Investigating the use of Flapping Foils for Power Generation

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A wing undergoing a combined pitching and heaving motion can extract power from the on coming fluid flow by harnessing the vertical velocity and the rotational motion. A quasi-steady method was developed using Matlab to test the equations of motion, and the mechanics involved in achieving this motion solely via the foils interaction with the flow. In an attempt to improve the solution, a method was developed that incorporated the wings interaction with its wake. However, this method failed to provide reliable results. The equations used in the quasi-steady model were converted to operate in the commercial fluid dynamics package Fluent, and a two dimensional model was created. The need to complete the testing and validation of the Fluent code was discussed. A plan for using the quasi-steady method to narrow the parameter space of interest was outlined. It was also identified that using the reduced parameter range would save a large amount of time once the Fluent model was being used. The results provided from Fluent are to be used to complete the investigation into power extraction from a flapping foil.

Nomenclature

A	=	wing area	L	=	lift force, $1/2\rho V^2 C_L A$
a	=	pivot point parameter, 2*Piv*c/c-1	M	=	moment about the pivot point, $1/2\rho V^2 C_D A$
b	=	airfoil semi-chord length, $c/2$	Piv	=	pivot point from leading edge
c	=	chord	St	=	Strouhal number, $hf/\pi\, U_\infty$
C_L	=	lift coefficient	*stop*	=	stop height, c(1-Piv)sin θ_{max}
C_M	=	pitching moment coefficient	U_∞	=	free steam velocity
$C(k)$	=	Theodorsen function, $F(k)+iG(k)$	V	=	vertical velocity
d	=	effective swept length	θ_{max}	=	maximum angle of attack
dist	=	distance of the foil pivot to the stop	θ_0	=	pitching amplitude
f	=	flapping frequency	θ	=	angle of attack
f^*	=	reduced frequency, fc/U_∞	Ω	=	angular velocity
h	=	heaving amplitude			
Ig	=	moment of inertia			

I. Introduction

A. Background

Power generation from the wind is not a new concept, in fact, using wind turbines has become a popular and socially acceptable means of generating sustainable energy. The number of projects being run around the world, looking at optimizing current wind turbine designs appears to be on the increase, driven, by a consumer desire to produce environmentally friendly power. It has also lead to researchers looking into alternative methods of utilizing the potential energy found in nature. Power extraction from a flapping foil, is one such alternate method that uses the recent advances in understanding of flapping foils, and the role vortex creation plays in lift force generation, to extract power from the wind. The term flapping, describes an airfoils movement, as it's undergoing a combined pitching and plunging motion.

To highlight the relevant aerodynamic behaviour that is applicable in this case, it is best to revisit the aerodynamics of conventional airfoil theory first. An airfoil with a constant small angle of attack will produce a lift force that will remain constant over time. Increase this angle of attack too much and it can lead to a dramatic loss of lift force. This condition is called stall, and it is caused by the flow separating from the foil. However, if the angle of attack is increased quickly, vortices can form on the leading edge, and these can dramatically

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increase the lift force. This increased lift is only available while the vortex is attached to the foil, once the vortex moves down the foil, and passes the trailing edge, the wing is once again in stall. The benefits that can be gained from vortices are wasted on most airfoil applications as the foil operates at a steady angle of attack.

This project will attempt to harness the increased lift force that can be generated by creating leading edge vortices, on a single flapping foil. This process will be simulated numerically on a symmetric, oscillating wing, using simple methods first and then increasing the complexity of the method until satisfactory results are produced.

B. Aim

Investigate the ability to extract power from a single airfoil, undergoing a combination pitching and heaving motion on a fixed vertical axis is the aim of this project. The airfoil motion is to be simulated mathematically using the lift and moment forces created by the foil's interaction with the oncoming flow. The essential objectives of this project are:

1) Derive the equations of motion for a single airfoil confined to rotate about a pivot point which is free to translate vertical and test their use in a quasi-steady method.
2) Establish alternate numerical methods to improve the solution generated and compare them to the quasi-steady results and any relevant published data.
3) Find the parameters that maximise power extraction.

C. Scope

This study will be limited to investigating the power extraction efficiency achieved, by varying three parameters, heaving and pitching amplitude, as well as Reynolds number. The heaving amplitude will be varied from $h=0.2$ *to* $h=2$. The pitching amplitude will be investigated from θ_{max}=10 degrees to θ_{max}=80 degrees. Lastly, the Reynolds number (*Re*) will be varied by adjusting the free stream velocity so as to achieve *Re*=1100 to *Re*= 1,000,000.

