

**THRUST GENERATION OF PITCHING AIRFOIL IN
UNIFORM FLOW**

**M.Sc. Thesis by
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**SERBEST AKIMDAKİ ÇIRPAN KANADIN
İTKİ ÜRETİMİ**

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FOREWORD

I would like to express my deep appreciation and thanks for my advisor, Prof Doctor Aydın Mısırlıoğlu for their time and interest in this thesis; and my loving family for their never-ending love, support and belief.

January 2011

Emre KARADENİZ
Astronautical Engineer

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THRUST GENERATION OF PITCHING AIRFOIL IN UNIFORM FLOW

SUMMARY

The objective of this thesis is to understand the general characteristics of pitching airfoil aerodynamics. The flow over NACA0012 airfoil, oscillating in sinusoidal pitching motion is examined numerically in unsteady Navier-Stokes solver, written in FORTRAN. Viscous, incompressible, laminar flow and moving body is simulated with structured mesh scheme. Navier-Stokes equations solved by Galerkin Finite Element Method with Arbitrary-Lagrangian-Eulerian (ALE) description together with Fractional Step Method (Misirlioglu, 1998).

We run few simulations in order to determine the optimal mesh to fit our researches. We use different meshes to collect wide range of data to compare. We found that the mesh giving the best results are not resource-time effective, less detailed mesh is used for the simulations.

Later, the code is run for different cases for validation. Simulations for the research are performed for wide range of combination of reduced frequency certain pitching amplitude mean angle of attack values. Behavior of vortex patterns observed and determined for its drag generating, neutral wake and thrust generating abilities. Results are compared with experimental and numerical data.

For the research, simulations are made for wide range of combination of reduced frequency, pitching amplitude and mean angle of attack values. Reynolds number is set at 10,000. Thrust generating abilities of the simulations is determined for the cases. First simulations made for certain pitching amplitude and mean angle attack values with wide range of reduced frequency values. Presented pitching amplitude values are $\alpha_0=2.5^\circ$, $\alpha_0=5^\circ$, $\alpha_0=7.5^\circ$, and $\alpha_0=10^\circ$. Angle of attack values with small differences have a little effect on the results so we did not include them in the thesis. Reduced frequency values are ranged from $k=3$ to $k=20$. After that, effect of the mean angle of attack is examined for certain value of reduced frequency with wide range of mean angle of attack values. Presented pitching amplitude values are $\alpha_0=2.5^\circ$, $\alpha_0=5^\circ$, $\alpha_0=7.5^\circ$, and $\alpha_0=10^\circ$. Reduced frequency is set at $k=10$. Presented mean angle of attack values is ranged from $\alpha_m=0^\circ$ to $\alpha_m=45^\circ$.

Vortex structure of the simulations is visualized for every case. Comparison of the vortex structure is made for its thrust generating abilities and general vortex structure behavior. Karman vortex street and reversed Karman vortex street is observed with the explanation separating starting from the trailing edge of airfoil.

Our study clearly proves us that flapping wing simulations could be solved with noncommercial FORTRAN code with using finite element method. Code can be improved for future studies.

SERBEST AKIMDAKİ ÇIRPAN KANADIN İTKİ ÜRETİMİ

ÖZET

Bu çalışmanın amacı saat yönü ve saat yönü tersi yönde sinusoidal salınım hareketi yapan çirpan kanadın aerodinamik analizini hesaplamalı akışkanlar mekaniği aracılığı ile yapmak ve kullandığımız ticari olmayan FORTRAN kodunun yeterliliğini göstermektir. Çalışmamızda NACA0012 kanat profili etrafında düzgün, zaman bağlı, viskoz, sıkıştırılamaz akış, kanat çevresinde oluşturulan çözüm ağı kullanılarak ve Navier-Stokes denklemlerini çözen FORTRAN kodu aracılığı ile sayısal olarak incelendi. Problemin sayısal çözüm algortimaları için Galerkin Sonlu Elemanlar yöntemi, zamanda ayırıştırma için parçalı adımlar yöntemi, akışkan ile cisim arasındaki etkileşimi tanımlamak için keyfi Lagrange-Euler tanımı ve hareketli sınırlarda integral işleminin yapılabilmesi için dört boyutlu uzay-zaman elemanları kullanılmıştır (Misirlioglu, 1998).

Problemin bilgisayar ortamında sayısal olarak çözülebilmesi için çeşitli çözüm ağları kullanılarak deneme amaçlı çözümler yapılmıştır. Çözüm ağları farklılıkları ile birlikte denenerek 113 tane, değişik yunuslama genliği, indirgeme frekansı ve hücum açısı değeri içeren simulasyon çalıştırılmıştır. Bu deneme amaçlı simulasyonlar sonunda en iyi sonuç veren çözüm ağının bilgisayar ortamındaki kaynak kullanımı ve zaman oranlaması esas alındığında çok verimli olmadığı görülmüş. Bunun sonucunda daha az doğru sonuç veren fakat daha hızlı çözüm sunan çözüm ağının kullanılmasına karar verilmiştir.

Kodumuzun doğruluğunu tespit etmek için, önceden yapılmış olan çalışmalar tekrarlanarak sonuç karşılaştırılmıştır. Simulasyonlar geniş bir indirgenmiş frekans değerler aralığı ve belirli yunuslama genliği değeri ile yapılmıştır. Kanat profilinin arkasında oluşan girdapların davranışları gözlemlenmiş, sürüklenme, nötür ve itki oluşturan durumlar belirlenmiştir. Simulasyonumuz yunuslanma genliği, $\alpha_0=2^\circ$ ve Reynolds sayısı, $Re=12.000$ olacak şekilde koşturularak ilgili deneysel referansla karşılaştırılmıştır. Diğer simulasyon ise yunuslama genliği, $\alpha_0=2.5^\circ$, Reynolds sayısı $Re= 10.000$ olacak şekilde koşturularak sayısal referansla karşılaştırılmıştır. Çalışmamız deneysel referanstaki verilerle daha uyumlu sonuçlar vermiştir.

Çalışmamızdaki simulasyonlar geniş bir indirgenmiş frekans değerleri, yunuslama genliği ve hücum açısı değerleri aralığı ile gerçekleştirilmiştir. Reynolds sayısı tüm çalışmalar için 10,000 olarak ele alınmıştır. Yaptığımız simulasyonlarda ki durumların itki üretme kapasitesi büyük ölçüde göz önünde bulundurulmuş ve incelenmiştir. İlk çalışmalarımız sabit yunuslama genliği değeri ve sabit hücum açısı değerleri ile geniş bir aralıkta değişen indirgenmiş frekans değerleri ile yapılmıştır. Çalışmada kullanılan yunuslama genliği değerleri, $\alpha_0=2.5^\circ$, $\alpha_0=5^\circ$, $\alpha_0=7.5^\circ$, ve $\alpha_0=10^\circ$.

İndirgenmiş frekans değeri ise $k=3$ ile $k=20$ arasında değişen değerler olarak ele alınmıştır. Sonrasında indirgenmiş frekans ve yunuslama genliği değerleri sabit tutulmuş, geniş bir aralıkta değişen hücum açısı değerleri ile simülasyonlar yapılmıştır. İtke sabiti değerleri belirlenmiş ve grafiklerle gösterilmiştir. Bu çalışmada kullanılan yunuslama genliği değerleri $\alpha_0=2.5^\circ$, $\alpha_0=5^\circ$, $\alpha_0=7.5^\circ$, ve $\alpha_0=10^\circ$ olarak, değişim hücum açısı değerleri de $\alpha_m=0^\circ$ ile $\alpha_m=45^\circ$ olarak ele alınmıştır.

İtke katsayısının kapsamlı incelemesi açısından çalıştırılan simülasyonlarda oluşan girdaplar belirli işlemler için görselleştirilmiştir. Bu çalışmada kullanılan yunuslama genliği değerleri, $\alpha_0=2.5^\circ$, $\alpha_0=5^\circ$, $\alpha_0=7.5^\circ$, ve $\alpha_0=10^\circ$, indirgenmiş frekans değeri ise $k=10$ olarak ele alınmıştır. Girdap yapıları itke üretme özellikleri ve genel girdap yapıları incelemesi açısından karşılaştırılmaları yapılmıştır. Karman girdap caddesi ve ters karman girdap caddesi yapıları gözlemlenmiş, firar kenarında oluşan akım ayrılmaları gözlemlenerek açıklanmıştır.

Çalışma sonucunda elde edilen değerler yunuslama hareketi yapan kanadın aerodinamik özelliklerini belirlemede yardımcı olmuştur. Yunuslama genliği ve indirgenmiş frekans değerlerindeki değişiklikler itke üretimini doğrudan etkileyen faktörler olarak gözlenmiştir. Bunun yanında hücum açısındaki değişiklikler belirli bir seviyeye kadar önemli bir etken oluşturmamıştır. Hücum açısındaki değişiklik belirli bir seviyenin üstüne çıktığında ise bu parametrenin baskın olduğu görülmüş ve kritik bir seviyeden sonra itke oluşumunun imkansız olduğu görülmüştür.

Firar kenarının arkasında oluşan girdap yapıları hipotezde tahmin edildiği şekilde oluşmuştur. Sürüklenme kuvvetinin baskınlık oluşturduğu simülasyonlarda Karman girdap caddesi gözlemlenmiş, sürüklenme kuvvetinin neredeyse sıfıra yakın olduğu durumlarda ise iz bölgesinin üzerinde ve altında eşyapılı, ters tönü girdaplar oluştuğu gözlenmiştir. Yüksek yunuslama katsayısı ve indirgenmiş frekansa sahip kanat hareketinde ise ters Karman girdap caddesi oluştuğu gözlenmiştir.

Sayısal simülasyonlarımız sonucunda, 2. dereceden çözüm yapılamadığı için, firar kenarının arkasında oluşan girdaplar hızlı bir şekilde kaybolmuş ve küçük girdaplar görüntülenememiştir. Bu sebepten dolayı sonuçlarımız referans değerlerimizden daha yüksek sonuçlar vermiştir. Bu farklılığa rağmen sonuçlarımızda ki değişiklikler referans verilerimizle paralel bir davranış göstermiştir.

