8th ANKARA INTERNATIONAL AEROSPACE CONFERENCE
10-12 September 2015 - METU, Ankara TURKEY

AIAC-2015-113

NUMERICAL OPTIMIZATION OF OSCILLATORY MOTION OF A FLAPPING AIRFOIL FOR MAXIMUM POWER PRODUCTION FROM WIND ENERGY

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ABSTRACT

Numerical optimization of the oscillatory motion parameters of a flapping airfoil under a freestream flow is conducted. The objective of the optimization is to maximize the produced power and/or the power production efficiency. Unsteady laminar flows around the airfoil are computed using a Navier-Stokes solver in a parallel computation environment. The Response Surface Methodology (RSM) is employed for the optimization. The periodic flapping motion is defined as a linear combination of sinusoidal plunge and pitch motions. The optimization variables are the parameters defining the flapping motion which are the flapping frequency, the plunge and pitch amplitudes and the phase shift between the pitch and plunge motions. For the cases studied, it is observed that the maximum power efficiency increases with increasing plunge amplitude. The calculated maximum power production efficiency is about 40%.

INTRODUCTION

Power generation based on the renewable energy sources is a recently spread idea. Extraction of the power from the air/water flow energy is a good example for the renewable energy sources. For this purpose, the conventional rotating wind turbines are commonly used for years. The non-conventional oscillating wings can be considered as another solution for extracting power from air.

Studies on oscillating-wing wind power generators have been started few years ago. McKinney and DeLaurier have conducted analytical and experimental analyses of flow over a flapping - wing power generator in order to examine its feasibility [McKinney and DeLaurier, 1981]. Their results have shown that oscillating (simultaneously pitching and plunging) wings can be used for extracting power from the wind energy. They have also shown the importance of the unsteady aerodynamics and reported higher power coefficient than did their linear analytical analysis. They have found power production efficiency of about 30 % at a proper combination of plunging and pitching amplitudes and a phase shift between them. The results they obtained were very encouraging. However, it is noticed that the full benefits of delayed stall and the formation of the associated leading edge vortices (LEVs) at high pitch amplitudes were not fully exploited in their experiment as they have considered only moderate pitch and plunge amplitudes.

For a long time after Mckinney and DeLaurier’s work, studies on oscillating/flapping wings have focused on mostly the thrust generation rather than power generation. Two important studies investigating the usage of oscillating wings for the purpose of extracting power from wind energy were

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conducted by Jones et al. [Jones, David and Platzer, 1999; Jones, Lindsey and Platzer, 2003]. They have investigated numerically and experimentally a single wing oscillating in the air flow in [Jones, David and Platzer, 1999], and dual wings in tandem oscillating in the water flow in [Jones, Lindsey and Platzer, 2003]. The numerical analyses in those studies have been done in two-dimension. They have investigated sinusoidal plunging and pitching motions which give high power efficiencies.

Kinsey and Dumas have used a 2-D Navier-Stokes solver to perform a parametric study of a sinusoidal plunging and pitching of an airfoil [Kinsey and Dumas, 2008]. They have reported a power production efficiency as high as 35%. They have found that dynamic stall plays an important role in maximizing the power. They suggested that the timing of the formation and shedding of a LEV during a flapping cycle is very important for achieving higher power in a flapping-wing power generator.

Kinsey and Dumas have also compared the results of 2-D and 3-D solutions of water flows over oscillating wings [Kinsey and Dumas, 2012]. They have observed that generated power production efficiencies based on 3-D solutions follow a similar trend to the 2-D solutions although 3-D solutions have provided relatively 20% - 30% less efficiency. However, in the case of using wing end plates, their 3-D solutions have not differed by more than 10% from the 2-D ones. Based on this observation, Kinsey and Dumas have suggested that 2-D solutions which take shorter computation durations can be validated against 3-D solutions using correction factors.

Kaya and Tuncer have shown that the nonsinusoidal motions perform better for thrust generation than sinusoidal motions [Kaya and Tuncer, 2007]. This observation might be true for power production as well. Based on this approach, Platzer et al. suggested that the power generating capacity may increase by using squarewave type oscillations [Platzer, Ashraf, Young and Lai, 2010]. They have observed from their experiments that wings oscillating in tandem configuration can enhance the power production.

Ashraf et al. have proposed a new oscillating-wing mechanism to generate power from wind and flowing water energy [Ashraf, Young, Lai and Platzer, 2011]]. Their numerical study has been based on 2-D Navier-Stokes solutions of air flows over oscillating airfoils. The results for an airfoil undergoing nonsinusoidal pitch-plunge motion showed an increase of about 17% in power generated and around 15% increase in efficiency over sinusoidal motion. They have also studied the case of dual airfoils operating in tandem and undergoing both sinusoidal and nonsinusoidal motions. However, according to the cases they studied and the mechanism they have used, they have found that both averaged power and efficiency per foil were not enhanced for tandem configuration compared to a single airfoil.

Kinsey and Dumas have focused on the determination of the optimal positioning of dual wings in a tandem configuration oscillating in water flow to obtain the maximum power production efficiency [Kinsey and Dumas, 2012]. For this purpose, they have used a 2-D Navier-Stokes solver. They have observed that a high efficiency may be obtained if the aft wing has a proper position.

In all the studies in literature so far, no numerical optimization was conducted to examine the optimum flapping parameters for maximum power production. This study aim at determining the flapping parameters for the maximum generated power and/or power production efficiency using optimization methods in order to fill the optimization gap in literature. For this purpose and airfoil oscillating as a linear combination of plunging and pitching motions will be analyzed numerically. The numerical investigation is based on the aerodynamic loads obtained from 2-D unsteady laminar flow computations. The flow computations are done in a parallel computing environment.

METHOD

Navier – Stokes Solver

The unsteady Navier-Stokes equations for compressible and viscous flows are solved on a structured grid [Kaya and Tuncer, 2007,2008, 2009]. The computations are performed in parallel based on domain decomposition (Figure 1). The flapping motion is obtained by moving the airfoil and its surrounding C-grid.

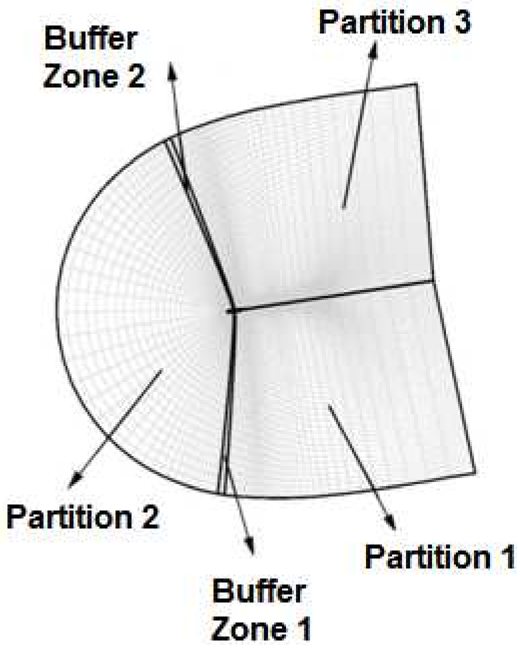

Figure 1: *Grid decomposition with 3 partitions*

The strong conservation law form of the 2-D, thin-layer, Reynolds averaged Navier-Stokes equations are solved on each subgrid partition. Boundary conditions for each subgrid are satisfied by interchanging the flow variables on the intergrid boundaries. The fluxes are computed using the third order Osher's upwind biased flux difference splitting implicit scheme.