D. Methodology

This project will look at three numerical methods for describing the motion of the foil. The simplest and computationally least expensive method will be developed first. This method will be used to refine the parameter space that will be investigated during this project. The remaining methods will be generated in order of increasing computational expense. Once these methods are all operational, a comparison of the results, produced by each method using the same parameters, will be conducted. This comparison will allow a decision to be made about which method is to be used for the final calculations.

E. Project management

To ensure the thesis aims are achieved in the available time this project will be managed using project management tools and techniques outlined in Burke (2007). The tasks to be completed have been derived from the client brief contained in appendix A and are listed in the task breakdown structure in appendix B. The projected timings for these activities are contained in the Gantt chart in appendix C. Progress will be gauged by the completion of the Milestone chart in appendix D.

II. Previous Research

The experimental work conducted by McKinney and DeLaurer (1981) indicates that a design based on a single airfoil is feasible. It also found the design could provide power at efficiency levels that would be comparable to other wind turbines in use at the time of writing. While the experiment used a single foil in an oscillating motion, the choice of angle of attack was restricted to a maximum of 30 degrees. While the results presented are encouraging, the selection of a maximum angle of attack of 30 degrees may not have fully utilised the possible benefits of leading edge vortex creation. An example of increased lift due to an oscillating foil can be seen in the circled area on Figure 1. This chart was produced during an experiment and clearly shows the lift force increasing past the angle of static stall, in this case 12.5 degrees (Campbell 2002). This is often referred to as delayed stall. The author had not been intentionally looking to utilize this fact in his work, but notes that such an increase in lift force would be useful.

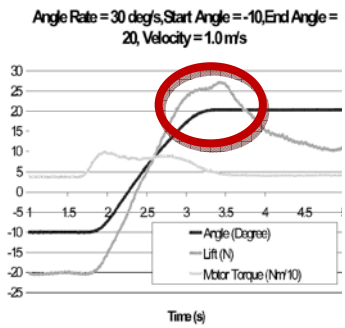

Figure 1. Example of delayed stall. (Campbell 2002)

A mathematical reproduction of McKinney and DeLaurer (1981) experimental work was presented by Zhu et al (2009). This study took a

two dimensional thin plate approach (Theodorsen 1935) to conduct initial parameter investigation, before switching to a three dimensional nonlinear boundary-element model, to take a closer look at areas of interest. The author, identified a range of Strouhal number, St < 0.12, and angle of attack, $\theta_{max} < 7$ degrees, that would produce a leading edge vortex and ensured his model parameters did not enter this region. The author avoided this region because the model he used for the study was unable to deal with vortex creation near the foil. As with McKinney and DeLaurer (1981) before him, this avoidance of high angles of attack may have prevented him generating the maximum lift force available. Interestingly the author states that the thickness of the foil has an effect on the power production efficiency. This is at odds with Kinsey and Dumas (2008) which presents data from a NACA 0002, NACA 0015 and a NACA 0020 airfoil that shows a negligible difference to efficiency. This difference in their findings may have occurred due to the different approaches taken in modelling the foil. Zhu et al (2009) was focusing on unseparated flow while Kinsey and Dumas (2008) were interested in the unsteady and viscous effects of an oscillating foil.

These works will provide a starting point for a number of the parameter values that are needed in this project and also identify how these parameters interact with each other in the form non-dimensional relationships. McKinney and DeLaurer (1981) concluded that reduced frequency, heaving amplitude, pitching amplitude, wing area and phase angle as the important parameters. This list is added to by Zhu et al (2009) who also includes Strouhal number as an important non-dimensional value of interest.

One example of the values given to these parameters is found in Jones et al. (2003), who used a prescribed motion for a foil in water to determine that the peak power extraction occurs at a reduced frequency (k^*) of 0.65. This was numerically simulated using a pivot point at 0.*25c* on a NACA 0014 airfoil, with a pitching amplitude of 73 degrees and a phase angle of 90 degrees. At this frequency it was found that the vortex formed on the leading edge, just arrived at the trailing edge of the foil in time for the wing to under go a rapid direction and angle of attack change. This fact is also highlighted by Kinsey and Dumas (2008) as they discuss that the level of power extracted can be influenced by how well the aerodynamic forces are synchronized with the heaving motion. The parameter values stated in Kinsey and Dumas (2008) that produce the maximum power extraction are different from those used by Jones et al. (2003), but this is possibly the result of each study using a different pivot point. The one point that they both agree on, is the use of 73 degrees as the maximum angle of attack. This angle will be adopted as the optimal maximum angle of attack for this project.