Çalışmamız çırpın kanat çalışmalarının ticari olmayan bir FORTRAN kodu ile yapılabileceğini kanıtlaması açısından önemlidir.

1. INTRODUCTION

Many successful flight attempts had been accomplished by the humanity even before the Wright Brothers. In all these years, we have been inspired by the flying creatures of nature and tried to create our own designs similar to them. However, we still do not have the ability to replicate flapping flying animals. Over a million species of insects and thousands of birds and bats fly by using their flapping wings. Considering the facts that we made our aerodynamic improvements quickly in short time, we can safely assume that humanity will solve the unknown phenomenon of the flapping wing flight, redesign and improve it by our own. We have started to understand nature of the flapping wing flight, with the help of multi-class scientific research and the helps induced by developments in the technology. Present stage of the study of this field resulted making small flying vehicles, known as micro air vehicles (MAV). Due to their size and payload limitations, installing thrust producing components is a serious problem. At this point, using the thrust producing method of the oscillating wing flying creatures becomes the most efficient and cheap solution. Analysis of the aerodynamic behavior of oscillating airfoils is a complex procedure; therefore, understanding the fundamental physics is the main difficulty of designing micro air vehicles. Oscillating airfoil in flow generates a wake structure behind its trailing edge. Behavior of this situation is the main reason of thrust generation. Low frequency oscillating airfoil generates wake structure type named as Karman vortex street that consist of a row clockwise vortices above a mean line and a row of anticlockwise below the mean line. This type of relation between two vortices behaves as a drag generating wake. High frequency oscillating airfoil generates a reversed Karman vortex street, which generates net thrust on the airfoil. Thrust generating wake structure is also called 'jet', main cause of thrust generation is the momentum demeanor behind the airfoil. There are two types of airfoil motions, which generate wake structure. First motion is heaving or plunging motion. Airfoils in heaving motion move up and down parallel to the horizontal axis due to certain oscillation frequency. Pitching motion means, airfoils move clockwise, counter

clockwise around a point usually placed on itself. Heaving and combined heaving-pitching motion have the highest thrust producing rate. Most of the researches focused on these types of motions.

1.1 Purpose of the Thesis

Due to their thrust generating abilities, heaving and combined heaving-pitching motions had been researched mostly. There are very few researches about pure pitching motion in a uniform flow. Our goal on this paper is to research pure pitching motion and its thrust generating nature that depended on wake structure behavior. We studied the behavior of the variables that have major or minor effect on the wake structure, such as; reduced frequency k , pitching amplitude α_0 , mean angle of attack α_m and location of pitching axis. We hope that our work may give important details about pitching motion behavior, to help other researches about both heaving-pitching and practical usage of flapping wing thrust generation for manmade designs.

1.2 Background

Many researchers through the years study flapping-wing aerodynamics. Both experimental and computational researches focused on dynamics of the wake and the vortex. (Katz and Weilhs, 1978), dynamic stall(Choudhuri et al., 1994, Ekaterinaris and Platzer, 1997, Isogai et al., 1999), flow control (Lai et al., 2002), hovering (Ansari et al., 2006, Dickinson et al., 1999, Liu and Kawachi, 1998, Platzer and Jones, 2006, Zbikowski, 2002), ornitophter (Grasmeyer, 2003) and thrust and lift production of the micro air vehicles (Ashley, 19998, Jones et al., 2001, Shyy et al., 1999). Although most of the researches' were computational, some researchers made experimental studies by using particle image velocimetry (Adrian, 2005 Freymuth, 1988, Jones et al., 1996, Lai and Platzer, 1999, Lighthill, 1975 Triantafyllou et al., 1993). Quick review on short history of aerodynamics would reveal us that Knoller was the first person who showed an effective angle of attack for flight could be generated by flapping foil (Knoller, 1909). This motion generates both lift and thrust force. Katzmayer made an experimental verification by placing a stationary airfoil

into a sinusoidal oscillating free stream and managed to measure average thrust (Katzmayr, 1922). Birnbaum made researches about thrust generation and determined its applicable conditions (Birnbaum, 1924), he was the first one who defined reduced frequency which is a useful parameter related to the flapping wing aerodynamics. Theoretical explanation of drag and thrust production, based on behavior of wake vortices made by Von Karman and Burgers. Karman Vortex street with a momentum deficit in the time-averaged flow is occurred during the drag producing with two alternating vortex rows, clockwise above and anticlockwise below. In thrust producing, wakes transpose the vortex rows and this formation of wake is called reverse Karman Vortex street. Garrick applied Theodorsen's inviscid, incompressible, oscillatory, flat-plate theory and proposed that thrust, produced by plunging airfoil, occurs nearly every frequency range (Garrick, 1936), their linearized theory proves that all types of plunging produce thrust. Silverstein and Joyner make experimental verification of Garrick's prediction (Silverstein and Joyner, 1939). Bratt made experiments about flow visualization (Bratt, 1950). Non-symmetrical, deflected wake pattern was recorded on Bratt's experiments but was never reported and discussed until Jones et al (Jones, K. D. and Dohring, 1996). Birnbaum, Kuchemann and Weber made suggestions about flapping wing as a propeller (Kuchemann, D. and Weber, 1953). During these researches, it has been realized that large amount of energy was lost due to vortices shed in the wake. Schmidt managed to save some of the energy, created by a flapping airfoil (Schmidt, 1965). Bosch examined the flapping airfoils and the combinations and developed a linear theory to predict propulsion (Bosch, 1977). DeLaurier and Harris made verification of flapping-wing propulsion by doing series of experimental process. Koochesfahani made experiments about thrust producing by pitching motions (Koochesfahani, 1989). Unlike plunging motion, pitching motion generates drag for low frequencies, which could cause flutter. Appearance of the drag profile in the wake of the foil and the motion amplification is the result of flutter, which is possible by extracting energy from the flow. Liu used vortex lattice panel method to examine flapping wing motion (Liu, 1991). Hovering insect is modeled by Liu and Kawachi (Liu and Kawachi, 1998) by using pseudo-compressibility method and unsteady three dimensional flow. Jones et al. made experimental and numerical progress and managed to describe behavior of wake structures formation as an inviscid phenomenon over a range of Strouhal numbers. Jones and Platzer used panel

methods to do numerical flapping-wing calculations and found performance improving airfoil flapping and ground effect (Jones and Platzer, 1997) . Stall is also a problem for aerodynamic vehicles and flying animals. If effective angle of attack changes rapidly, leading- edge vortex appears, lift increases whereas pitching moment decrease and sheds downstream, therefore stall occurs (Smith, 2005).

2. FORMULATION AND NUMERICAL METHOD

2.1 Governing Equations

Unsteady, incompressible, viscous, laminar flow conditions used in the present study. Governing equations of the problem would start with continuity equation

$$\nabla \cdot u = 0 \quad (2.1)$$

that is derived from the conservation of mass. Navier-Stokes equation

$$\rho \frac{Du}{Dt} = F - \nabla p + \mu \nabla^2 u \quad (2.2)$$

derived from conservation of momentum and the constitutive relations for the shear stress (White, 1974). In the equation, ρ is the fluid density, μ is the viscosity, u is velocity vector, p is pressure and F is the body force vector. This force becomes dominant under the conditions of gravity, buoyancy, etc. We can safely neglect this force in our study, so it is taken as zero. Navier-stokes and continuity equations are non-dimensionalized for proper and easy numerical calculations. Non-dimensionalized variables are:

$$x^* = \frac{x_i}{L} \quad u = \frac{u}{u_0} \quad p^* = \frac{p - p_0}{\rho_0 u_0^2}$$

$$t^* = \frac{tu_0}{L} \quad \rho^* = \frac{\rho}{\rho_0} \quad \nabla^* = L \nabla$$

non-dimensionalized version of the governing equations are

$$\nabla \cdot u = 0 \quad (2.3)$$

$$\frac{Du}{Dt} = -\nabla p + \frac{1}{Re} \nabla^2 u \quad (2.4)$$

u and p are dimensionless versions of u^* and p^* .

Re is the Reynolds number:

$$\text{Re} = \frac{\rho U d}{\mu}$$

ρ and μ stand for density and viscosity of the fluid, U and d stand for reference velocity and characteristic length.

Equations above need modifications in order to suit space-time formulation. ALE (Arbitrary Lagrangian e.) for a fixed coordinate system version of the governing equations are:

$$\nabla \cdot (u - u_g) = 0 \quad (2.5)$$

for the continuity equation, Navier-Stokes equation as;

$$\frac{\partial u}{\partial t} + (u - u_g) \cdot \nabla u = -\nabla p + \frac{1}{\text{Re}} \nabla^2 u \quad (2.6)$$

Where u is the absolute velocity vector and u_g is the grid velocity at the point under consideration.