Flapping Motion

The unsteady flapping motion is characterized by sinusoidal plunge, $h(t)$, and pitch, $\alpha(t)$, motions. Those motions are defined as:

$$h = -h_0 \cos(\omega t) \quad (1)$$
$$\alpha = -\alpha_0 \cos(\omega t + \phi) \quad (2)$$

where h_0 and α_0 are the amplitudes of the plunge and pitch motions respectively, $\omega = 2\pi f$ is the circular frequency of the flapping motion, t is the time and ϕ is the phase shift between plunging and pitching. $f = 1/T$ is the flapping frequency and T is the flapping period. h and h_0 are non-dimensionalised with respect to the airfoil chord length, c.

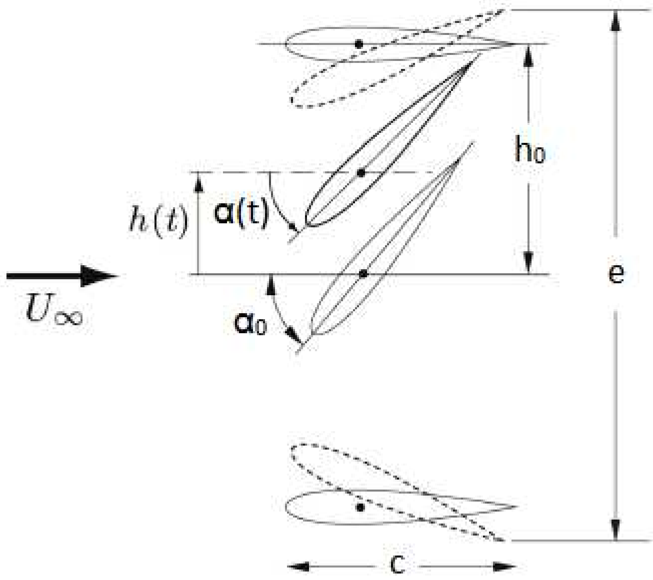

Figure 2: *Flapping motion*

The flapping motion is shown in (Figure 2). In this figure, e, is the total excursion of the airfoil, that is, the maximum distance in the plunge axis that the airfoil can travel during an oscillation period. U_∞, is the freestream velocity. The arrow in the figure shows the flow direction.

In literature, there are various parameters used to investigate the flapping motion of airfoils. In this study the investigated parameters are the reduced frequency, k, the effective angle of attack ,α_{eff}, and the feathering parameter ,χ. Those parameters are defined in Equations 3, 4 and 5.

$$k = \frac{\omega c}{U_\infty} \quad (3)$$

$$\alpha_{eff}(t) = \alpha(t) - arctan\left(\frac{\dot{h}c}{U_\infty}\right) \quad (4)$$

$$\chi = \frac{\alpha_0}{arctan(kh_0)} \quad (5)$$

In this study, the non-dimensional power coefficient $C_P^*(t)$ is considered instead of the instantaneous generated power, $P(t)$, during the flapping motion. $C_P^*(t)$ is defined in Eq. 6. ρ in the equation is the freestream density. The average power coefficient,C_P, obtained in one flapping period is defined in Eq. 7. $C_l(t)$ and $C_m(t)$ in this equation are the instantaneous lift and moment coefficients respectively. The moment is computed with respect to the pitching center.
As seen from Eq. 7, a flapping motion with smaller flow window gives higher power coefficient compared to another motion with larger flow window.

The power production efficiency, η, is defined in Eq. 8. This efficiency is ratio of the useful power to the available power. The total excursion of the airfoil, e, may be thought as the two dimensional flow/wind window. As noticed from Eqn. 8, an oscillation motion with smaller flow window gives higher efficiency compared to another motion of the same power coefficient but with a larger flow window.

$$C_P^*(t) = \frac{P(t)}{1/2\rho U_\infty^3 c} \quad (6)$$

$$C_P = \int_0^1 \left(C_l(t)\,\dot{h}(t) + C_m(t)\,\dot{\alpha}(t)c\right) d(t/T) \quad (7)$$

$$\eta = \frac{1}{e/c} C_P \quad (8)$$

Parallel Computation

A simple parallel algorithm based on a master-worker paradigm on more than one processor is used for the flow computations. As mentioned before, the computational domain is decomposed into subdomains and the solution of each domain is assigned to a different processor. The communication between the processors is attained by the PVM library routines (Parallel Virtual Machine, version

3.4.6). The parallel computations are conducted on a PC cluster consisting of multi-processor computers running on a 64 bit Linux Operator System.

RESULTS

In order to comply with the past studies in literature [Ashraf, Young, Lai and Platzer, 2011; Kinsey and Dumas, 2008], the flow solutions are based on Laminar flow assumption. In the compressible flow solver used, the freestream Mach number is chosen as $M_\infty = 0.1$. This Mach number assumes the incompressible nature of the low wind speed. Again to be consistent with literature [Ashraf, Young, Lai and Platzer, 2011; Platzer, Ashraf, Young, and Lai, 2010] and also to be able to compare this numerical study to the planned experimental study in the near future, the freestream Reynolds number is selected as Re = 1100.

All the computations are carried out in a parallel computation environment by decomposing the grid into 3 partitions. Out of the cases spanning the parametric space, some are calculated simultaneously in case of available processors in the PC cluster. The computation of a typical unsteady flow solution for the 5-period oscillation motion takes about 30-40 minutes of wall clock time. The power coefficient and the power production efficiency are both calculated using the aerodynamic loads obtained during the 5th period.

Parametric space is spanned over a certain range of reduced frequency, k, pitch amplitude, α_0, plunge amplitude, h_0, and the phase shift between plunging and pitching, ϕ . k, varies logarithmically in the range between 0.15 – 1.50, where, α_0, varies linearly in the range 5°-90°. h_0, and, ϕ, vary linearly in the ranges 0.5-1.5 and 60°-90° respectively. The sp anned parametric space is given in (Table 1).

Table 1: *The parametric space of the flapping motion*

<table>
<tr><td colspan="2"></td><td colspan="5">Plunge Amplitude, h_o</td></tr>
<tr><td colspan="2"></td><td>0.50</td><td>0.75</td><td>1.00</td><td>1.25</td><td>1.50</td></tr>
<tr><td rowspan="5">Phase Shift, ϕ_0 (°)</td><td>120</td><td colspan="5" rowspan="5">Reduced Frequency, $k =$
0.150, 0.194, 0.250, 0.323, 0.417,
0.539, 0.696, 0.899, 1.160, 1.500

Pitch Amplitude (°), $\alpha_o =$
5.0, 10.0, 15.0, 20.0, 25.0, 30.0,
35.0, 40.0, 45.0, 50.0, 55.0, 60.0,
65.0, 70.0, 75.0, 80.0, 85.0, 90.0</td></tr>
<tr><td>105</td></tr>
<tr><td>90</td></tr>
<tr><td>75</td></tr>
<tr><td>60</td></tr>
</table>

In the spanned space there are $5 \times 5 \times 10 \times 18 = 4500$ elements which results in 4500 cases to be solved. However, since only the cases which satisfy $\chi > 1$ condition will be taken into account [Kinsey and Dumas, 2008], the number of cases to be solved reduces to 3235 since 1265 cases don't satisfy the, $\chi > 1$, condition. The computation of the 3235 cases requires about 2-months duration of solver running.