From the previous work done, the research presented by Kinsey and Dumas (2008) is the closest in parameters and method to those being used in this project. Kinsey and Dumas (2008), used the commercial finite volume computational fluid dynamics code, Fluent, to conduct a parametric study of a single oscillating airfoil. The parameters of this study was $0 < f^* < 0.25$ and $0 < \theta_0 < 90$ degrees for a NACA 0015 airfoil at a Reynolds number of 1100. However, the motion of the foil is prescribed and not a result of the foil's interaction with the on coming flow. While it would be ideal to directly compare the results of a prescribed motion, against those that can be achieved by the foils interaction with the on coming flow, the difference in pivot location may produce similar differences to those noted between Jones et al. (2003) and Kinsey and Dumas (2008). Table 1 contains a summary of some of the recent work conducted in this field.

The most encouraging results are found in the comparison of Kinsey and Dumas (2008) and Simpson et al. (2008). These studies are both at low Reynolds numbers, but they indicate that up to a value of at least *Re= 13,000* a vortex can be created and maintained on an oscillating airfoil to produce a higher than normal lift force.

Table 1. Summary of recent experimental and computational work.

Author	Type of Study	Airfoil	Re	h (m)	θmax	U∞	St	*f**	comment
McKinney (1981)	Experimental, defined motion	NACA 0012	110,000	0.006	25 & 30	8 &6.2	0.008 to 0.016 #	0.006 to 0.01 #	28.3% efficient at theta = 30 @ 8m/s phase = 90 degrees, span 0.105, aspect ratio 5.25
Simpson et al. (2008)	Experimental defined motion (water)	NACA 0012	13,800	0.085	11 to 57	0.2	0.31 to 0.94 #	0.23 to 0.7 #	Max efficiency 43% @ θ=34.4 degrees(relative angle of attack). F*=0.15
Campbell (2002)	Experimental defined motion (water), bi-plane arrangement	NACA 0015	48,600 to 107,000	0.46	0 to 20	1	$	$	Initial results only
Jones et al. (2003)	Numerical 2D N-S	NACA 0014	1,000,000	1.3c	73	$	$	0 to 2	k=0.65, experiment conducted, but results fell 4 times less than predicted
Kinsey & Dumas (2008)	Numerical 2D N-S	NACA 0015	1,100	$	20 to 80	$	$	0 to 0.25	Max efficiency 34% @ *θmax*=70 -80 degrees. *F*=0.15*

$ Value not vlearly identified # Derived from authors data.

III. Mathematical Model

A. Mathematical descriptions

The motion of the foil has been restricted to the vertical axis and rotationally fixed to a single pivot point at *c*/2. This assumption of two degrees of freedom allows the drag and thrust forces developed to be ignored. A diagram of the arrangement is shown in Figure 2. The heaving motion of the foil is then calculated using equation (1).

$$L = m\ddot{y} + c1\dot{y} + ky \tag{1}$$

The pitching moment is given by equation (2).

$$M = Ig\ddot{\theta} + c_2\dot{\theta} + k_2\theta \tag{2}$$

The foil has been allowed to rotate up to a prescribed maximum angle of attack. This free rotation is due to the moment generated by equation (2). This free rotation is only restricted at the upper and lower ends of the foils travel, which is given by the heaving amplitude *h*. As the foil approach's its maximum travel a physical barrier is simulated that will cause the foil to rotate. This barrier will redefine the angle of attack by using a relationship depicted in Figure 3 and shown in equation (3). The amount of rotation the foil undergoes in this region is controlled by the momentum of the foil. In this way the rotation at these points is not fully defined, if the momentum is insufficient then the rotation will not be complete. This form of restriction will allow the foil to stall if insufficient momentum exists to rotate past a zero angle of attack.

