vector, $\mathbf{V}$ and vorticity, ω as follows:

$$\nabla \cdot \mathbf{V} = 0 \quad (11)$$

$$\frac{D\omega}{Dt} = \nu \nabla^2 \omega \quad (12)$$

Nondimensional and explicit form of the two equations are also written in Eq.'s (13) and (14). The equations are nondimensionilized for the boundary layer by using the freestream velocity and chord length.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (13)$$

$$\frac{\partial \omega}{\partial t} + u \frac{\partial \omega}{\partial x} + v \frac{\partial \omega}{\partial y} = \frac{1}{Re} \frac{\partial^2 \omega}{\partial y^2} \quad (14)$$

The vorticity definition, $\omega = \nabla \wedge \mathbf{V}$ can be simplified in the boundary layer because of boundary layer concept as below:

$$\omega = -\frac{\partial u}{\partial y} \quad (15)$$

With the help of this simplification, horizontal component of the velocity vector can be obtained at any station in boundary layer by integrating the vorticity values.

Another useful expression, sectional skin friction coefficient formula for a thin airfoil is written below in nondimensional form

$$c_f = \frac{2}{Re} \omega_0 \quad (16)$$

,where ω_0 is the vorticity value measured on the surface in the inertial frame of reference. Integration of Eq. (16) along the top and bottom surfaces of the airfoil gives viscous drag coefficient, $c_{d,f}$ which is the force opposing the propulsion.

Numerical Formulation

Finite difference discretization schemes are used for the solution of the boundary layer equations. Eq. (14) is spatially discretised on an equally spaced Cartesian grid. While the central differencing is used in y-direction, forward differencing is used both in time and in x direction. Discretised form of the equation is as follows:

$$\begin{aligned} \frac{\omega_{i,j}^n - \omega_{i,j}^{n-1}}{\Delta t} = & -u_{i,j}^{n-1} \frac{\omega_{i,j}^n - \omega_{i-1,j}^n}{\Delta x} - v_{i,j}^{n-1} \frac{\omega_{i,j+1}^n - \omega_{i,j-1}^n}{2\Delta y} \\ & + \frac{1}{Re} \frac{\omega_{i,j+1}^n - 2\omega_{i,j}^n + \omega_{i,j-1}^n}{(\Delta y)^2} \end{aligned} \quad (17)$$

In the equation above, the superscript n and $n-1$ denote the values at new time and old time levels, respectively. The discrete points in x and y directions are represented by subscripts i and j , respectively. In order to obtain new vorticity values inside the boundary layer, the vorticity values at the surface and the boundary layer edge must be known. At the edge of the boundary layer, the vorticity values, $\omega_{i,j_{max}}$ are set to be equal to zero because of boundary layer concept. On the other hand, the values of the surface vorticity along the boundary layer, $\omega_{i,0}$ are calculated from Eq. (15) using numerical integration with the trapezoidal rule. In Eq. (18) details of the calculation are written for station i :

$$U_e|_i = -\int_0^{\delta} \omega dy|_i = -\left[\omega_{i,0}/2 + \sum_{j=1}^{J-1} \omega_{i,j} \right] \Delta y \quad (18)$$

Combining the Eq.'s (17) and (18) and writing the resulting equations in a matrix form yields following equation:

$$\begin{bmatrix} 1/2 & 1 & 1 & \dots & 1 \\ a_2 & d_2 & c_2 & \dots & \dots \\ \dots & a_3 & d_3 & c_3 & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & a_j & d_j \end{bmatrix} \begin{pmatrix} \omega_{i,0} \\ \omega_{i,1} \\ \omega_{i,2} \\ \dots \\ \omega_{i,J-1} \end{pmatrix} = \begin{pmatrix} -U_e/\Delta y \\ b_2 \\ b_3 \\ \dots \\ b_J \end{pmatrix}_i \quad (19)$$