The power production efficiency values are calculated according to the last period average. Unsteady solutions of each case in Table 1 are computed for 5 periods of oscillation.

The maps of the calculated power production efficiency at fixed h_0, and, ϕ, values are plotted in the, $k - \alpha_0$, parametric space. The maps are plotted in Figures 3-7 and only the power producing cases are shown.

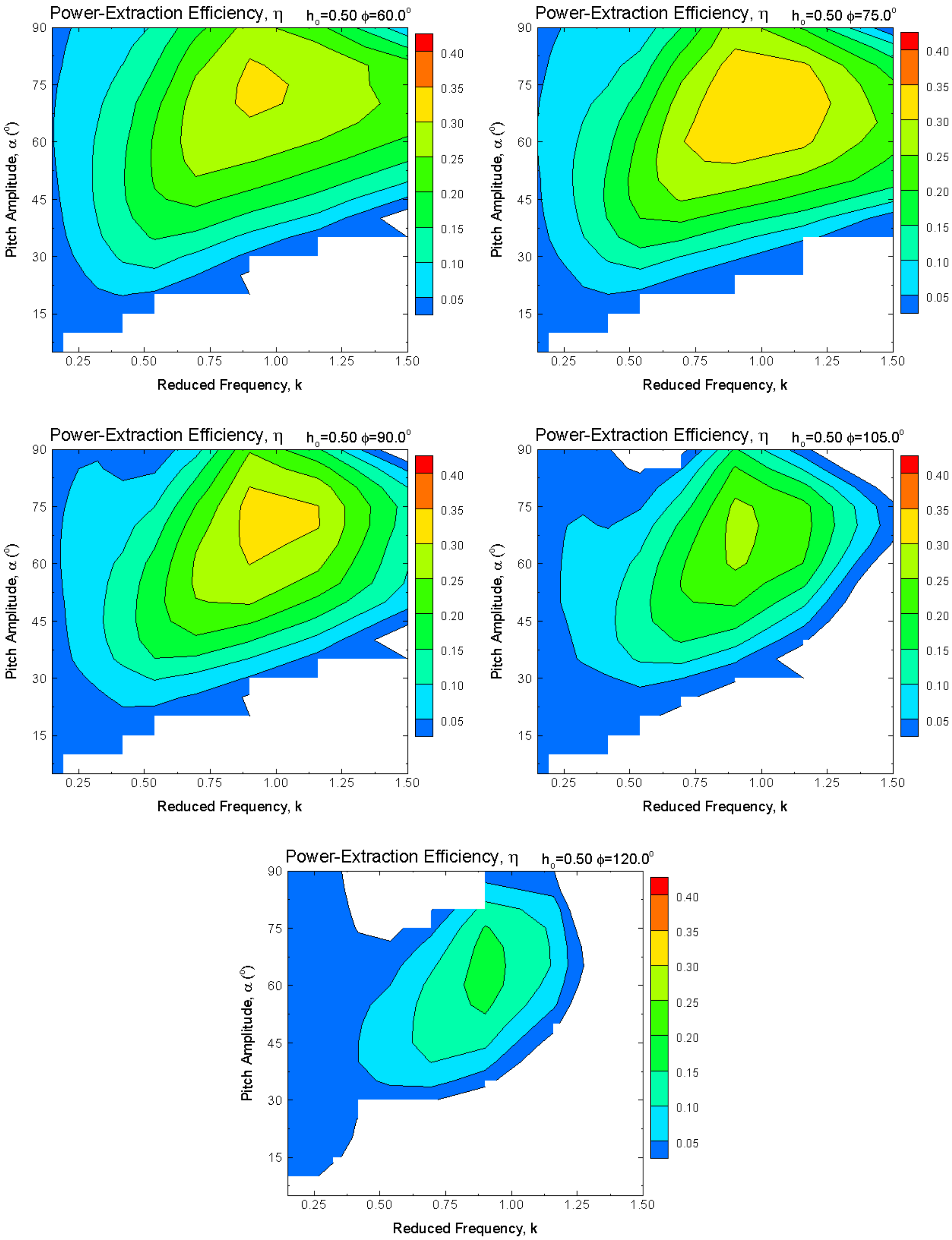

Figure 3: *Power production efficiency maps in the,* $k - \alpha_0$*, parametric space for,* $h_0 = 0.5$ *case*