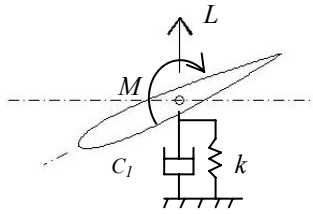

Figure 2. Diagram of proposed mathematical model.

$$\theta = \sin^{-1}\left(\frac{dist}{c(1-piv)}\right) \tag{3}$$

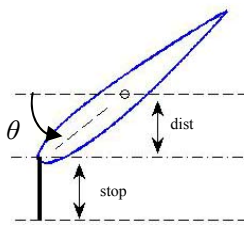

Figure 3. An example of the turning arrangement.

The instantaneous power extracted from the foil has been assumed to come from both the heaving and pitching motions. The instantaneous power can be calculated using equation (4). The mean power output ($\overline{P}$) can be obtained by integrating equation (4) over one cycle.

$$P = La + M\Omega \tag{4}$$

The power extraction efficiency will be calculated using equation (5). This assumes that all the energy available in the flow can be used to generate power. It should be noted that the swept area of the foil is larger than the area given by the heaving amplitude. Figure 4 depicts the swept area, *d*.

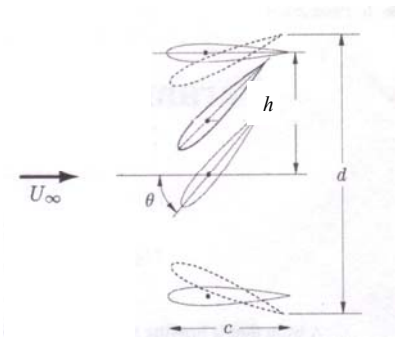

Figure 4. Geometry definitions. Modified from Kinsey (2008)

$$\eta = \frac{\overline{P}}{\frac{1}{2}\rho U_\infty d} \tag{5}$$

B. Limitations

The driving mechanism for physically induced rotation, described in the mathematical model section, has one limitation that will restrict the range of the heaving amplitude *h*. This limitation is present due the fact it has been assumed that the airfoil will be at its maximum prescribed angle of attack, prior to the commencement of any vertical force or displacement calculations. This situation can be seen in Fig 3, if you assume the foil is at θ_{max} and no vertical motion has occurred,

you can see the minimum heaving amplitude would be the size of the stop plus the value of the variable *dist.* This assumption was made, in anticipation, of computational difficulties that may be faced by some of the software packages to be used. The limitation in h is given by equation. (6).

$$h_{\min} = cSin\theta_{\max} \tag{6}$$

While the need for this limitation has not yet been tested it may be able to be adjusted at a later stage if required. However, due to the fact that a symmetric airfoil is being modelled some initial value of angle of attack other than zero must be made.

IV. Quasi-Steady Method

A. Method

To commence this project the simplest method of calculation was adopted. The quasi-steady method ignores all aerodynamic effects other than lift and moment forces, the value of these are calculated as function of the angle of attack. Such simplistic models have been shown to produce results that are not always consistent with those in real life (Kinsey & Dumas 2008). However, in this project it has been useful for a number of reasons. Firstly, it has been used to validate the equations of motion. Secondly, it has proven the concept of simulating a mechanical stop to force a foil rotation at the end of its vertical travel. Lastly, it has provided an initial estimate into the acceleration, both translational and rotational, that a wing may encounter.

The model consisted of using a second order, backward difference integration of the equations of motion of the foil, Eq (1) and Eq (2), to provide the velocity of the foil at any given time. The historical data generated was then integrated to produce the foils current position. The same approach was taken for the pitching moment. This approach allowed the foil to rotate due to the moment induced as well as translate in the vertical axis. Once the foil rotated to the prescribed maximum angle of attack the rotation was halted and this angle was maintained. As this method relies on forces generated at a given angle of attack an initial rotation from $\theta = 0$ to $\theta = \theta_{\max}$ was conducted. Force and moment data was recorded during this period, but the motion was restricted to the prescribed rotation only. The coefficient of lift felt by the foil was given by $C_L = 2\pi\theta$ while the pitching moment coefficient was given by $C_M = 2\pi\theta/10$. The velocity of the foil in the vertical axis was then calculated using equation (7). The angular velocity was calculated in a similar manner using equation (8).