2.1.1 Weak Formulation

Weak formulation of the ALE version of Navier-Stokes equation (2.6) would become

$$\int_{\Omega} \int_t \frac{\partial u}{\partial t} N d\Omega dt = \int_{\Omega} \int_t \left[-(u - u_g) \cdot \nabla u - \nabla p + \frac{1}{\text{Re}} \nabla^2 u \right] N d\Omega dt \quad (2.7)$$

N is the arbitrary weighting function. We integrate the left-hand side of the equation (2.7) for a fractional time step

$$\int_{\Omega} (u^{n+1/2} - u^n) N d\Omega = \int_{\Omega} \int_t^{t+\Delta t} \left[-(u^n - u_g) \cdot \nabla u^n - \nabla p^n + \frac{1}{\text{Re}} \nabla^2 u^n \right] N d\Omega dt \quad (2.8)$$

If we integrate for the full time step where pressure is evaluated at $n+1$, (2.7) becomes

$$\int_{\Omega} (u^{n+1} - u^n) N d\Omega = \int_{\Omega} \int_t^{t+\Delta t} \left[-(u^n - u_g) \cdot \nabla u^n - \nabla p^{n+1} + \frac{1}{\text{Re}} \nabla^2 u^n \right] N d\Omega dt \quad (2.9)$$

Also we are taking the divergence of (2.6) and express it in a weak form outcomes in

$$\int_{\Omega} \int_t \nabla \cdot \left(\frac{\partial u}{\partial t} \right) N d\Omega dt = \int_{\Omega} \int_t \nabla \cdot \left[-(u^n - u_g) \cdot \nabla u - \nabla p + \frac{1}{\text{Re}} \nabla^2 u \right] N d\Omega dt \quad (2.10)$$

Assumption is, u_g remains constant for a time step, after left-hand side integrated with respect to time, (2.8) changes into,

$$\begin{aligned} & \int_{\Omega} \nabla \cdot (u^{n+1/2} - u_g - u^n + u_g) N d\Omega \\ &= \int_{\Omega} \int_t^{t+\Delta t} \nabla \cdot \left[-(u^n - u_g) \cdot \nabla u^n - \nabla p^n + \frac{1}{\text{Re}} \nabla^2 u^n \right] N d\Omega dt \end{aligned} \quad (2.11)$$

At the full step, after the integration, (2.8) becomes

$$\begin{aligned} & \int_{\Omega} \nabla \cdot (u^{n+1} - u_g - u^n + u_g) N d\Omega \\ &= \int_{\Omega} \int_t^{t+\Delta t} \nabla \cdot \left[-(u^n - u_g) \cdot \nabla u^n - \nabla p^{n+1} + \frac{1}{\text{Re}} \nabla^2 u^n \right] N d\Omega dt \end{aligned} \quad (2.12)$$

After the subtracting (2.11) from (2.12) for the usage of continuity equation at n and $n+1$ results in,

$$\int_{\Omega} \nabla \cdot (u^{n+1/2} - u_g) N d\Omega = \int_{\Omega} \int_t^{t+\Delta t} \left[\nabla^2 (p^{n+1} - p^n) \right] N d\Omega dt \quad (2.13)$$

Also, subtracting (2.8) from (2.9) gives,

$$\int_{\Omega} (u^{n+1} - u^{n+1/2}) N d\Omega = - \int_{\Omega} \int_t^{t+\Delta t} \nabla \cdot (p^{n+1} - p^n) N d\Omega dt \quad (2.14)$$

Finally, equations (2.8), (2.13) and (2.14) are in the right form for discretization with introducing the auxiliary potential ϕ ,

$$\phi = p^{n+1} - p^n \quad (2.15)$$

2.1.2 ALE Formulation

Integral form of the equations needs discretizing for proper calculation procedure. We choose N to consist of basic functions of approximation which are trilinear forms of brick element. M_i are the mapping functions. N stands for shape functions, which used for basic functions of interpolation. Mapping function written as

$$\begin{aligned}
M_i &= \frac{1}{2}(1-\tau)N_i & i=1,\dots,8 \\
M_{i+8} &= \frac{1}{2}(1+\tau)N_i & i=1,\dots,8
\end{aligned} \tag{2.16}$$

Here, τ is the time coordinate on the parent element that ranged between -1 and 1. Parent element is shown in Figure 2.1. Four-dimensional cube (hypercube) in $\xi-\eta-\zeta-\tau$ dimensions, corresponding physical element in $x-y-z-t$ coordinates is also shown in the figure.

In the direction of $\alpha = x, y, z$, Galerkin Finite Element formulation of (2.8, 2.13-2.15) given as;

$$Mu_\alpha^{n+1/2} = Mu_\alpha^n + \left[B_\alpha + p_e C_\alpha - \left(\frac{A}{\text{Re}} + D \right) u_\alpha \right]^n \Delta t \tag{2.17}$$

$$A\phi = -E_\alpha (u_\alpha^{n+1/2} - u_\alpha^n) / \Delta t \tag{2.18}$$

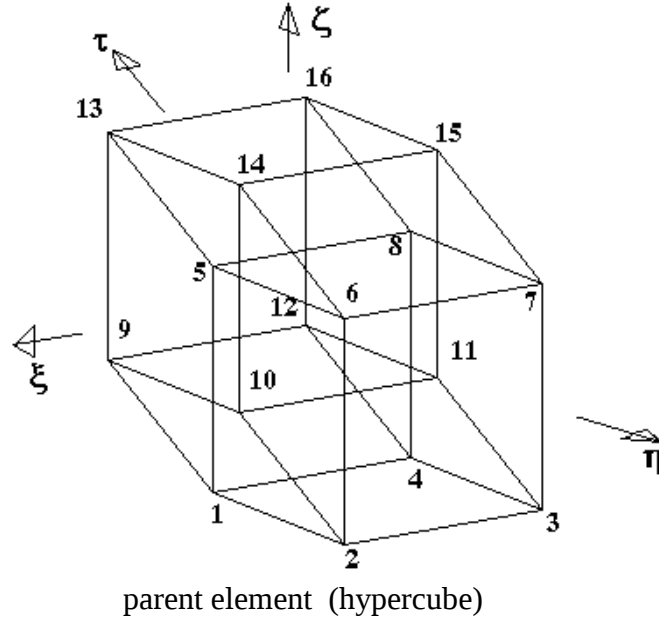
$$Mu_\alpha^{n+1} = Mu_\alpha^{n+1/2} - E_\alpha \phi \Delta t \tag{2.19}$$

$$p_e^{n+1} = p_e^n + \phi_e \tag{2.20}$$

In the formulas, M is lumped element mass matrix evaluated at each time step using the associated space element. A is the stiffness matrix, D is the advection matrix, C is the coefficient matrix for pressure calculation, B is the vector related to boundary conditions, E is the matrix related to incompressibility. Matrices given above are evaluated over the space-time element. At a given time, element potential is

$$\phi_e = \frac{1}{\text{vol}(\Omega_e)} \int_{\Omega} N_i \phi_i d\Omega_e, i=1,\dots,8 \tag{2.21}$$

Ω , N_i are flow region and shape function respectively. Calculations of high Reynolds number flows require second order artificial viscosity added to diffusive terms for stabilization. So algorithm for the solution of the problem would be; Result of the equation (2.17) gives the fractional step velocities which is needed for the auxiliary potential in the equation (2.18). Equation (2.19) solves the new time velocity field u^{n+1} . At last, equation (2.20) gives the new pressure field p^{n+1} .



$$M_i = 0.5(1-t)N_i, \quad i=1,\dots,8$$

$$x = M_i x_i, y = M_i y_i, z = M_i z_i, \quad i=1,\dots,16$$

$$M_{i+8} = 0.5(1+t)N_i, \quad i=1,\dots,8$$

$$t = M_i t_i, t_i = t_n, \quad i=1,\dots,8 ; \quad t_i = t_{n+1}, \quad i=9,\dots,16$$

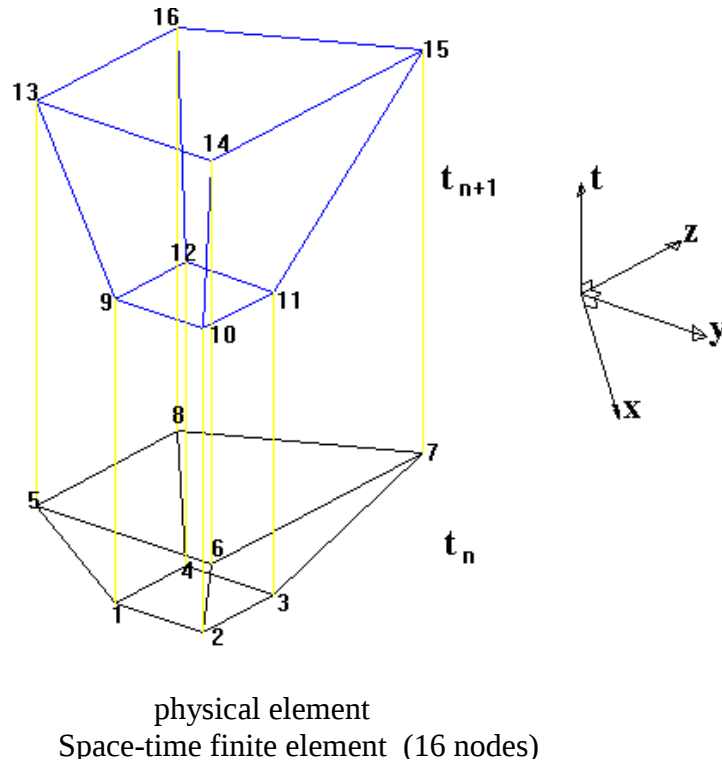


Figure 2.1. The parent element, hypercube and corresponding physical element, adapted from Misirlioglu (1998).

2.2 Pitching Motion

The main idea of this section is to clarify its objectives. We aim to find thrust producing abilities of the pure pitching motion, depending on the flow's properties such as reduced frequency, pitching amplitude and mean angle of attack. Airfoil in pitching motion will move clockwise, counter clockwise due to certain oscillation frequency, around a point usually placed on it. Vortex structure appears behind the trailing edge of the airfoil. Type of the vortex structures depends on the frequency of the oscillation. Several parameters are shown in the Figure 2.2.

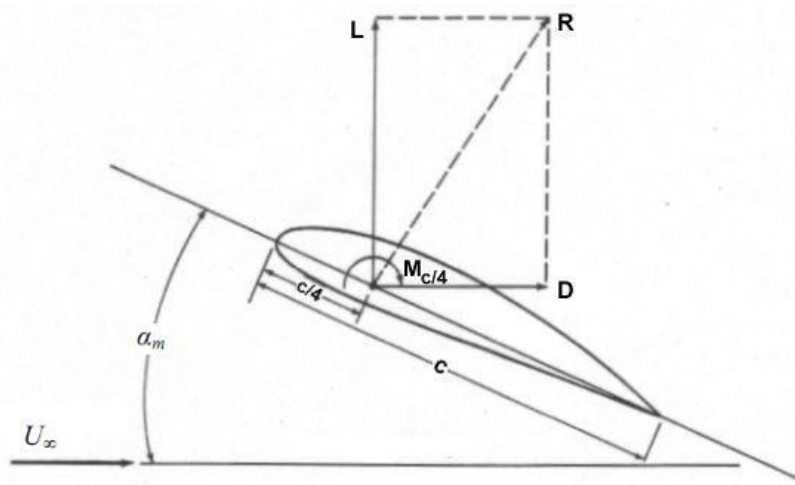


Figure 2.2: Pitching motion.