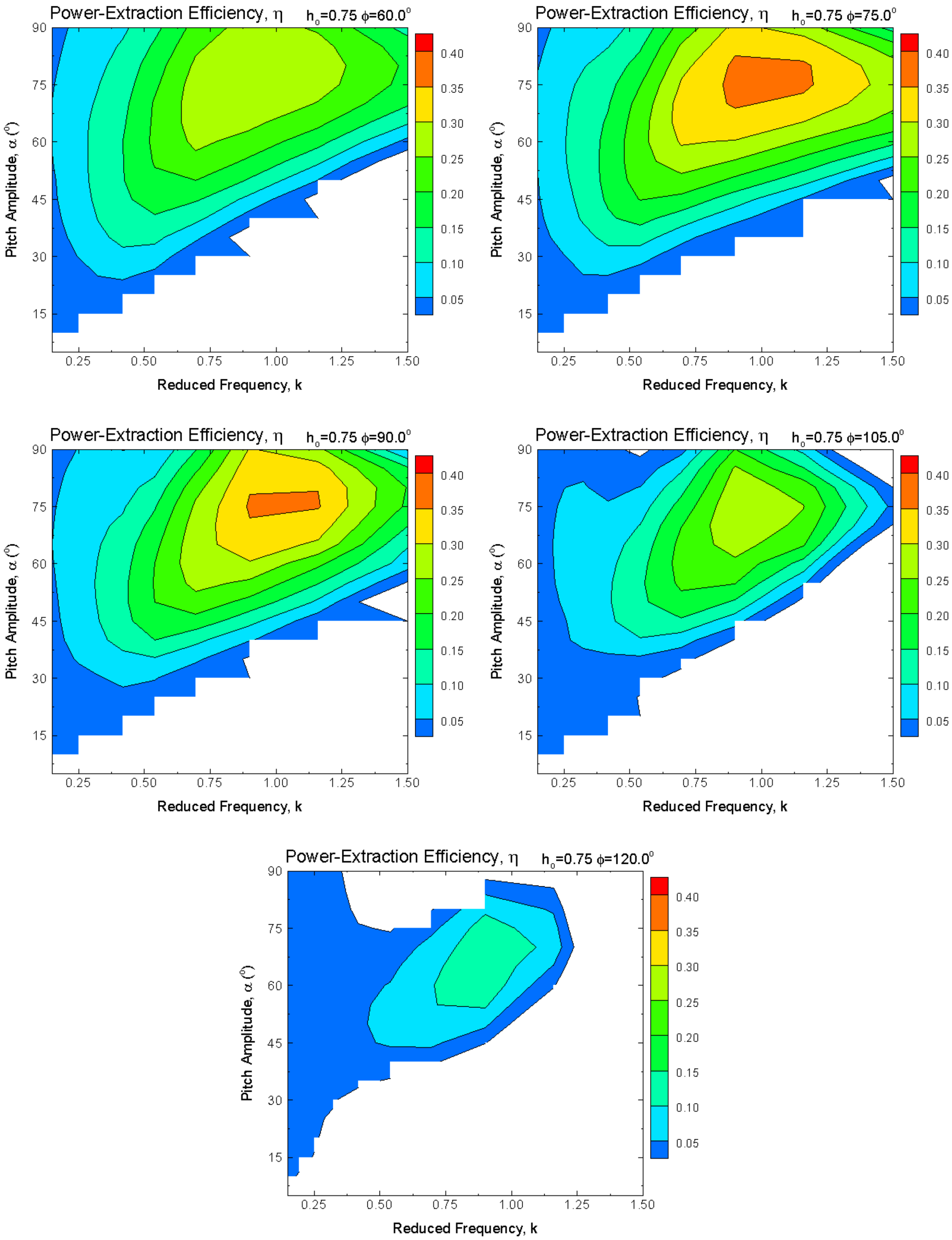

Figure 4: *Power production efficiency maps in the,* $k - \alpha_0$*, parametric space for,* $h_0 = 0.75$ *case*

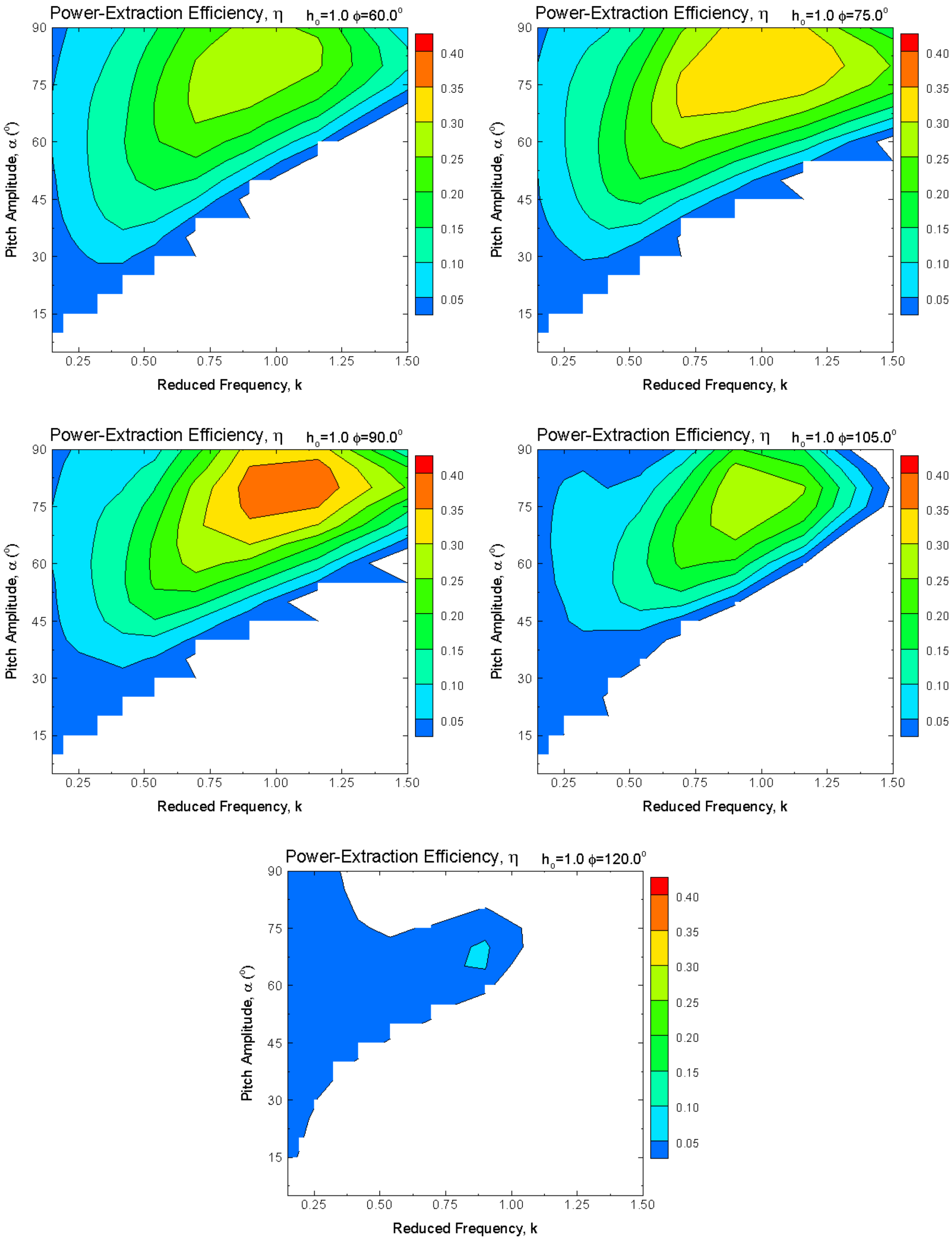

Figure 5: *Power production efficiency maps in the,* $k - \alpha_0$*, parametric space for,* $h_0 = 1.0$ *case*