$$V^n = \frac{2\Delta t \dfrac{L}{m} + 4V^{n-1}V^{n-2}}{3 + 2\Delta t \dfrac{c_1}{m}} \tag{7}$$

$$\Omega^n = \frac{2\Delta t \dfrac{M}{Ig} + 4\Omega^{n-1}\Omega^{n-2}}{3 + 2\Delta t \dfrac{c_2}{Ig}} \tag{8}$$

The computer software package Matlab (Version 7.4.0) was then used to generate the solutions for this method. Matlab allowed for quick fault finding to be conducted, as the solution could be visualised by graphing a moving foil, after each iteration was performed. The main difference between this method, and previous studies conducted by others (ie Kinsey & Dumas 2008), is that parameters such as reduced frequency or Strouhal number could not be dictated directly. Only the free stream velocity, chord length, pitching and heaving amplitude could be allocated. To calculate values, such as the Strouhal number, the frequency of operation is required. A short Matlab script, was written to examine the data produced in the quasi-steady method and provide the frequency of operation.

The frequency analysis script is based on the simple mathematical principle, of locating all turning points, in the data produced by the quasi-steady code. The data up to, and including, the first maxima is discarded. This is to prevent the data, containing the initial prescribed rotational motion, from being included in the frequency calculation. The number of iterations between the next two turning points is found, and the result is multiplied

by the time step to provide the period. The period is inverted to produces the frequency of oscillation in cycles per second (Hz).

It is expected that a large number of simulations will be required, to produce data for comparison to existing work. The frequency analysis script has been written to allow for multiple free stream velocities to be calculated concurrently. However, at this stage, the parameters of chord length, maximum angle of attack, pitching and heaving amplitude would need to be adjusted manually.

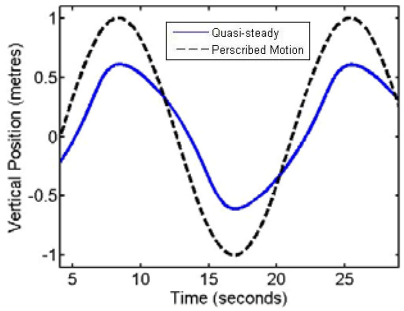

Figure 5. Vertical position versus time, quasi-steady method and *h=2m*, θ_{max}=*73* degrees.

B. Initial results

It was found that the code worked well, the most obvious and expected result, was the shape of the angle of attack against time plot. The form was now dependant on the moment generated and the foils interaction with the simulated stops. Of greater interest, is the fact that at small free stream velocity and heaving amplitude values the maximum angle of attack is never reached. Figure 5 shows the angle of attack produced at U_∞=0.8 m/s, and the corresponding perscribed sinusoidal motion used in (Kinsey & Dumas 2008).

In a similar fashion to the angle of attack, the vertical position of the foil differs slightly from the one used in prescribed motion. At low free stream and heaving amplitude values, the momentum is not great enough to carry the foil to the maximum allowed heaving amplitude. Figure 6, shows the prescribed motion and the one achieved by the quasi-steady method at U_∞=0.8 m/s and h = 2.

It was found that using a value of free stream velocity above 1.1 m/s caused the foil to strike the maximum travel limits imposed by the heaving amplitude. The code had been written to impart a zero vertical velocity, and zero acceleration at this point. As this was a sudden change that could lead to numerical instability, it was decided, that only values of free stream velocity that did not allow this to occur, would be considered.

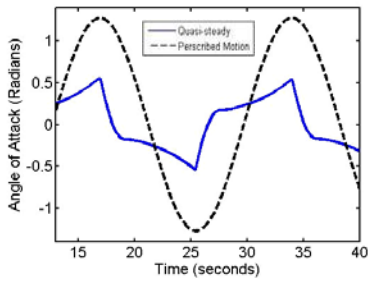

Figure 6. Angle of attack versus time, quasi-steady method and prescribed motion for U_∞=.8 m/s, *h=2m*, θ_{max}=*73* degrees.

V. Wake Interaction Method

A. Method

It is well documented that a flapping foils lift is generated in a more complex manner than the one used in the quasi-steady method (Ashraf et al. 2007; Lu et al. 2003). To this end, a second method was derived to attempt to account for the foils interaction with its wake. The equations that underpin this method were presented by Garrick (1937). However, these equations were represented by Young (2005), with the direction of lift redefined to be positive in the upward direction. While the Young (2005) equations were used, the method will be referred to from this point forward as the Garrick method.