As can be seen from Eq. (19), the vector appearing on the left-hand side of the equation contains the unknown vorticity values along the normal direction of station i . The vorticity and the velocity values appearing in the coefficient matrix and the right-hand side vector are known from the previous time step calculation. The value of edge velocity, U_e that appears on the first row of the right-hand side vector is obtained from Eq. (18) at current time step. The values other than those appearing in the first row are calculated using the old time step values as in the following expressions:

$$\begin{aligned} a_j &= -v_{i,j-1}^{n-1} \frac{\Delta t}{2\Delta y} - \frac{\Delta t}{Re \Delta y^2} \\ b_j &= \omega_{i,j-1}^{n-1} + u_{i,j-1}^{n-1} \frac{\Delta t}{\Delta x} \\ c_j &= v_{i,j+1}^{n-1} \frac{\Delta t}{2\Delta y} - \frac{\Delta t}{Re \Delta y^2} \\ d_j &= 1 + u_{i,j}^{n-1} \frac{\Delta t}{\Delta x} + \frac{2\Delta t}{Re \Delta y^2} \end{aligned} \quad (20)$$

After obtaining the vorticity values, horizontal component of the velocities at discrete points are obtained by integration as follows:

$$u_{i,j} = -\int_0^{y_j} \omega dy|_i = -\left[\sum_{m=1}^{j-1} (\omega_{i,m-1} + \omega_{i,m})/2 \right] \Delta y \quad (21)$$

$$j = 2, \dots, J$$

Finally, vertical components of the velocity vectors are obtained from the continuity equation as follows:

$$v_{i,j}^n = v_{i,j-1}^n - \frac{\Delta y}{2\Delta x} (u_{i,j} + u_{i,j-1} - u_{i-1,j} - u_{i-1,j-1}) \quad (22)$$

,where $2 \leq j \leq j_{max}$.

4. SOLUTION PROCEDURE

In Sections 3 and 4, the equations required for net propulsive force calculation of a heaving-plunging airfoil are given in detail. The equations are solved in accordance with the flow chart in Figure 1 and in words as follows.

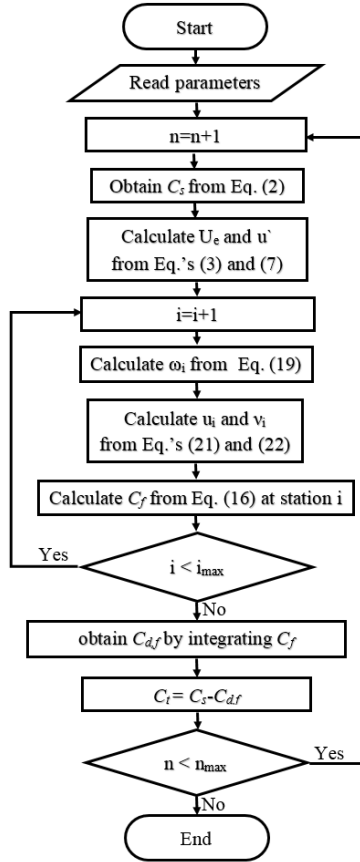


Figure 1. Flow Chart

1. The coefficient of time dependent suction force is obtained from Eq. (2).
2. Unsteady edge and/or extended edge velocities are obtained from Eq. (3) and (7), respectively.
3. Using the known values of edge velocity and other relevant parameters, vorticity values are obtained from the solution of Eq. (19) at a given time n and station i along the boundary layer.
4. Two velocity components, u and v are calculated from Eq.'s (21) and (22) for station i .
5. At the station i , surface skin friction coefficient is computed from Eq. (16).

6. The solution is marched in i direction for the same time level.
7. Drag coefficient, C_{df} is obtained by integrating the skin friction coefficient, C_f obtained in step 5.
8. The net propulsive force coefficient is calculated by subtracting the drag force coefficient from the suction force coefficient that are obtained in steps 7 and 1, respectively.
9. To reach the desired number of cycle, the steps between 3 and 8 are repeated.
10. Time averaged net propulsive force coefficient is obtained from time wise integration of the instant values obtained in step 8.

5. RESULTS AND DISCUSSION

Heaving plunging flat plate

The developed code is tested for a heaving-plunging flat plate, where Reynolds number and reduced frequency are equal to 10^5 and 0.4, respectively. For comparison, the obtained thrust coefficients are listed in Table. 1 for $h = 0.4, 1.0$, and 1.2 . The C_t values with * and ' correspond to results with and without thickness corrections, respectively. As can be seen from the table, effects of extended edge velocity formula on C_t becomes evident as h increases. The C_t values obtained from extended edge velocity formula perfectly matches the results by Gulcat [7].