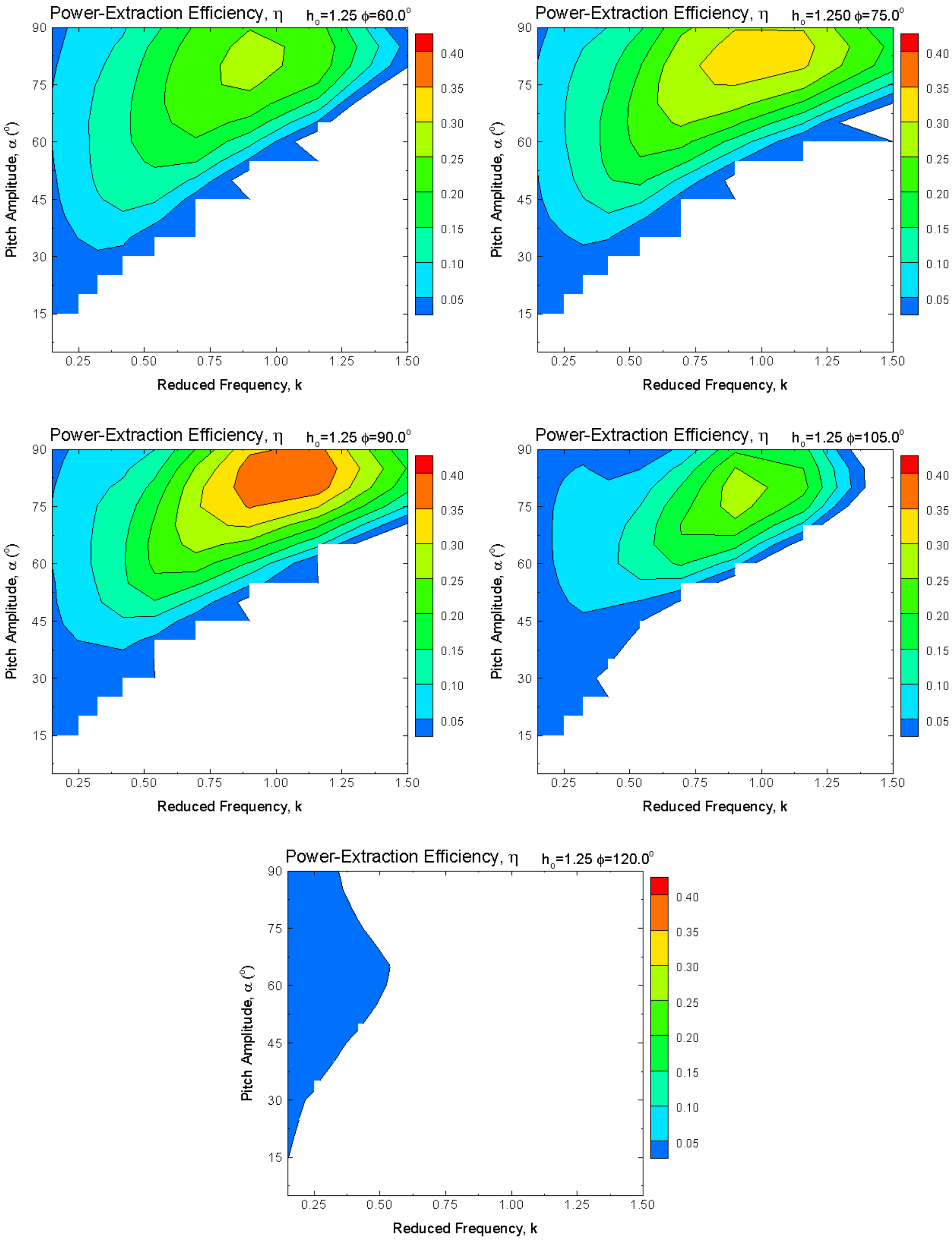

Figure 6: *Power production efficiency maps in the, $k - \alpha_0$, parametric space for, $h_0 = 1.25$ case*

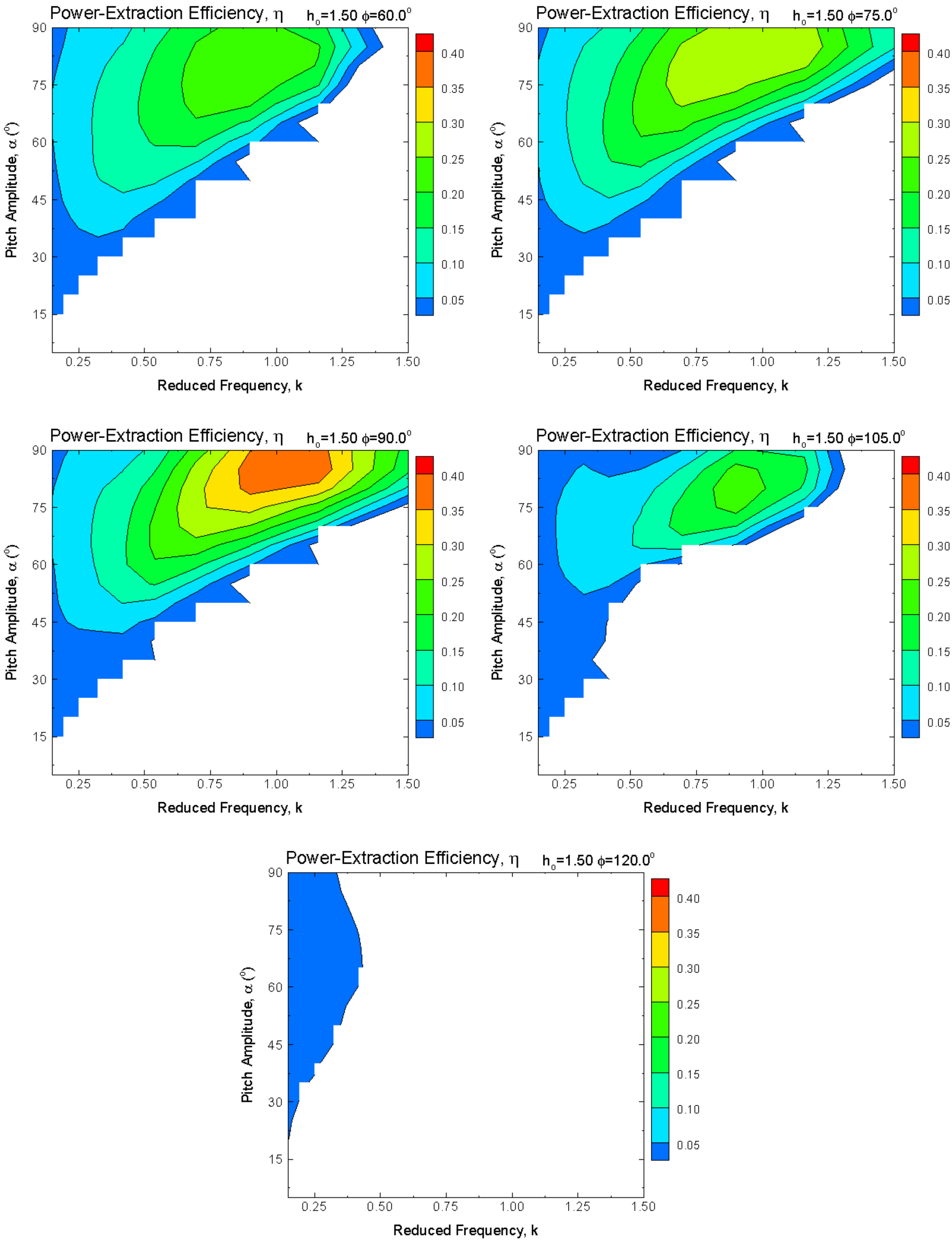

Figure 7: *Power production efficiency maps in the,* $k - \alpha_0$*, parametric space for,* $h_0 = 1.5$ *case*

From the maps, it is seen that, for any plunge amplitude and phase shift, the maximum power production efficiency are obtained when k, and, α_0, fall in the ranges $0.9 - 1.2$ and $75° - 85°$ respectively. Also it is noticed that the power production efficiency is maximum when h_0 is in the range 0.75-1.25 and when ϕ is close to 90°.

More precise values for the optimum power production efficiency can be obtained by transforming the maps into response surfaces. For this purpose, a 2[nd] degree polynomial response surface is produced at fixed, h_0, and, ϕ, values. The response surfaces are plotted in Figures 8-11.