The code developed using Matlab for the quasi-steady method was adjusted for use with the Garrick method. This was achieved by replacing the lift and moment force calculations with equations (9) and (10). The disadvantage of this approach is that the Garrick method depends upon knowing the frequency of operation, all velocities and accelerations for the current time step. As this method is trying to establish the motion of the foil without prescribed motion, none of these parameters could be supplied ahead of time. The frequency issue was resolved by supplying an initial estimate of the frequency of oscillation. This estimate was then compared to the output frequency supplied by the code and the initial estimate changed to halve the error. The routine was then iterated until the output frequency is within 5% of the input frequency.

$$L = \pi\rho b^2 (U_\infty \dot{\theta} - \ddot{y} - ba\ddot{\theta}) + 2\pi\rho U_\infty C(k) Q$$
$$Q = U_\infty \theta - \dot{y} - b(a - \frac{1}{2})\dot{\theta} \tag{9}$$

Where *C(k)=F(k)+iG(k)* is the Theodorsen function defined using Bessel functions J0,J1, Y0 and Y1 in equation (10).

$$F = \frac{J_1(J_1 + Y_0) + Y_1(Y_1 - J_0)}{(J_1 + Y_0)^2 + (Y_1 - J_0)^2}$$
$$G = \frac{Y_1 Y_0 + J_1 J_0}{(J_1 + Y_0)^2 + (Y_1 - J_0)^2} \tag{10}$$

The need for the current time step values of velocity and acceleration was not so easily resolved. It was decided that if the time step remained small, the difference of these value between time steps would also be small. Using this methodology, the time step was set to 0.001 seconds, and all the required values were used from the previous time step.

This method has been derived with some known limitations. These limitations are apparent in the assumptions that were made during the initial derivation of these equations (Theodorsen 1935; Garrick 1937). They were assumed to be valid for small values of heave and pitch amplitude. The derivation also assumes an infinitely thin vortex wake and a sinusoidal motion in heaving and pitching. In an attempt to reduce the impact of these limitations the initial testing of this routine is to be conduct using only small amplitudes. However, as it was shown in the quasi steady method, the form of the displacement is not sinusoidal.

B. Initial Results

Several runs were conducted using a parameter range from U_∞=.8 m/s to U_∞=1.5 m/s. Within these limits the values of *h* was varied from *h*=.8 to *h=2, while* θ_{max} was *tested at* θ_{max}=5 degrees to θ_{max}=16 degrees. All results produced were similar to those shown in Figure 7 and Figure 8. The rotational acceleration was similar to the results produced by the quasi-steady method, but the vertical acceleration was significantly less. This resulted in less momentum for the foil to use once it reached the stops designed to rotate the foil. This lead to a far reduced effective heaving value and as a small heaving value was already imposed, the foil did not have time to rotate to its maximum allowable angle of attack.

As the only other data available to compare these results to come from the quasi steady method, it was decided to halt any further testing. Once another method is developed, further testing can be conducted to determine if there is a range of variables that this method can be reasonably applied to.

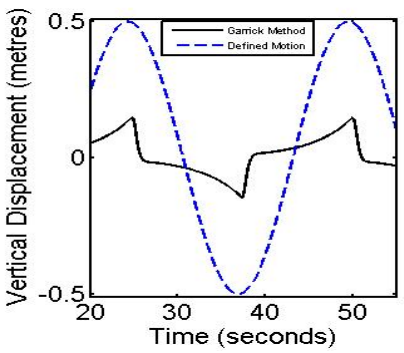

Figure 7. Garrick method and prescribed motion for U_∞=.8 m/s, *h=2m*, θ_{max}=*16* degrees.

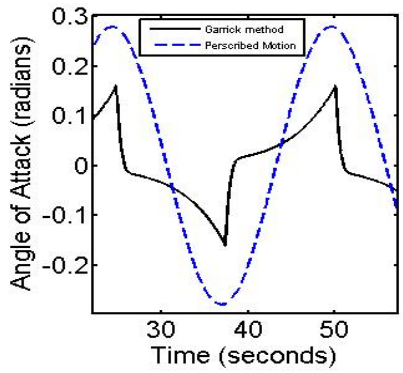

Figure 8. Garrick method and prescribed motion for U_∞=.8 m/s, *h=2m*, θ_{max}=*16* degrees.