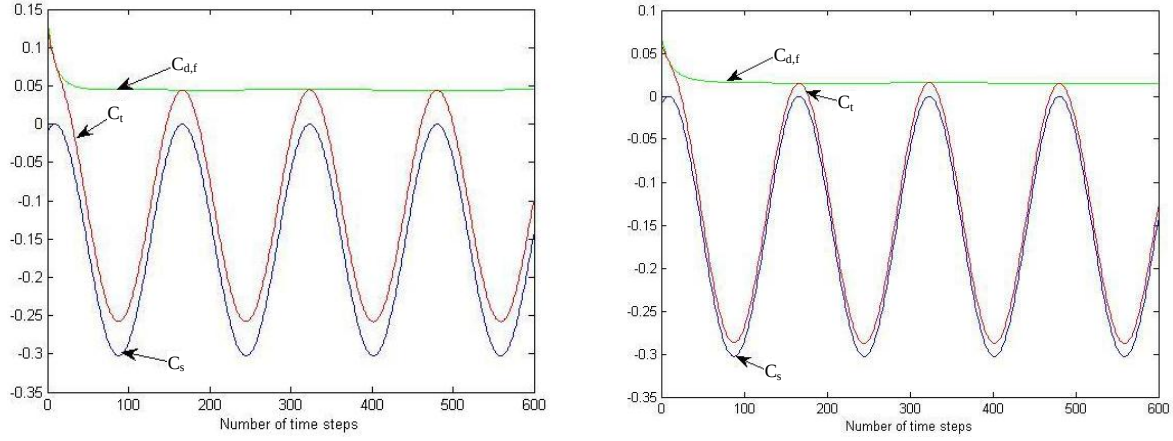
Heaving-plunging NACA 0012

Temporal variations of propulsive force coefficients with and without thickness corrections are shown in Fig. 2 for the first 600 iterations. Both results are obtained for $Re=10^4$, $k=1$, and $h=0.4$. The averaged propulsive force coefficients for the results with and without thickness corrections are equal to -0.1065 and -0.1360, respectively. As can be seen from the figure, while the drag coefficient becomes steady after a short while from the start, leading edge suction coefficients are time periodic. With the thickness correction, C_{df} values are estimated more realistically which results in lower values of averaged C_t .

In order to investigate the effects of Reynolds number on propulsive force coefficient, mean values of the coefficient were calculated for a heaving plunging NACA 0012 profile at 6 different Reynolds numbers. The average thrust coefficients were calculated at each Reynolds number value for kh range of $0.1 \leq kh \leq 0.5$. The variations of averaged C_t are shown in Fig. 3. During the calculation k is set to be equal to 1. As can be seen from the figure, average thrust coefficient is higher at lower Reynolds number for $0.1 \leq kh \leq 0.5$ without exception.

Table 1. Comparison of the obtained results with Reference [7]

	h=0.8		h=1.0		h=1.2	
	c_t^*	c_t'	c_t^*	c_t'	c_t^*	c_t'
Results with first edge velocity	-0.1287	-0.119	-0.204	-0.1942	-0.2962	-0.2863
Results with extended edge velocity	-0.1298	0.1204	-0.2054	-0.1961	-0.2979	-0.2886
Reference Study [7]	-0.129	-0.119	-0.205	-0.195	-0.298	-0.288

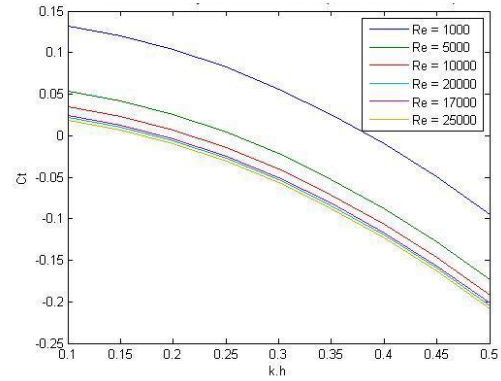

Figure 2. Variation of C_t , C_s , and $C_{d,f}$ in time with (left) and without (right) thickness correction