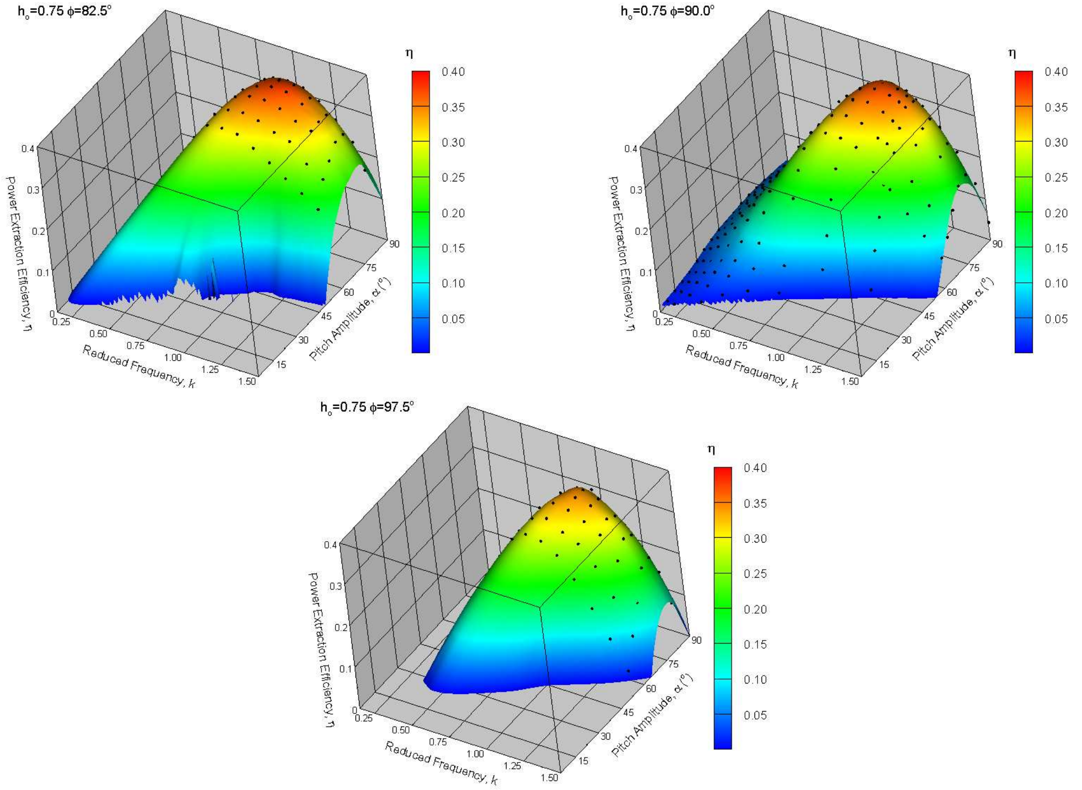

Figure 8: *Power production efficiency response surfaces for,* $h_0 = 0.75$ *case (The calculated values are shown in •)*

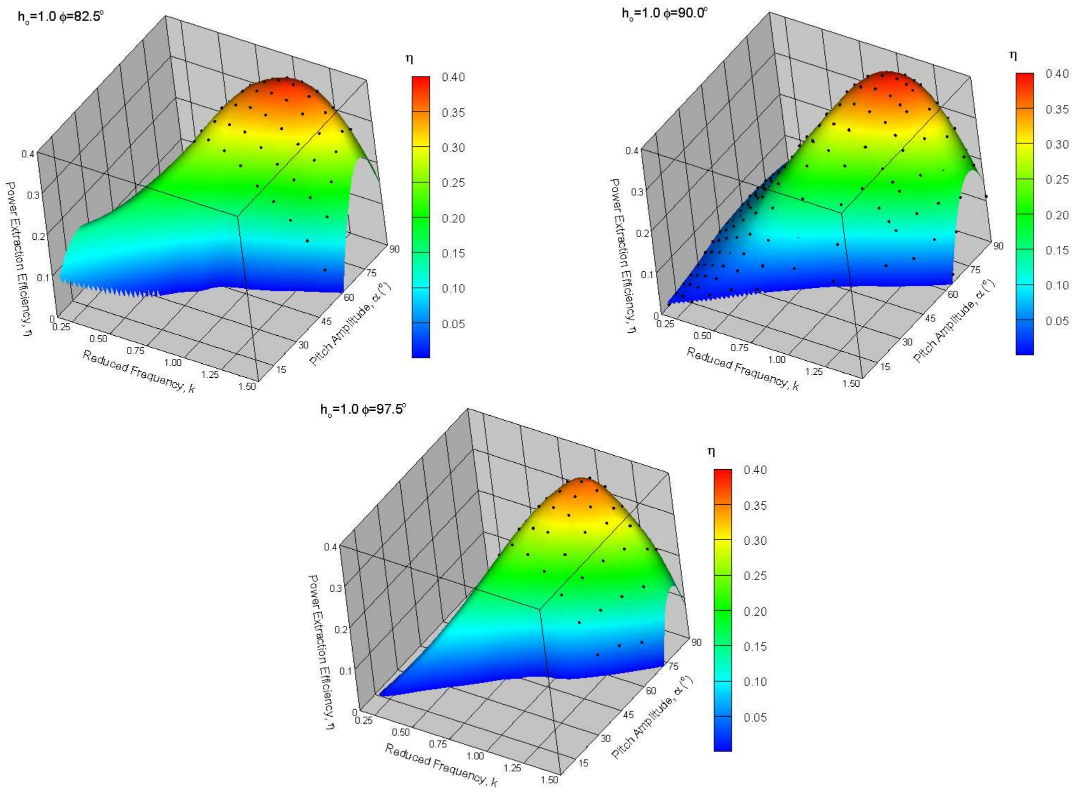

Figure 9: *Power production efficiency response surfaces for,* $h_0 = 1.0$ *case (The calculated values are shown in •)*