VI. Computational Fluid Dynamics Model

A. Flow solver

The commercial fluid dynamics software package Fluent was used to provide the next level of accuracy to the solution. To achieve this, the equations of motion used in the previous methods were converted to first order and entered into a User Defined Function (UDF) that could be used in Fluent. The need to convert to first order, was driven by the decision to use Fluent's in built functionality that allows for a moving mesh. This way the mesh is presented in an inertial frame of reference with both the wing section and the surrounding grid translating in the vertical axis, while the wing section also rotates as the angle of attack changes. Initial motion is confined to the wing section as it slowly rotates to the prescribed maximum angle of attack before any vertical motion is allowed. At every time step the numerical value for moment, lift, position and angle of attack is

recorded. Parameters of interest, such as frequency of oscillation, will be calculated in a separate process after the completion of the simulation.

B. Model

A two dimensional model of a NACA 0014 airfoil was drawn as a sketch in the commercial drawing package Catia. This was achieved by using a spline tool tracing the outer profile of the airfoil with approximately one hundred points whose coordinates were generated from the equation of a NACA series four digit airfoil (Abbot 1953). This sketch was then imported in to the commercial finite volume meshing tool Gambit where the geometry was defined and meshed. This included the allocation of two zones that separated the grid immediately around the wing from the rest of the mesh to allow the UDF to define the motion of these grids independently. This was achieved by defining a circular nonconforming rotating interface (Kinsey & Dumas 2008). The nonconforming interface and the dimensions used in this model can be seen in Figure 9.

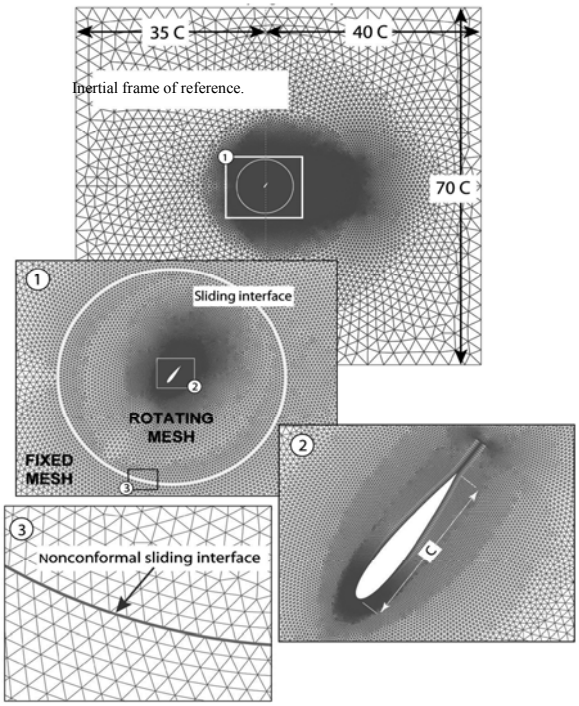

Figure 9. Geometry and grid details showing the rotating interface. Modified diagram first presented in Kinsey & Dumas (2008)

This procedure was used to create two models with identical geometry, but vastly different grid resolution. The low resolution model contains approximatly 15 000 mesh cells and was designed to be used as the test bench for the UDF and to conduct some initial parameter limit investigations. The high resolution model has a detailed boundary layer on the wing surface and contains approxamitly 155 000 mesh cells.

C. Initial Results

Initial trials of the UDF were conducted using a course grid. This reduced the computational time required while each of the routines in the UDF was tested. These trials identified that the routine controlling the vertical motion was not preforming correctly. Once the code reached the point that allowed vertical motion, the angle of attack was instantly reduced to zero. At the same time a sudden spike in the lift force was also recorded. The remaining code appears to be operating correctly. Figure 10 and Figure 11 shows the angle of attackand lift force over a rapid initial rotation period.