C_L is the lift coefficient and C_D is the drag coefficient. N and D are normal and drag forces which effects airfoil. α_m is the mean angle of attack. U_∞ is the free stream velocity. Reduced frequency is formulated as:

$$k = \frac{2\pi fc}{U_\infty} \quad (2.22)$$

C_D , drag coefficient is formulated as;

$$C_D = \frac{1}{T} \int_t^{t+T} C_D(t) dt \quad (2.23)$$

Where f oscillation frequency as hertz, c is the chord length of airfoil. The angular velocity of the pitching airfoil is formulated as:

$$\omega = \alpha_0 k U_\infty \cos(k U_\infty t) \quad (2.24)$$

3. RESULTS

3.1 Verification

First, we made some simulations to compare our code with other published papers. Comparisons are far from being perfect but our results have similar behaviour compared to the experimental results (Koochesfahani, 1989). Simulation is made for $Re=12,000$ and pitching amplitude, $\alpha_0=2^\circ$. We made our simulations by using two different meshes; low resolution mesh and high resolution mesh as shown in Figure 3.1 and 3.2. Blue curve represents low resolution mesh result, green curve represent high resolution mesh results and red curve represents experimental data. At the point $k=3.5$, experimental and low mesh results intersect and at point $k=5.5$ experimental and high mesh result intersect. After that point, both numerical simulations give higher thrust coefficient values than experimental results. Nevertheless, demeanors of the results seem parallel. Considering that our simulation is made in 2D, first order method, it is an acceptable error ratio. Our second validation simulations made for Sarkar, Vankatraman results (Sarkar,Vankatraman, 2005). Simulations presented in Figure 3.3 is made for $Re=10,000$ and Pitching amplitude, $\alpha_0=2.5^\circ$. Results are totally different in both values and behaviour. Considered that, values of Sarkar, Vankatraman are also result of a CFD method, we may neglect their method and accept the experimental results for our validation.

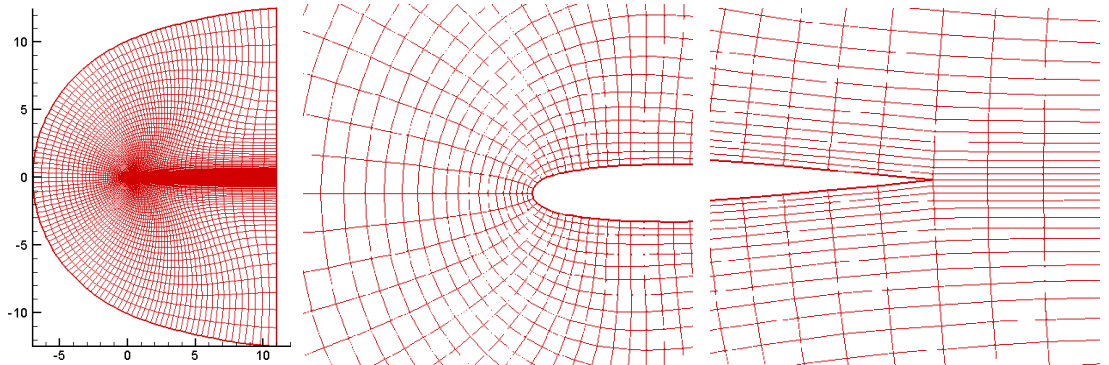


Figure 3.1: Low resolution mesh.

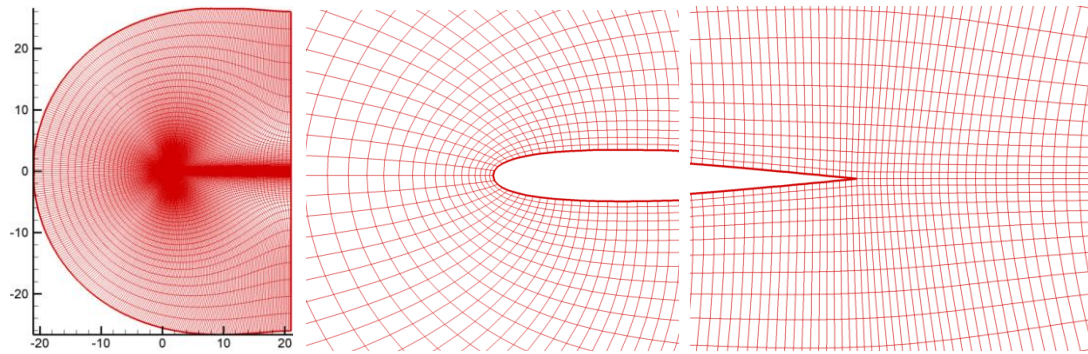


Figure 3.2: High resolution mesh.

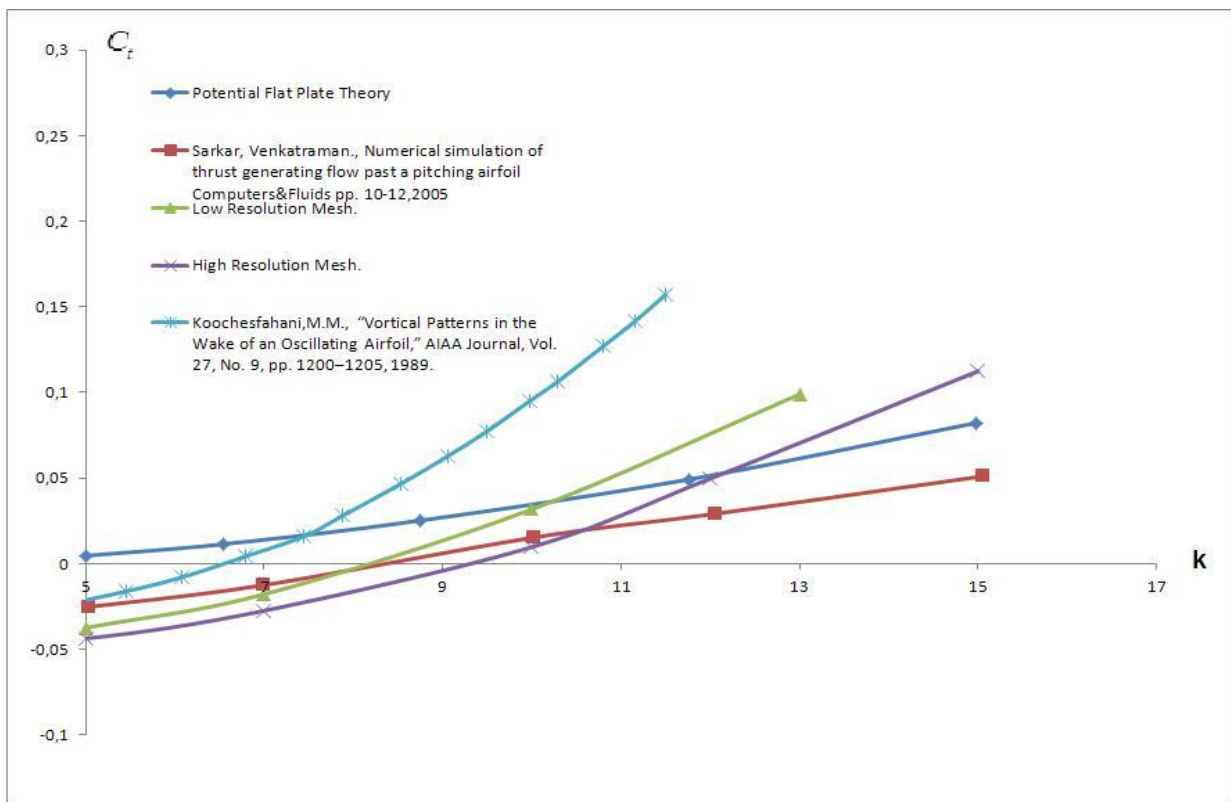


Figure 3.3: Validation simulations with experiment and numerical results.

Table 3.1: Numerical results of simulations and experiment.

k	Low Res.	High Res.	Kooc.
1	-0.04577	-0.04633	-0.03203
3	-0.03744	-0.04023	-0.03281
5	-0.00195	-0.02422	0.004297
7	0.059869	0.037295	0.028125
9	0.140595	0.111785	0.127344
11	0.250322	0.201985	0.157031

3.2 Zero angle of attack

Numerical simulation of the unsteady, incompressible, viscous flow passing a NACA 0012 airfoil, which has a sinusoidally oscillating pitching motion, is discussed. Main parameters of the numerical simulations are reduced frequency and pitching amplitude. Reduced frequency, which we used in simulations, differs from 3 to 20. Pitching amplitude values are set for 2.5° , 5° , 7.5° , 10° . Mean angle of attack angle is set for 0° , 5° and 10° , for low resolution meshes and it proved that mean angle of attack has a minimum effect on the thrust producing. Reynolds number is set at 10,000. We also made additional numerical simulations for examining the effects angle of attack. For these simulations, reduced frequency is set at 10, pitching amplitude is set at 2.5° , 5° , 7.5° , 10° where angle of attack differs from 0° to 40° degrees.