Zero net propulsive force values were obtained for $100 \leq Re \leq 25000$ and $0.1 \leq kh \leq 0.5$ ranges. Using the Matlab's polyfit feature a curve is fitted to the obtained data. Graphical representation of the curve on $Re - kh$ space is shown in Figure 4. The zero net propulsive force coefficient curve divides the map into two sections, where the upper and lower portions correspond to region of propulsion and drag, respectively. Equation of the curve and its coefficients are given in the equation and the table below:

$$Re(kh) = A_1 e^{B_1 kh} + A_2 e^{B_2 kh} \quad (23)$$

Table 2. Coefficients of the fitted curve

$A_1 = 3.375 \times 10^6$,	$B_1 = -31.5$
$A_2 = 7.059 \times 10^4$,	$B_2 = -11.07$


Figure 3. Variation of thrust coefficient, C_t with kh for NACA 0012 at various Re

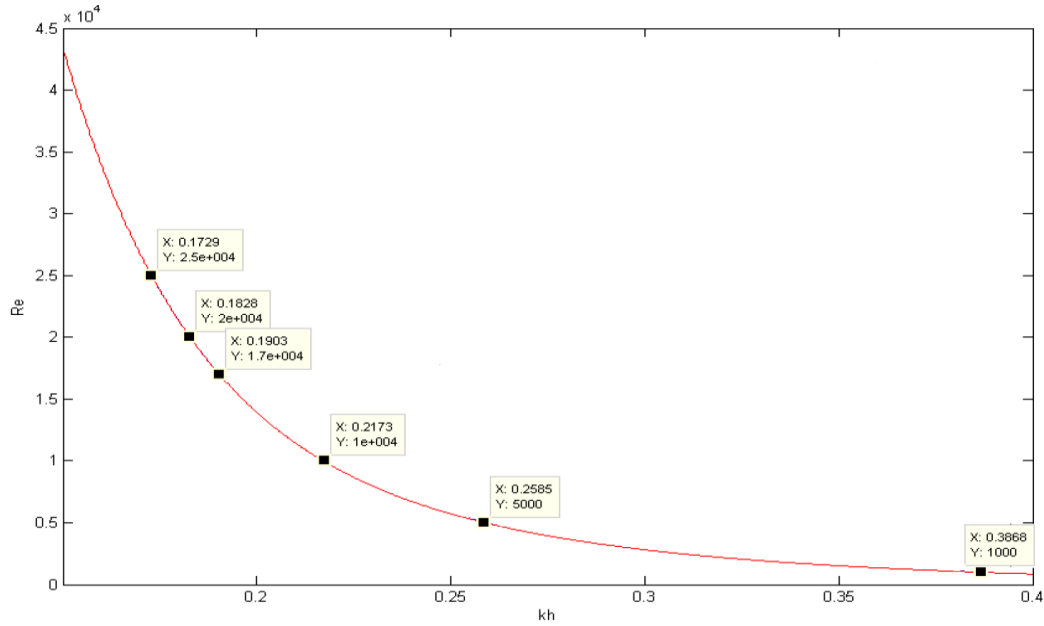


Figure 4. Zero net propulsive force coefficient variation as a function of Re and kh

CFD Results

For comparison, the flows are also modelled by using a commercial CFD solver, FLUENT. Computational details and the results are given in the following sections.

Mesh, initial and boundary conditions

A C – type domain, where NACA 0012 airfoil is placed 12.5c and 25c away from the left and right ends of the boundary is shown at the top of the Figure 5. The computational domain is filled with a structured mesh of quadrilateral elements. Each of upper and lower surfaces of the airfoil is represented by 70 grid points. Grid points are clustered both at the leading and the trailing edges.

The C-type course mesh consists of 44,154 cells. A fine and a finest meshes are obtained by increasing the elements number in both horizontal and vertical directions 2 and then 4 times, respectively. So, the fine and the finest meshes consist of 176,616 and 706,464 cells, respectively. Details of the course mesh, which consist of 44,154 hexahedral elements are also shown in the vicinity of trailing (bottom left) and leading edges (bottom right) in the figure.