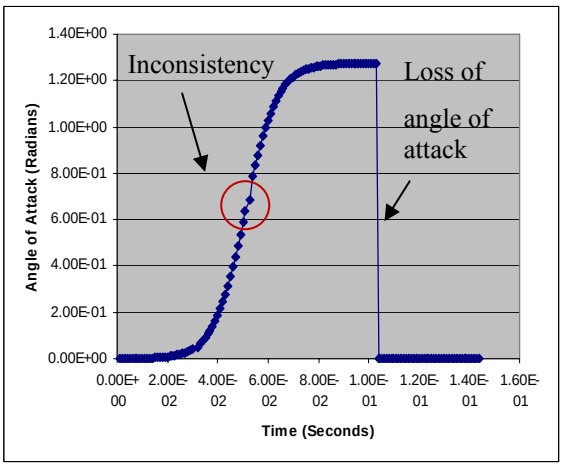

Figure 11. Angle of attack during the initial rotation period. Short rotation period.

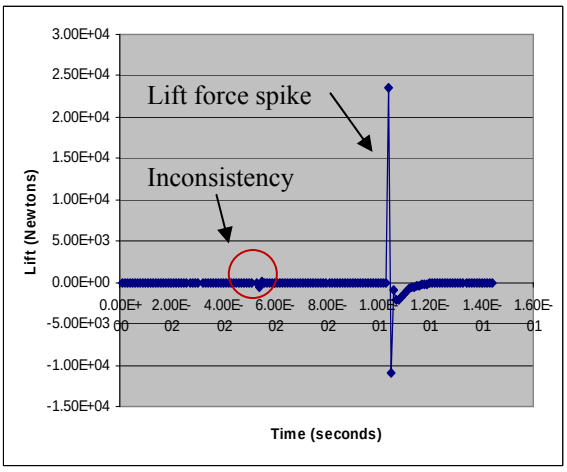

Figure 10. Lift force during the initial rotation period. Short rotation period.

In an attempt to locate the source of the error two additional tests were under taken. The first increased the number of time steps the initial rotation occurred in, from 100 to 1000. The second reduced the maximum angle of attack from 73 degrees to 10 degrees. These changes were made to ensure that there was a smooth transition of forces for Fluent to deal with. The results from both of these test were identical to those presented in the figures above. The vertical motion routine is still the subject of on going fault finding.

A close inspection of both graphs, Figure 10 and Figure 11, also reveals a small inconsistency when the angle of attack is mid way through its rotation. This point occurs when the foil is undergoing its initial prescribed rotation. As this motion is prescribed the rotation should be smooth and not disjointed. A closer look at the data also reviled a second point that was not consistent with the prescribed motion, but at this scale it is hard to see. While only minor, this anomaly is also the subject of on going investigation.

VII. Future work

The focus for the short term will be on using the low resolution two dimensional grid to continue to fault find the Fluent UDF. Once the UDF appears to be providing sensible results, a short study can be conducted using the quasi-steady method to reduce the parameter space that will be investigated. This narrowed range of parameters can be further reduced by running the Fluent code using the lower resolution grid. Once this is completed the high resolution grid can be loaded and a validation process will be undertaken, to ensure the results provided are grid size, and time step independent. With the areas of interest identified by the low resolution grid, a number of simulations will be conducted to provide enough data to identify the parameters that will maximize power extraction. It is expected, that the time required by each run on the high resolution grid will take several hours to complete. For every set of parameters checked using Fluent, a run will also be conducted using identical parameters in the other methods. This will allow an estimation of the error for the simpler methods.

At this stage the essential objectives will be completed and if time permits several three dimensional models can be created to look at the impact the inclusion of end effects has on power extraction efficiency. The process of commencing with low resolution grids will be used as the expected time to complete the three dimensional study will be significantly larger than the two dimensional case. The results produced from the three dimensional modal will be compared against those produced in two dimensions. This will allow a continuation of the work done by Simpson (2008) and find the minimum aspect ratio required to neglect end effects. The final thesis report will be written concurrently with all the above activities.

VIII. Summary

Three methods of simulating a single oscillating foil have been presented that rely on the interaction of the foil and the on coming flow to produce motion. The quasi-steady method proved the equations of motion used, and provided a method to test the rotation criteria. The wake interaction method proved to be unstable due to the equations being used having been derived for prescribed motion. These equations produced unreliable results when the rotational motion was not consistent, and the heaving motion was large. The third method using the Commercial software package Fluent has not yet been completed and is under going a fault finding process. The need to conduct rigorous validation of the Fluent model has been discussed. Upon completion of the fault finding process a plan has been described that will ensure the completion of all the objectives of this project.

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Appendices

Appendix A - Client Brief
Appendix B - Task List
Appendix C - Gantt Chart
Appendix D - Milestone Chart