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3.2.1 Pitching Amplitude 2.5

For pitching amplitude, $\alpha_0=2.5^\circ$, thrust coefficient and reduced frequency values are researched. As the reduced frequency increases, maximum-minimum limits of the drag producing values gets wider. Minimum value is changing dramatically compared to maximum value. Minimum value ranges between 0.1 and 0.2, maximum value ranges between 0.05, 0.8. Absolute values of maximum, minimum points of angular velocity of the airfoil are equal, as the natural result of harmonic motion. Highest absolute values of the angular velocity usually occur when airfoil is in horizontal position. Average of the drag coefficient gives us the net drag rate. If the net drag value is negative, there is a “jet” stream, which produces thrust. For $k=3$, sinusoidal drag curve stays in entirely positive values, thus producing drag. For both low and high-resolution meshes, at $k=5$, min value of drag curve goes down about zero, for low resolution mesh, drag values of $k=7$ goes down below zero. For high-resolution mesh, drag values of $k=9.5$ min value goes down below zero, nearly balancing up with the positive values of the drag curve. Only drag producing wake also known as Karman vortex street occurs for reduced frequency values lower than 7 and 9 for low and high resolution meshes respectively. For $k=7$ and $k=9.5$ for low and high resolution meshes respectively, there is neutral wake, having zero thrust producing rate. In this situation leading edge vortex barely pairs with the trailing

edge vortex but does not interfere with each other. At $k=10$ average value of the drag curve becomes positive, making it a thrust producing reversed Karman vortex street pattern for both meshes. For values above $k=10$, leading edge vortex weakens. For $k=10$ detailed vortex pattern graphics are given in the Figure 3.4. Images show a low thrust producing, reversed Karman Vortex street which is similar to neutral wake. We can clearly see that leading edge vortices started to get weak due to increased value of reduced frequency. As frequency increases proportional to reduced frequency value, leading edge vortices stretch and merge with the trailing edge vortices rather than advecting it.

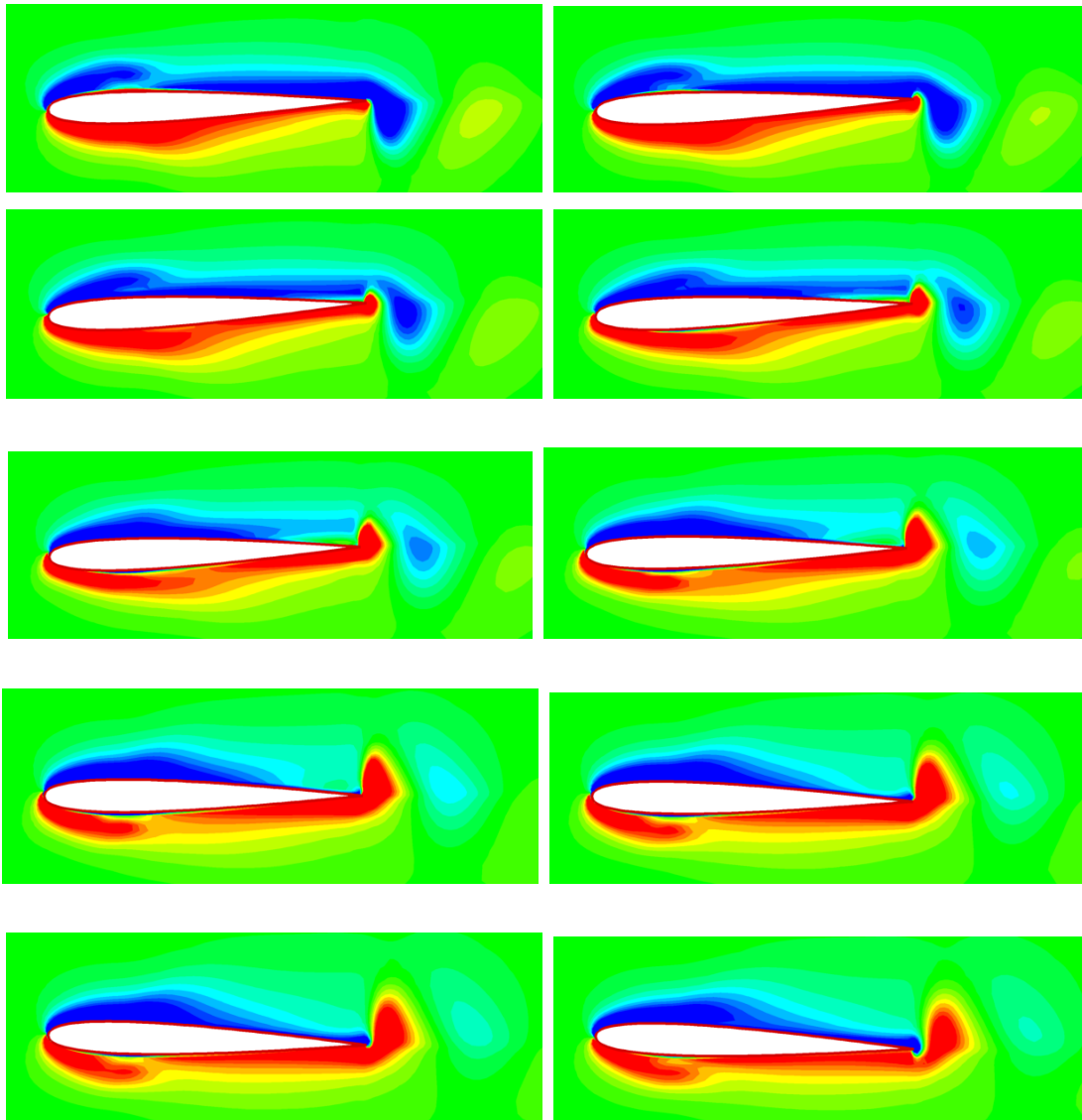


Figure 3.4: Detailed vortex pattern graphics, $k=10$.

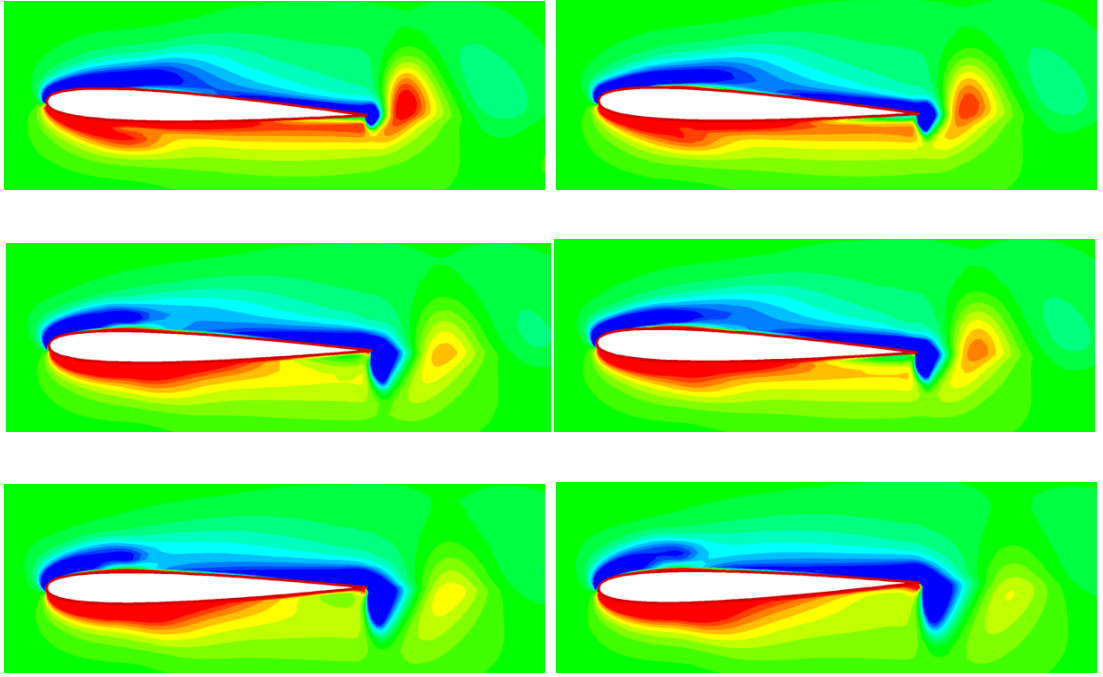


Figure 3.4 (contd): Detailed vortex pattern graphics, $k=10$.

3.2.2 Pitching Amplitude 5.

For pitching amplitude, $\alpha_0=5^\circ$, mean angle of attack, $\alpha_m=0^\circ$, thrust coefficient and reduced frequency values are researched. Similar to previous pitching amplitude examples, with the increasing reduced frequency, maximum-minimum limits of the drag producing values are getting wider. Minimum value is changing dramatically compared to maximum value. Min value is set between 0.05 and -3.5, max value ranges between 0.05 and 0.5. Absolute values of max, min points of angular velocity of the airfoil are equal as the natural result of harmonic motion. Highest absolute values of the angular velocity seem to occur when airfoil is in horizontal position as same as in the previous example. For $k=3$, sinusoidal drag curve stays in entirely positive values. At $k=5$, min value of drag curve goes down below zero, nearly making small amount of thrust. We may assume this case as neutral vortex pattern. For $k=7$ min value goes nearly down to -0.4, making the case a thrust producing case. Reduced frequency values lower than 5, only drag producing wake also known as Karman street occurs. For $k=5$, there is neutral wake, leading edge vortex barely pairs with the trailing edge vortex but does not interfere with each other. Values for above $k=7$, average value of the drag curve becomes positive, making it a thrust

producing reversed Karman vortex street pattern. As frequency increases proportional to reduced frequency value, leading edge vortices stretch and merge with the trailing edge vortices rather than advecting it. For other reduced frequency values until 20, thrust value is increasing proportional to k value as previous examples. Thrust values are greater than $\alpha_0=2.5^\circ$ cases. In the Figure 3.5, images of $k=10$ are shown. For the $\alpha_0=5^\circ$ case, leading edge vortices are stronger than the previous cases. Results of low and high resolutions meshes are somewhat similar compared to previous case. High-resolution mesh gives lower thrust coefficient results as expected.