No-slip and zero-pressure gradient boundary conditions are set on the airfoil surfaces. While the freestream velocity value is prescribed at the left, top, and bottom sides of the computational domain, pressure outlet boundary condition is set at the right end.

In order to model the heaving-plunging airfoil, oscillating vertical velocity is introduced to the solver

as a freestream boundary condition utilizing a solver feature, so called User Defined Function (UDF).

The flow is laminar. The pressure and velocity coupling is handled by SIMPLE scheme. A second order implicit formulation is used for transient solution. Green-Gauss Cell Based, second order and second order Upwind schemes are used for spatial discretization of gradient, pressure, and momentum, respectively.

By increasing the mesh resolution systematically and checking the temporal variation of C_t we reached mesh independent results with 176,616 cells. Vorticity contour snapshots obtained with the fine (top) and the course (bottom) meshes for $Re=17,000$ and $kh=0.45$ are shown in Figure 6. Although the course mesh is not able to capture the downstream vortex structures properly, time averaged thrust coefficients obtained with course and fine meshes are almost identical, $C_t=-0.156$ and $C_t=-0.157$, respectively.

In Figure 7, vorticity snapshots of the flow in the vicinity of the airfoil are shown with a time increment of $t=1/8T$, where T is the period of heaving-plunging motion. The arrow on the top left corner of each snapshot indicates the direction of the airfoil movement. The instant are also written on the top left corners. The instants where the airfoil reaches upper- and lower-most positions are marked by a horizontal line instead of an arrow. In calculations, Δt is set to be $T/1000$. It is observed that the results are independent of chosen Δt value of $T/1000$.

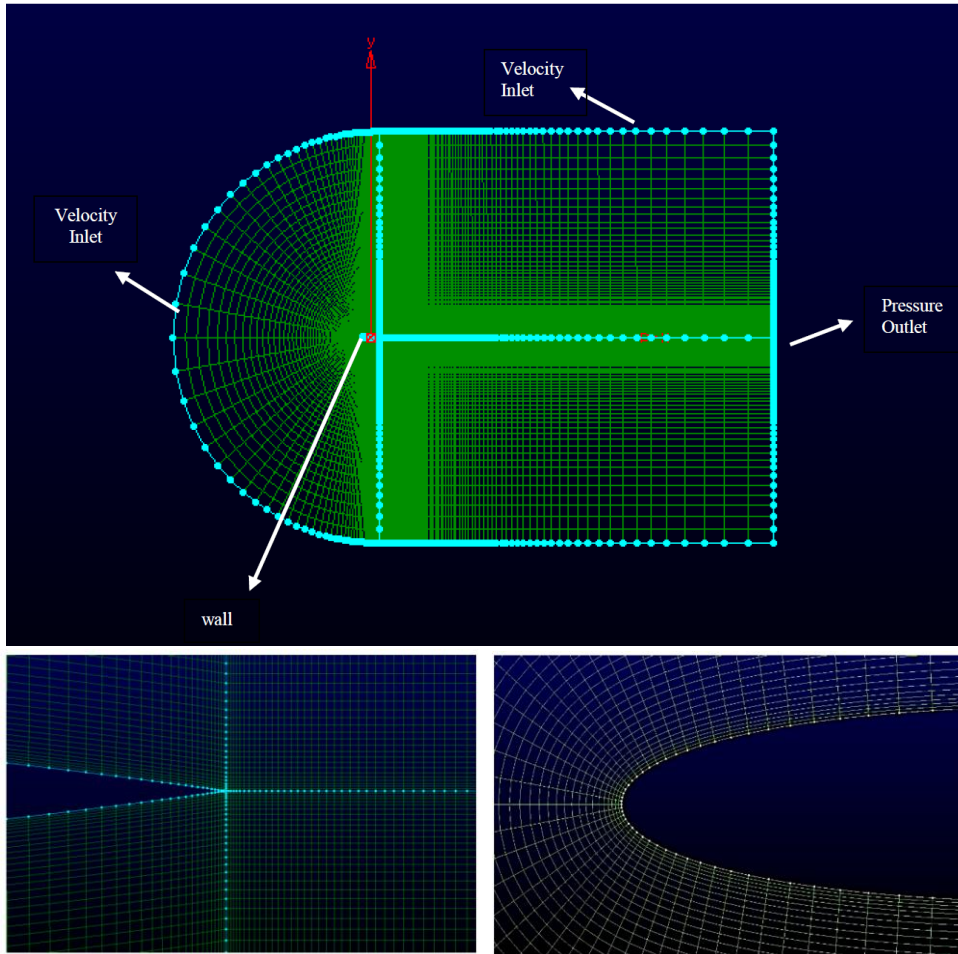


Figure 5. Computational domain and boundary conditions (top), mesh details around trailing edge (bottom left), and leading edge (bottom right)