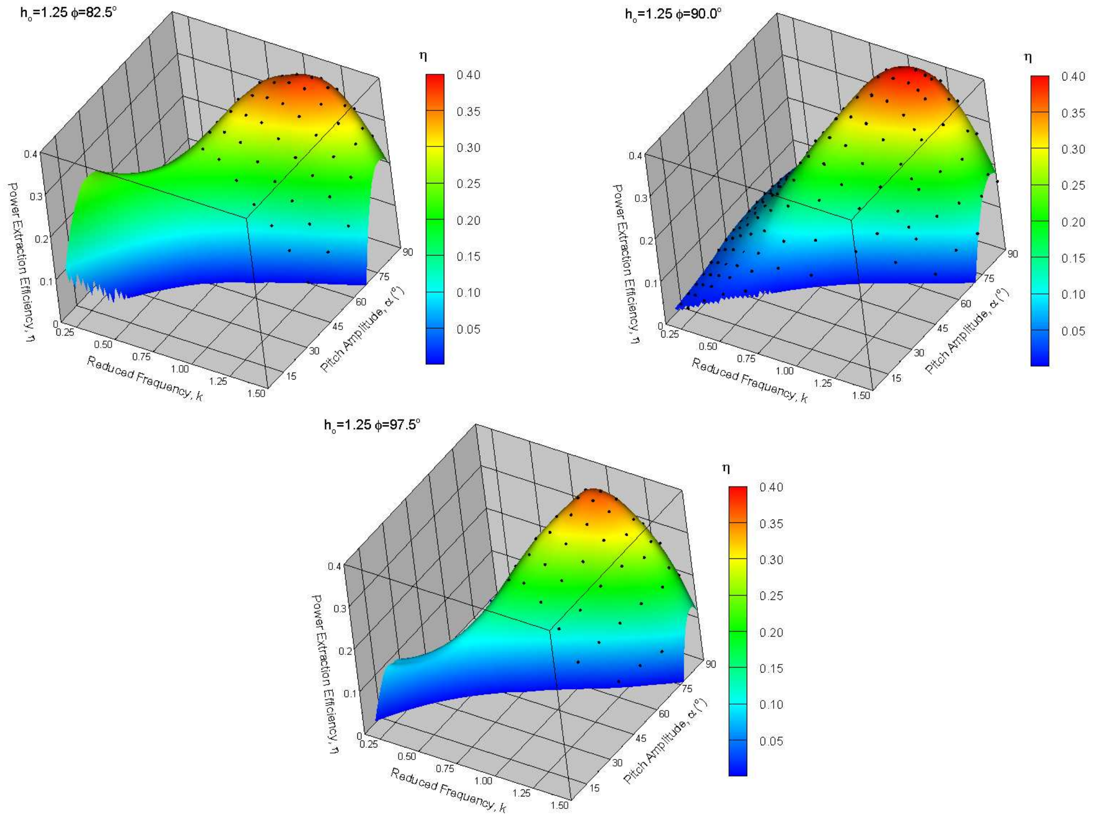

Figure 10: *Power production efficiency response surfaces for,* $h_0 = 1.25$ *case (The calculated values are shown in •)*

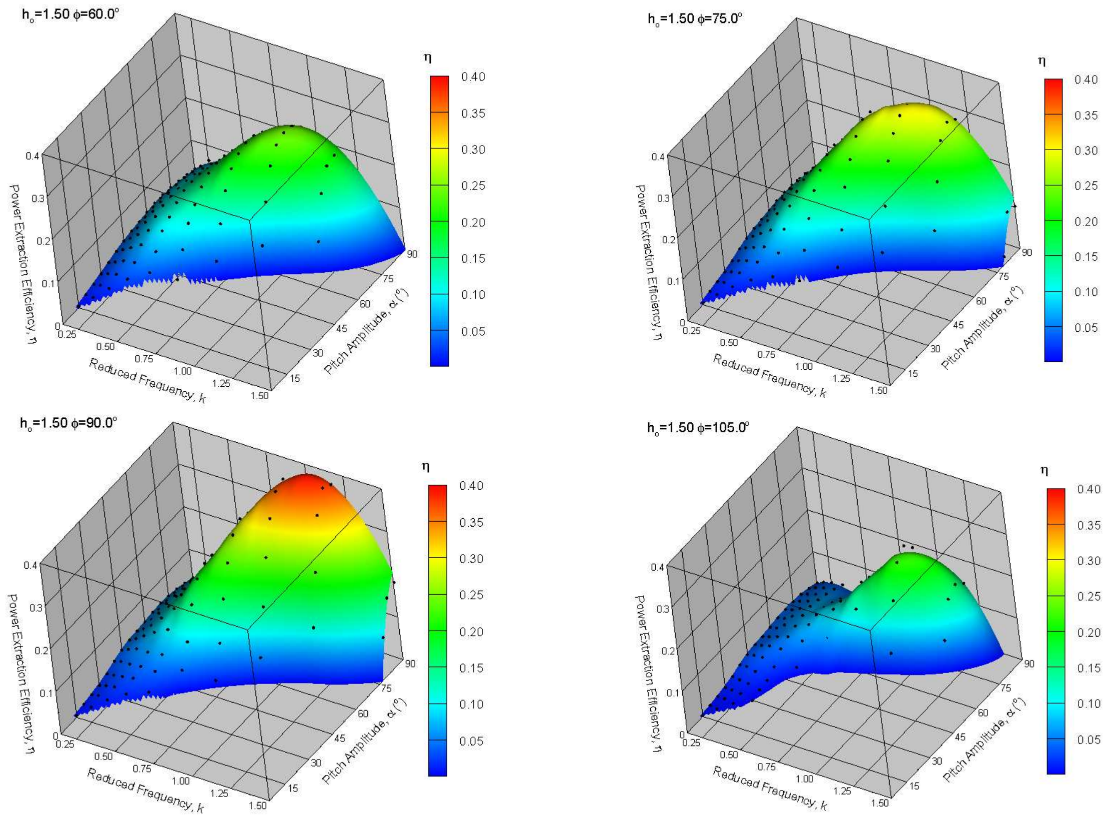

Figure 11: *Power production efficiency response surfaces for,* $h_0 = 1.5$ *case (The calculated values are shown in •)*

The maximum values of the 2nd degree polynomial response surfaces are computed for each pair of plunge amplitude and phase shift. The calculated maximum, C_P, values and the corresponding $k - \alpha_0$ pair are shown in Figures 12 - 15.