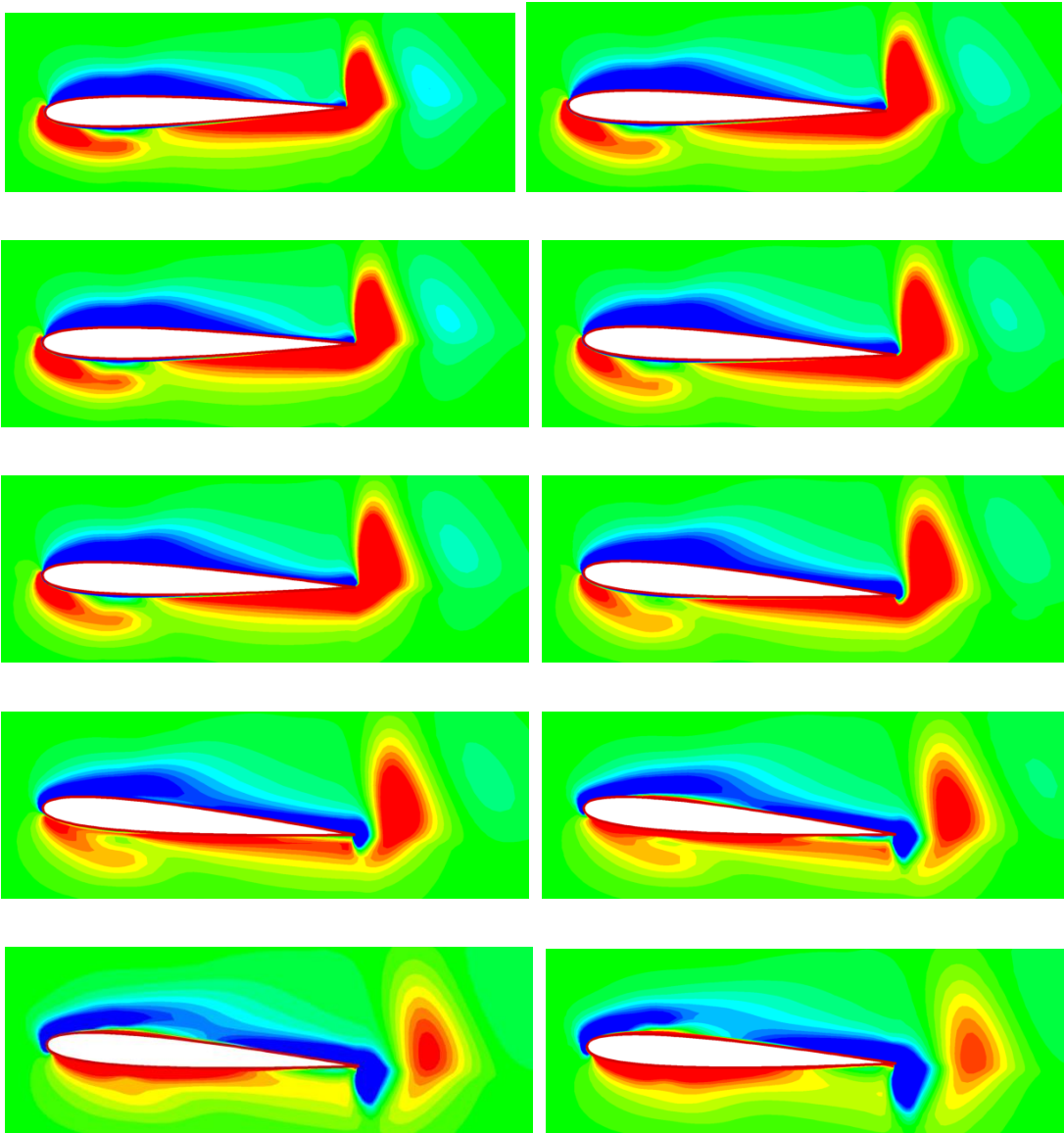


Figure 3.5: Detailed vortex pattern graphics, $k=10$.

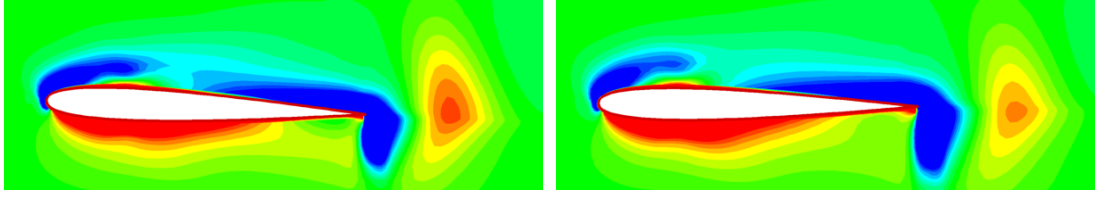


Figure 3.5 (contd): Detailed vortex pattern graphics, $k=10$.

3.2.3 Pitching Amplitude 7.5.

For pitching amplitude, $\alpha_0=7.5^\circ$, mean angle of attack, $\alpha_m=0^\circ$, thrust coefficient and reduced frequency values are researched. Only high resolution mesh used for these simulations because as pitching amplitude values increases, results of both mesh types getting closer, leaving little concern for comparison. As we expect from the previous pitching amplitude examples, with the increasing reduced frequency, maximum-minimum limits of the drag producing values are getting wider. Minimum value is changing dramatically compared to maximum value. Highest absolute values of the angular velocity seem to occur when airfoil is in horizontal position. For $k<3$, sinusoidal drag curve stays in both positive and negative values. At $k>3$ min value of drag curve goes down below zero, nearly making small amount of thrust. We may assume this case as neutral vortex pattern. For $k=5$ min value goes nearly down to -0.4, making the case a thrust producing case. Reduced frequency values lower then 3, only drag producing wake also known as Karman street occurs. For $k=3$, there is neutral wake, leading edge vortex barely pairs with the trailing edge vortex but does not interfere with each other. Values for above $k=5$, average value of the drag curve becomes positive, making it a thrust producing reversed Karman vortex street pattern. As frequency increases proportional to reduced frequency value, leading edge vortices stretch and merge with the trailing edge vortices. For other reduced frequency values until 15, thrust value is increasing proportional to k value as previous examples. Thrust values are greater than $\alpha_0=2.5^\circ$ and $\alpha_0=5^\circ$ cases. In the Figure 3.6, images of $k=10$ are shown. For the $\alpha_0=7.5^\circ$ case, leading edge vortices are stronger than the previous cases.

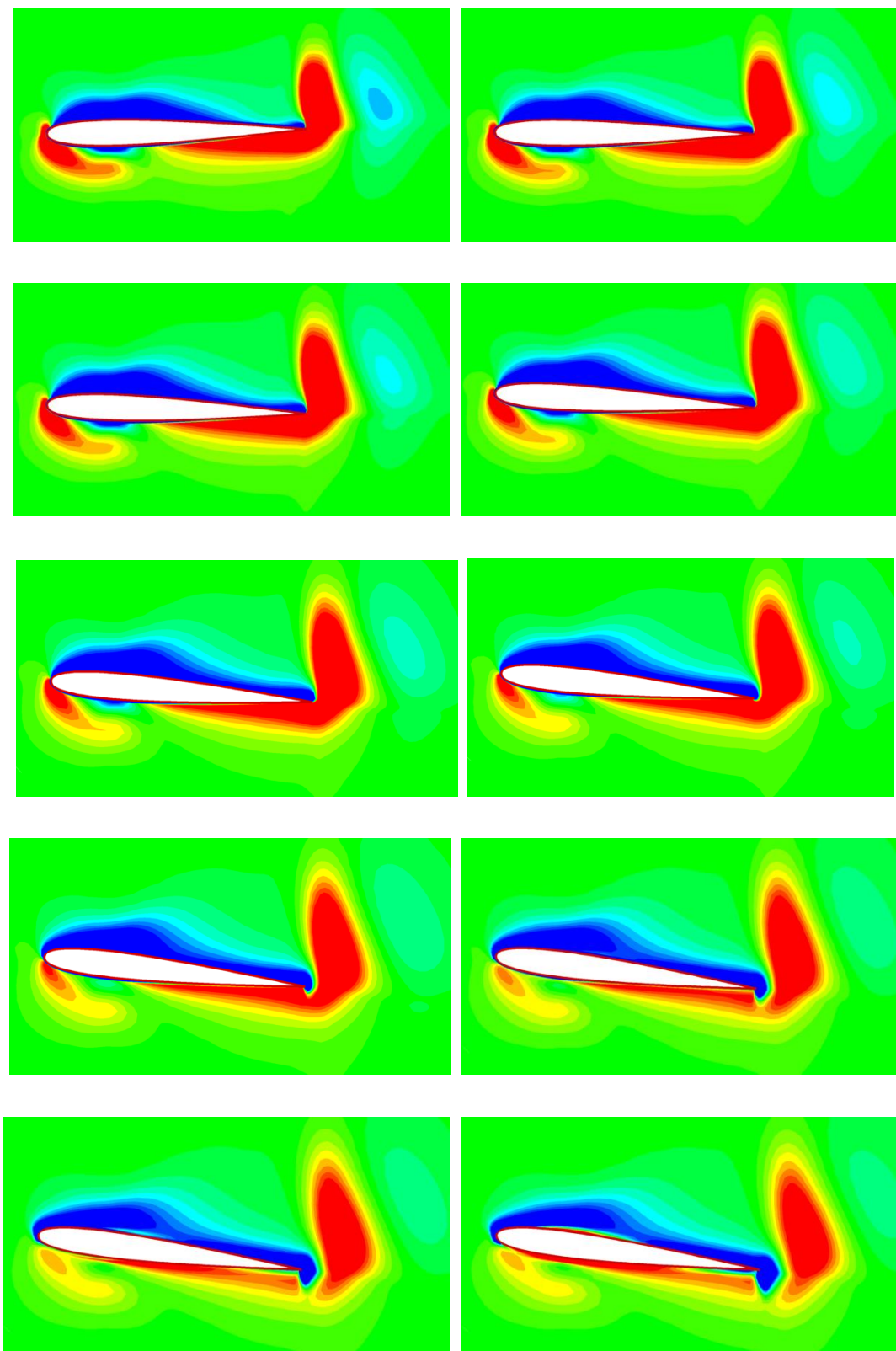


Figure 3.6: Detailed vortex pattern graphics, $k=10$.