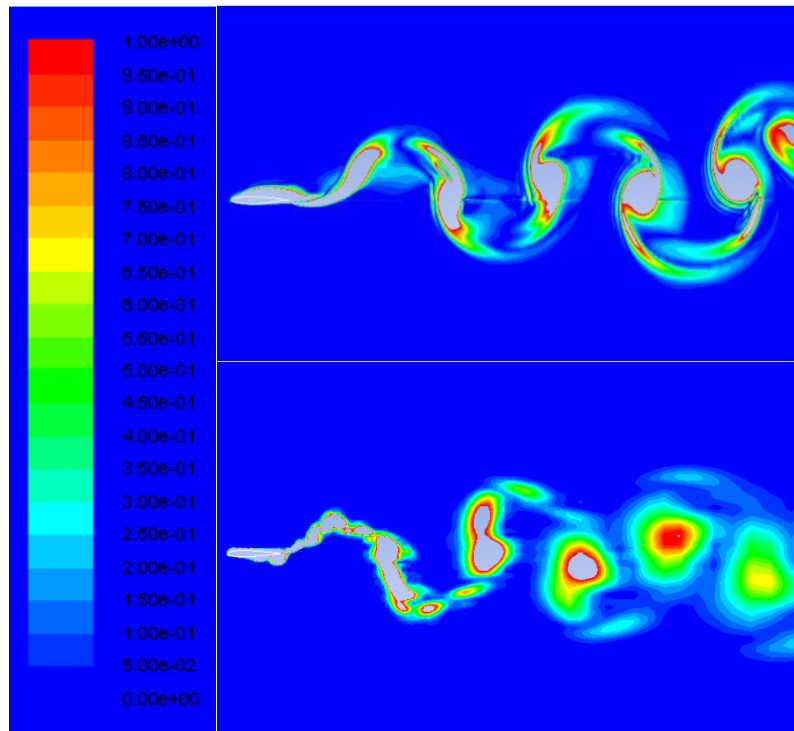


Figure 6. Vorticity contour instants obtained from fine (top) and course meshes (bottom) for $kh=0.45$ at $Re=17,000$