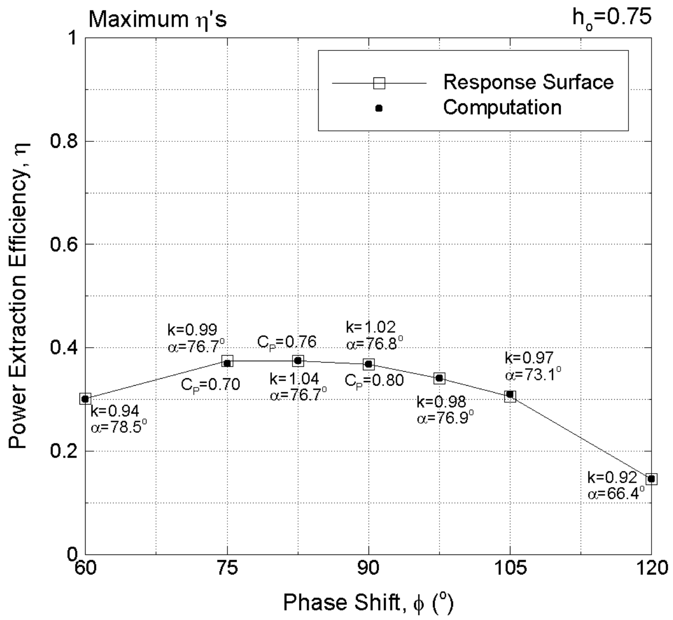

Figure 12: *The maximum power production efficiency for* $h_0 = 0.75$

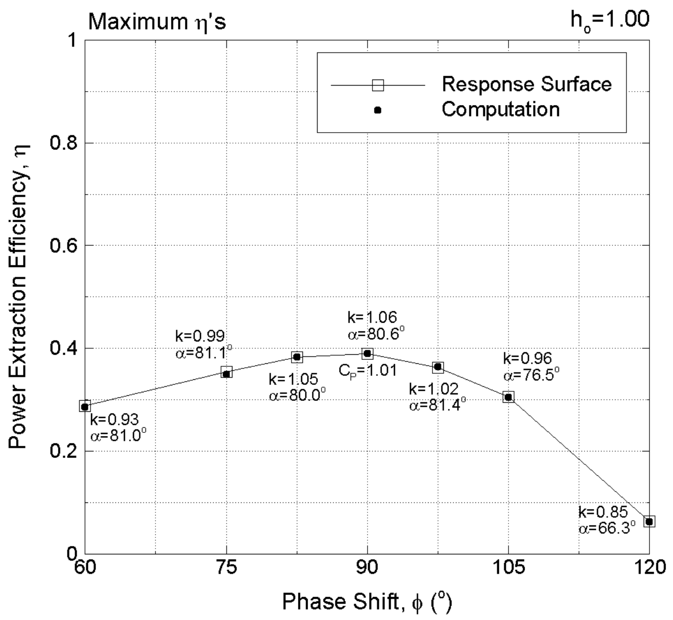

Figure 13: *The maximum power production efficiency for* $h_0 = 1.0$

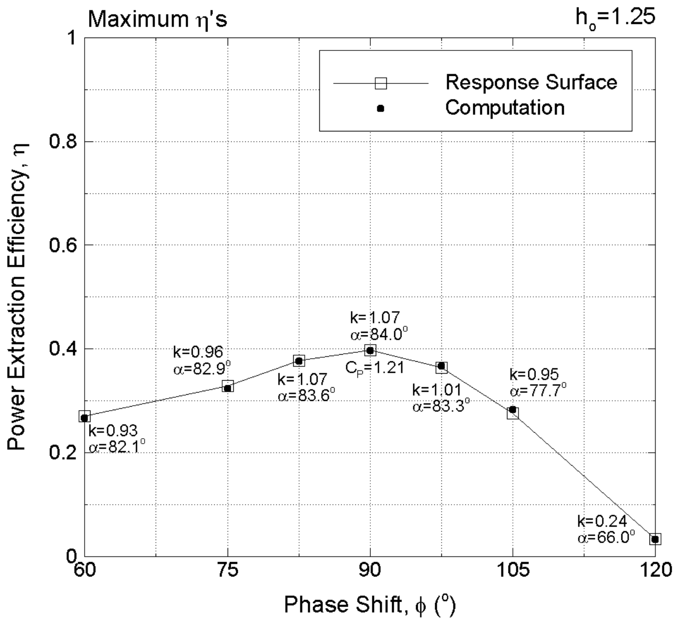

Figure 14: *The maximum power production efficiency for* $h_0 = 1.25$

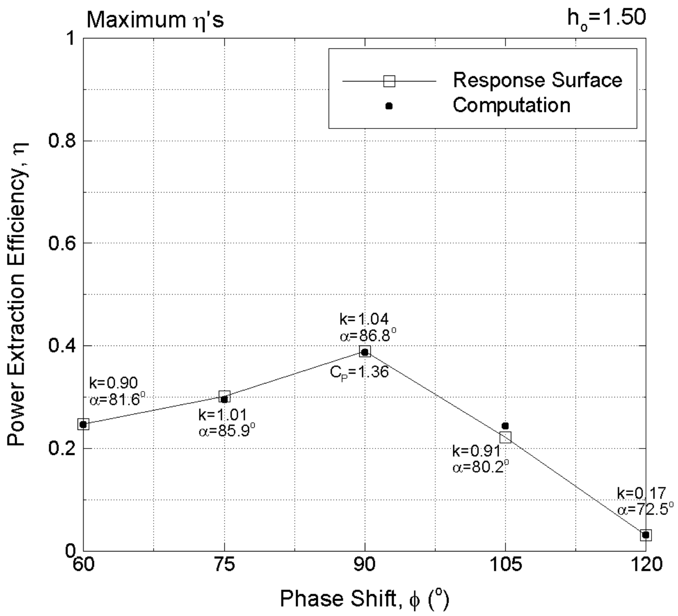

Figure 15: *The maximum power production efficiency for* $h_0 = 1.5$

The figures above show how the maximum values vary with the phase shift for constant plunge amplitude. In the figures, the response surfaces results are compared with the results calculated by Navier-Stokes to check the accuracy of the response surfaces.

The results obtained from those figures are interesting and beneficial as explained below.

It is observed that, for low h_0 values, the highest maximum power production efficiency is obtained when $\phi < 90°$ (between $75° - 90°$) (Figure 12). On the other hand, for high h_0 values the highest maximum C_p value is obtained when $\phi = 90°$ (Figures 13-15). Most probably, the reason is because of the definition of power efficiency given in Equation 8. According to this definition, the most efficient flapping motion in producing approximately the same power efficiency is when the area swept by the airfoil is the least. At low plunge amplitude, in the case of the phase shift between plunge and pitch motions is between $75° < \phi < 90°$, the airfoil sweeps less area than if the phase shift is $\phi = 90°$. Another interesting result, as the plunge amplitude increases, the pitch amplitude for the maximum power efficiency also increases.

The highest numerical values for the maximum η, calculated according to the phase shift are given in Table 2. As expected, as the plunge amplitude increases, the obtained maximum power efficiency increases too. The highest power production efficiency is obtained when $h_0 = 1.25$ and is calculated as 0.4.

Table 2: The highest maximum power coefficient and efficiency values according to the phase shift

$\boldsymbol{h_o}$	$h_o = 0.50$	$h_o = 0.75$	$h_o = 1.00$	$h_o = 1.25$	$h_o = 1.50$
$\boldsymbol{\eta}$	0.343	0.374	0.389	0.396	0.386
$\begin{pmatrix} \boldsymbol{\phi} \\ \boldsymbol{k} \\ \boldsymbol{\alpha_o} \end{pmatrix}$	$\begin{pmatrix} \phi = 75° \\ k = 1.02 \\ \alpha_o = 69.4° \end{pmatrix}$	$\begin{pmatrix} \phi = 82.5° \\ k = 1.04 \\ \alpha_o = 76.7° \end{pmatrix}$	$\begin{pmatrix} \phi = 90° \\ k = 1.06 \\ \alpha_o = 80.6° \end{pmatrix}$	$\begin{pmatrix} \phi = 90° \\ k = 1.07 \\ \alpha_o = 84.0° \end{pmatrix}$	$\begin{pmatrix} \phi = 90° \\ k = 1.04 \\ \alpha_o = 86.8° \end{pmatrix}$

CONCLUSION

For the cases studied, it is observed that the maximum power coefficient and efficiency increases with increasing plunge amplitude.

The results show that for any plunge amplitude and phase shift, the maximum power efficiency is obtained when k, and, α_0, fall in the ranges $0.9 - 1.2$ and $75° - 85°$ respectively. The highest power coefficient is obtained when $h_0 = 1.25$ and calculated as 0.40.

Using the actuator disk theory for inviscid flow, Betz has calculated the maximum power efficiency for the ideal case as $\eta = 0.59$ [Betz, 1920]. The result obtained in this study ($\eta = 0.39$) for a flapping airfoil is an encouraging result for further research on the flapping airfoil for power production. In practice, a power efficiency of even 0.30 is sufficient for the flapping airfoil to be another solution for wind energy production [Kinsey and Dumas, 2008].

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