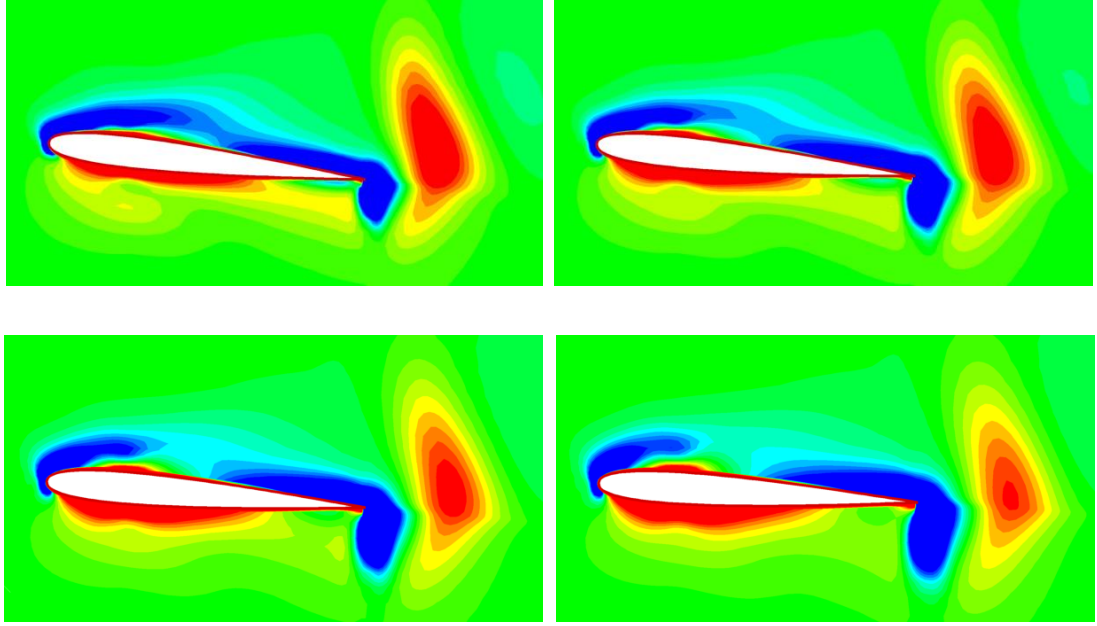


Figure 3.6 (contd): Detailed vortex pattern graphics, $k=10$.

3.2.4 Pitching Amplitude 10.

For pitching amplitude, $\alpha_0=10^\circ$, mean angle of attack, $\alpha_m=0^\circ$, thrust coefficient and reduced frequency values are researched. Only high resolution mesh used for these simulations for the same reasons explained in the previous case. As we expect from the previous pitching amplitude examples, with the increasing reduced frequency, maximum-minimum limits of the drag producing values are getting wider. Minimum value is changing dramatically compared to maximum value. Min value is set between 0.05 and -3.5, max value ranges between 0.05 and 0.5. Again, absolute values of max, min points of angular velocity of the airfoil are equal as the natural result of harmonic motion. Highest absolute values of the angular velocity seem to occur when airfoil is in horizontal position as same as previous examples. For $k=3$, sinusoidal drag curve stays in both positive and negative values. At $k=3$ min value of drag curve goes down below zero, nearly making small amount of thrust. We may assume this case as neutral vortex pattern. For $k=5$ min value goes nearly down to -0.4, making the case a thrust producing case. Reduced frequency values lower than 3, only drag producing wake also known as Karman street occurs. For $k=3$, there is neutral wake, leading edge vortex barely pairs with the trailing edge vortex but does not interfere with each other. Values for above $k=5$, average value of the drag curve

becomes positive, making it a thrust producing reversed Karman vortex street pattern. As frequency increases proportional to reduced frequency value, leading edge vortices stretch and merge with the trailing edge vortices rather than advecting it. For other reduced frequency values until 15, thrust value is increasing proportional to k value as previous examples. Thrust values are greater than all previous cases. In the Figure 3.7, images of $k=10$ are shown. For the $\alpha_0=10.^\circ$ case, leading and trailing edge vortices are stronger than the previous cases.

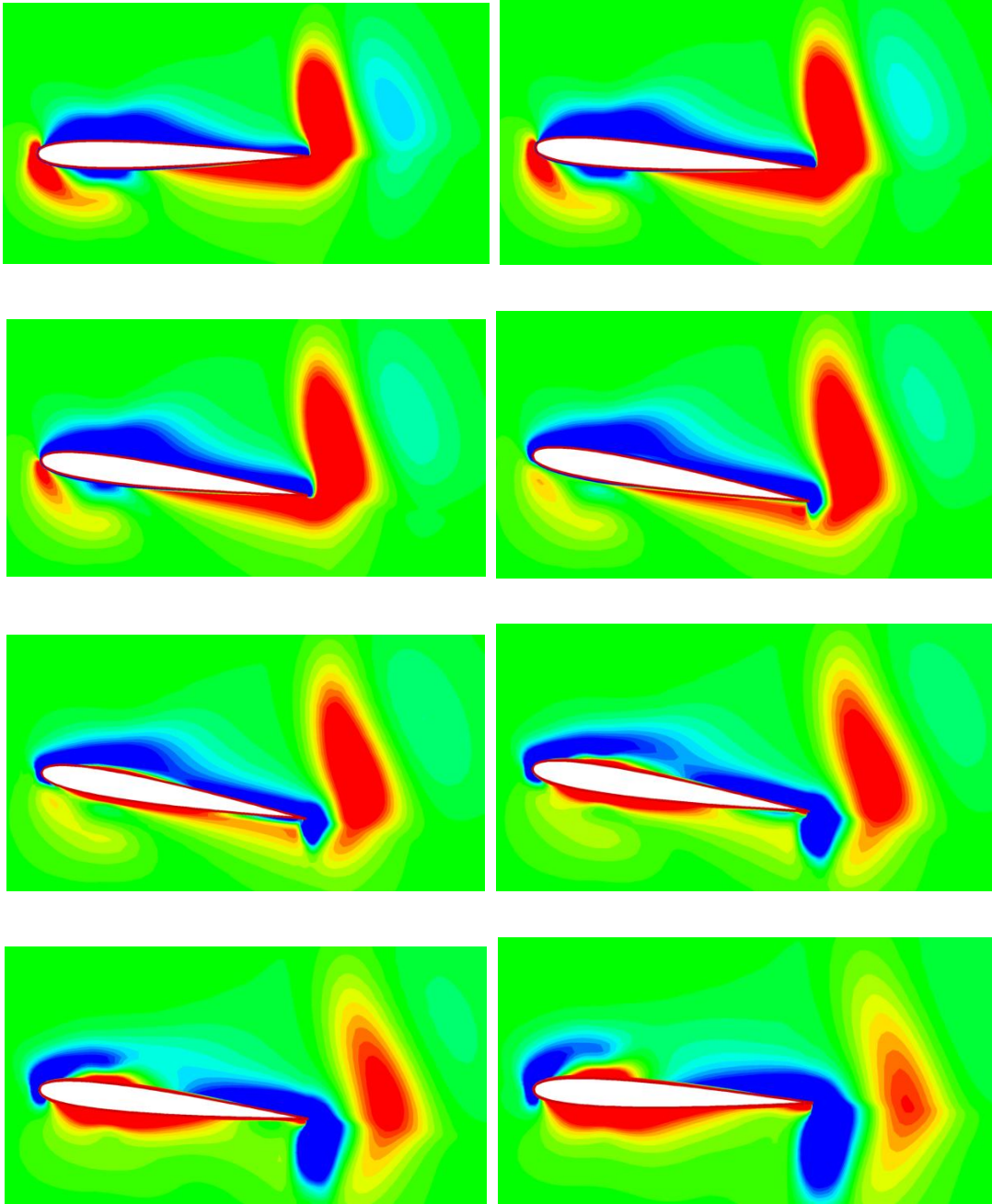


Figure 3.7: Detailed vortex pattern graphics, $k=10$.

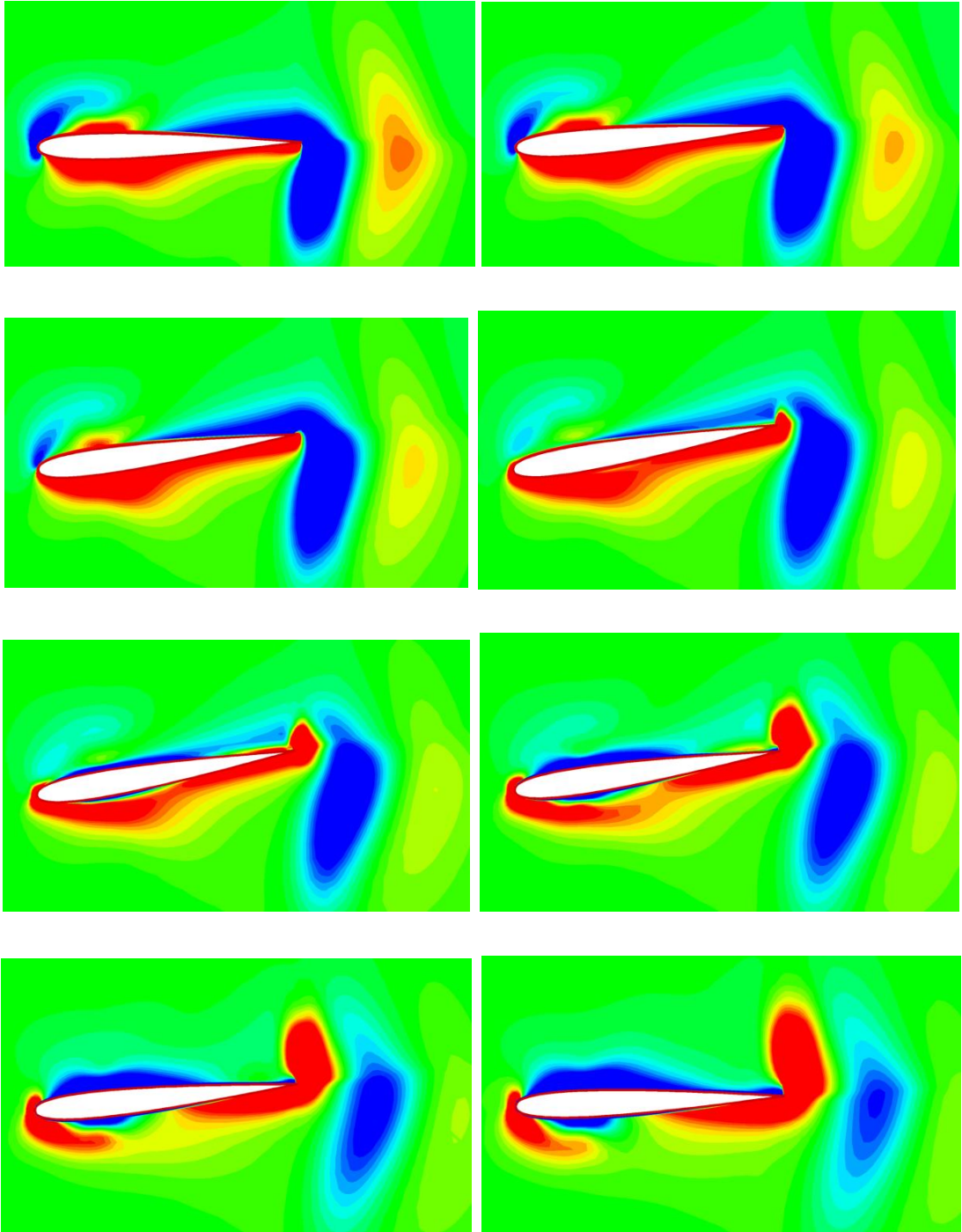


Figure 3.7 (contd): Detailed vortex pattern graphics, $k=10$.