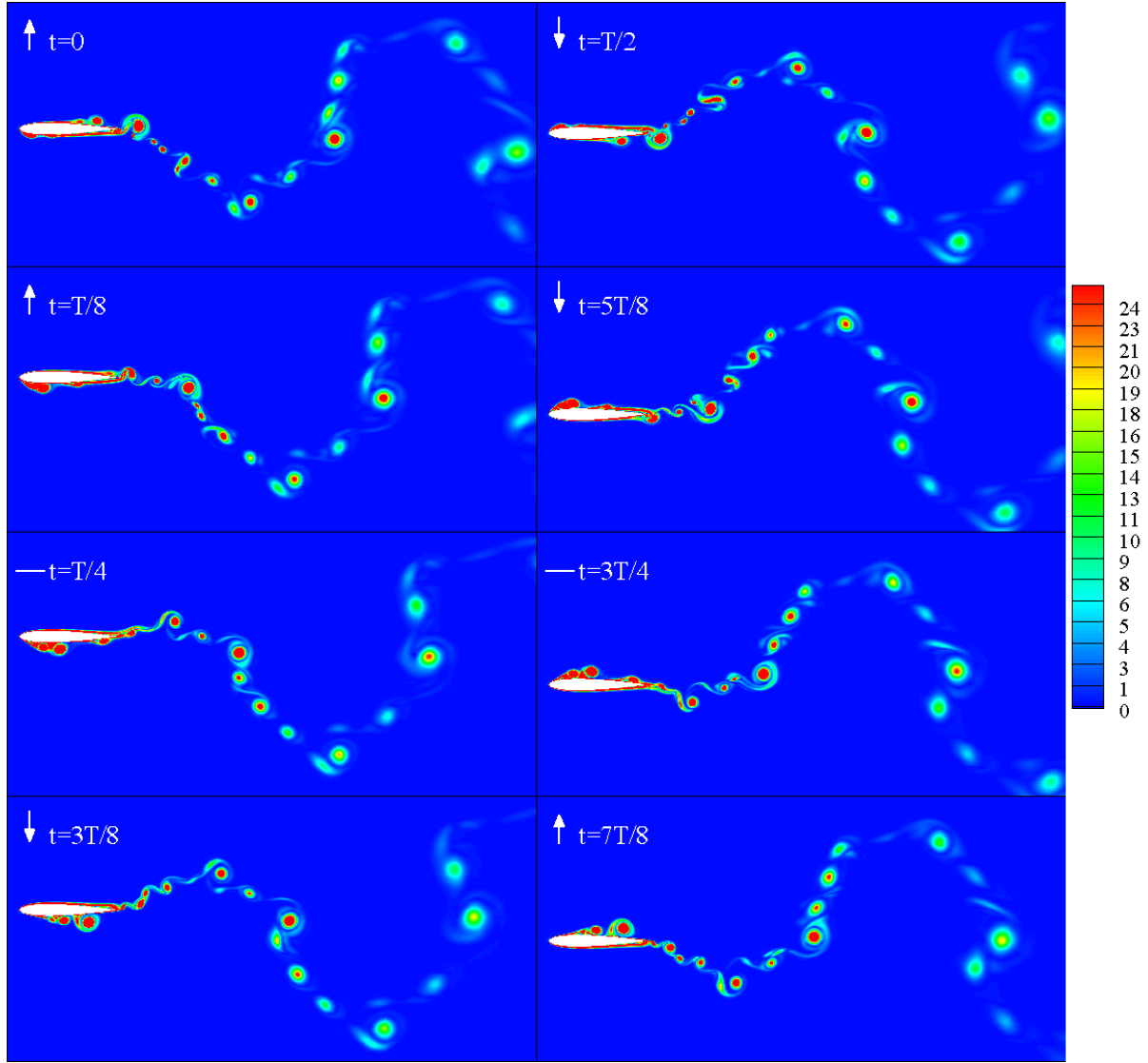


Figure 7. Vorticity contour instants for $kh=0.45$ at $Re=17,000$ ($\uparrow$ upstroke, downstroke $\downarrow$)

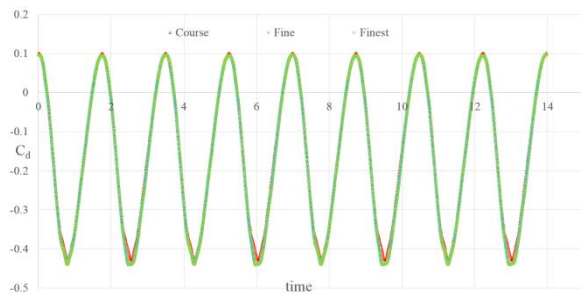


Figure 8. Temporal variation of C_d for $kh=0.45$ and $Re=17,000$

As can be seen from the Figure 8, the fine and the finest meshes are in good agreement and the difference in their time average C_d values is less than 0.4 %.

Viscous and pressure components of total C_d along with itself are plotted in Figure 9 for a period of the heaving plunging airfoil. As can be seen from the figure, pressure component of drag coefficient, $C_{d,p}$ is

dominant. This observation confirms the behaviour in Figure 2 obtained from the developed code.