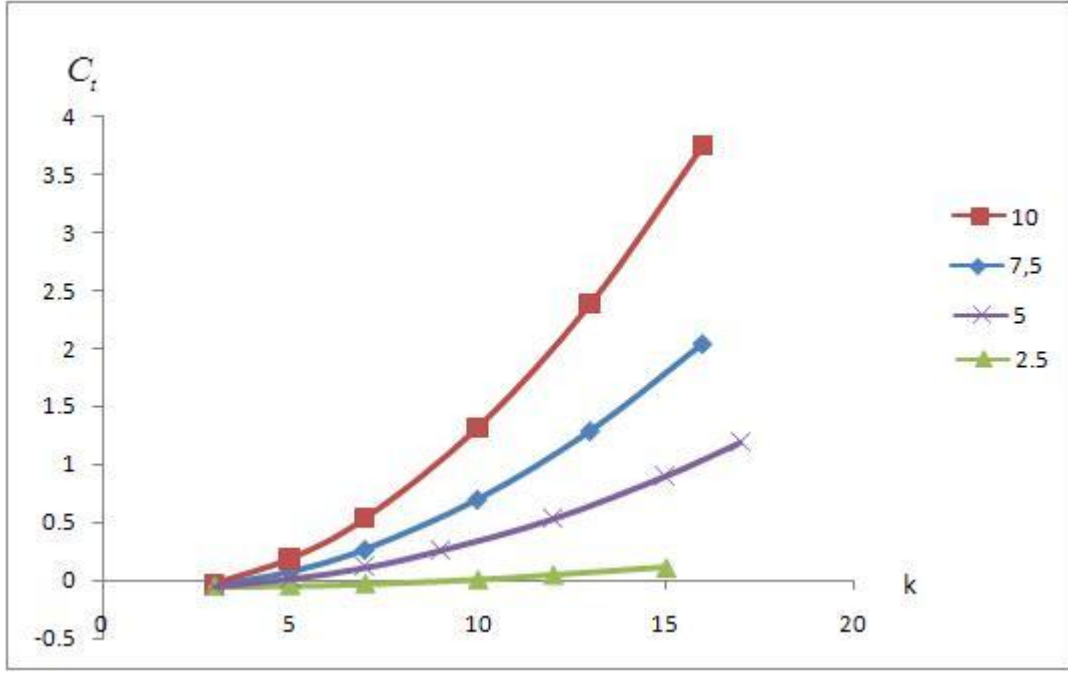


Figure 3.8: Pitching amplitude 2.5, 5, 7.5, 10.

In the Figure 3.8 we could easily see the effect of reduced frequency and pitching amplitude compared to each other. For small reduced frequency values like $k < 5$, different pitching amplitudes make no significant difference. Thrust coefficient results start to differ for the cases $k > 5$. Both reduced frequency and pitching amplitude parameters are proportional to thrust coefficient. Pitching amplitude parameter has a significant effect for thrust generation. $\alpha_0 = 10^\circ$ case has the highest thrust production rate compared to other cases. On the other hand $\alpha_0 = 2.5^\circ$ case does not produce thrust rate for practical usage.

3.3 Effects of Angle of Attack

Several simulations are made to determine the effect of angle of attack for pitching motion. Simulations set for $k = 10$ and $\alpha_0 = 2.5^\circ$, $\alpha_0 = 5^\circ$, $\alpha_0 = 7.5^\circ$ and $\alpha_0 = 10^\circ$. Angle of attack values are set from 10° to 40° . Values represented in Figure 3.9. For $\alpha_0 = 2.5^\circ$ case, thrust coefficient values decrease greatly after angle of attack $\alpha_m = 10^\circ$, having a neutral case at angle of attack, $\alpha_0 = 10^\circ$. Greater angle of attack values generate drag producing vortex patterns. For $\alpha_0 = 5^\circ$ case, thrust coefficient values drops below zero after angle of attack, $\alpha_0 = 15^\circ$. At this point, there is neutral case. Angle of attack

values for greater than 25° gives drag producing vortex patterns. For $\alpha_0=7.5^\circ$ case, thrust coefficient values decreases to negative values at the angle of attack $\alpha_m=20^\circ$, having a zero thrust coefficient at that angle. Higher values of the angle of attack give negative values. For $\alpha_0=10^\circ$ case, thrust coefficient values decreases after the angle of attack $\alpha_m=27^\circ$. Previous cases show that higher pitching amplitude cases give higher thrust coefficient values than lower pitching amplitude values. Angle of attack $\alpha_m=40^\circ$ cases give the nearly same result for all pitching amplitude values. It is clear that occurrence of the stall at that angle, make the effects of pitching motion obsolete. This behavior is still in use for higher angle of attack values, making it very useful for extreme angle of attack conditions.

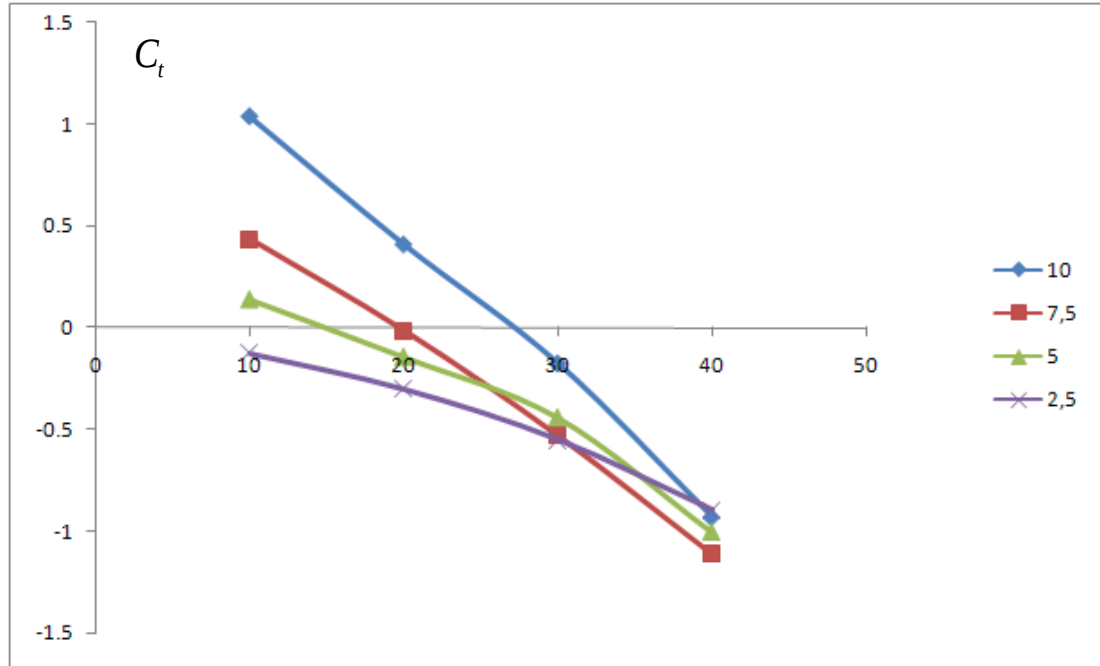


Figure 3.9: Thrust due to angle of attack.

4. CONCLUSION AND RECOMMENDATIONS

In this study, we managed to determine the characteristics of flapping wing in a uniform flow, which in the pure pitching motion by using a homemade FORTRAN code. Series of algorithms used for calculations, including; Galerkin finite element method for solving viscous Navier-Stokes equation, along with the Fractional Step Method in Arbitrary-Lagrangian-Eulerian (ALE) description (Misirlioglu,1998).

Thrust producing capability of the pitching motion is examined due to wide range combination of reduced frequency, pitching amplitude and mean angle of attack. Reynolds number is set at 10000; reduced frequency is set at 2.5, 5.0, 7.5 and 10.0; mean angle of attack is set for 0 to 45 degrees. Vortex behavior behind the trailing edge is observed for increasing values of reduced frequency. Results are compared with experimental data.

Three types of vortex shedding occurred; drag, neutral and thrust producing. Reduced frequency that higher than certain values for different properties setting, resulted as thrust generating vortex street all the time. Drag generating vortex behavior is dominant for lower reduced frequency values. Pitching amplitude values are another main property of pitching motion. Airfoils moving in higher pitching amplitude values, generated strong vortices therefore higher thrust coefficient values.

Mean angle of attack is a minor element for thrust producing in pitching motion for small angles. However; as the angle increases, thrust coefficient values decreases greatly, making it the key limit of the thrust generating. For mean angle of attack that is higher than certain level, thrust generating is impossible.

Equations in the simulation are solved in first order. Because of this, small vortices can not be generated. First order solution of the problem also affected the vortex appearance. Vortices dissolved very quickly after they past the trailing edge. Our results suffered greatly in precision. However, our results show similar behavior

compared with experimental data. For getting accurate solutions, second order solution of equations must be implemented in the code.

Finally, this study shows us, pure pitching motion flapping wing problem could be solved in non-commercial homemade FORTRAN code with using finite element approach.

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