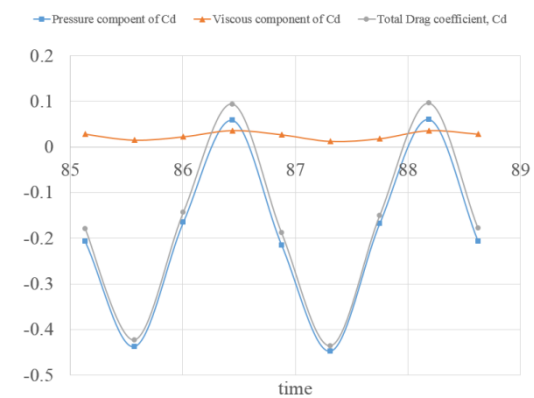


Figure 9. Temporal variation of C_d and its components, $C_{d,f}$ and $C_{d,p}$ for $kh=0.45$ and $Re=17,000$

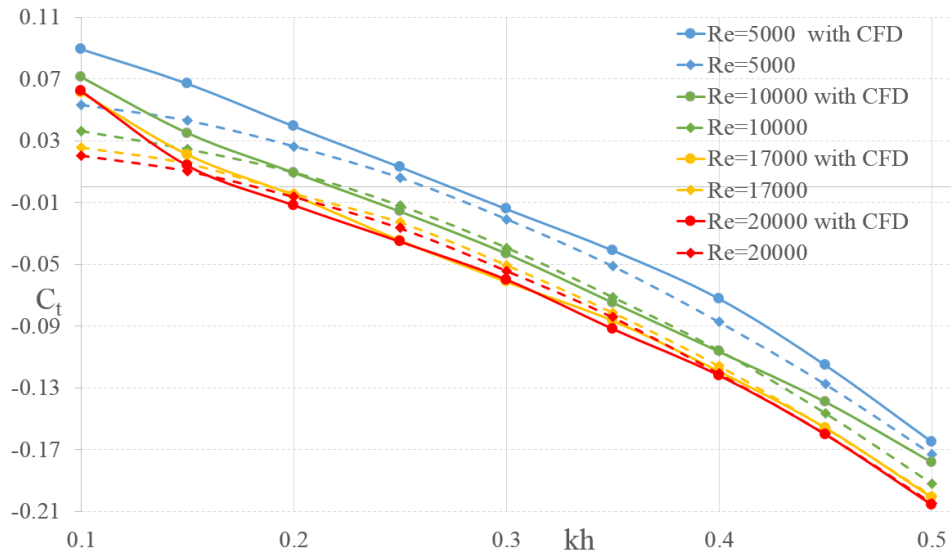


Figure 10. Comparison of the results obtained from the developed code (dashed lines) and the commercial Navier-Stokes solver (solid lines)

Thrust coefficient values are obtained for 4 different values of Reynolds number ($Re=5000, 10000, 17000$, and 20000) and kh range of $0.1 \leq kh \leq 0.5$. In Figure 10, the C_t values (solid line) are shown with those obtained from the developed code (dashed line) for comparison. The difference between the two results is less than 0.6 % for $Re=17,000$ and $20,000$ at $kh=0.5$. However, the difference can reach 40% for low kh values such as $Re=5000$ at $kh=0.1$.

5. CONCLUSIONS

In order to determine net propulsive force of a heaving-plunging NACA 0012 airfoil as a function of Re and kh , the method developed by Gulcat [7] is implemented to a Matlab code by considering thickness correction that is specific to the airfoil. Comparison of the results obtained from the developed code with Reference study for heaving plunging flat plate shows that the method based on unsteady-viscous interaction is coded properly. Then, critical values of Reynolds number, amplitude (h) and reduced frequency (k) that give zero net propulsive force are determined for $0 \leq kh \leq 0.4$ and $0 \leq Re \leq 4.5 \times 10^4$. A curve is fitted to obtained zero net propulsive force data and its equation is given in this study. For comparison, the flows are also solved using a commercial CFD solver, FLUENT. The results obtained from both solvers are consistent.

The developed code gives appropriate results for low Reynolds numbers. The method is useful, especially considering the amount of memory, time, pre- and post-processing stages required for conventional Navier-Stokes solvers. Computational time requirement of the developed code is less than a minute while the other requires 3 days on the same computer for the result with fine mesh.

Our analysis show that

- thickness correction is crucial for improving the results,
- for lower Reynolds numbers, higher kh values are required for the suction force to overcome the drag coefficient,
- for a fixed value of kh , as Reynolds number increases, the magnitude of the propulsive force also increases,
- and the parametric studies performed with the developed code are made way faster than the commercial solvers.

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