DEVELOPMENT OF DARRIEUS-TYPE VERTICAL AXIS WIND TURBINE FOR STAND-ALONE APPLICATIONS

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Abstract

A theoretical model for the design and performance simulation of Darrieus-type vertical axis stand alone wind turbine for small scale energy applications was developed. The model is based on application of momentum theory and blade element theory to multiple stream-tubes. Software was developed to solve the resulting non-linear equations for the flow-field. Results were used to analyze the effects of blade profile, rotor solidity, Reynolds number and aspect ratio on the maximum power and torque coefficients, optimum tip speed ratio, and ability to self start, which lead to design of optimum rotor configurations.

Keywords: *Wind energy, Vertical axis wind turbine, Darrieus rotor, multiple stream-tube*

Nomenclature

A	Swept area
A_f	Frontal area of the struts
AR	Aspect ratio
a	Induction factor
c	Chord length
C_D	Infinite span drag coefficient
C_{Dmax}	Finite span aerofoil maximum drag coefficient
C_L	Infinite span lift coefficient
C_p	Power coefficient
C_T	Thrust coefficient
D	Rotor diameter
h	Blade height
N	Number of blades
n	Number of support arms
R	Radius of the rotor
Re	Reynolds number
U	Ambient air velocity
U'	Air velocity enters to the rotor
α	Angle of attack
$\Delta\theta$	Magnitude of a stream-tube
ε	Surface roughness
θ	Azimuth angle
λ	Tip speed ratio
ρ	Air density
σ	Solidity
ω	Angular velocity

Abbreviations

HAWT	Horizontal Axis Wind Turbine
MSM	Multiple Stream-tube Model
NACA	National Advisory Committee of Aeronautics
TSR	Tip Speed Ratio
VAWT	Vertical Axis Wind Turbine

1. Introduction

In the context of harnessing resources of wind energy, decentralized stand alone systems have unique benefits. Such systems could be a more viable option in rural areas where grid electricity cannot be implemented due to lack of infrastructure. Moreover, in an interruption or a breakdown of the grid, stand alone systems could act as a backup. In un-electrified areas, basic electric energy needs are usually obtained by batteries, which are charged by grid-electricity available in city centers. Therefore stand alone systems could play an important role as an alternative and cost effective source of battery charging.

Within the broad context of harnessing energy from wind, wind turbine rotors could be considered as the key component. Basically, based on the driving force, they can be divided as lift driven and drag driven. They are also categorized based on orientation of the axis of rotation as vertical axis and horizontal axis turbines (VAWT and HAWT, respectively), and both of which have intrinsic advantages and drawbacks. In the category of lift driven, VAWTs consist of variety of rotor configurations such as troposkine, straight bladed (or cylindrical) Darrieus, delta Darrieus, etc. VAWTs are Omni directional and, unlike HAWTs, variations of wind direction do not influence the performance. Therefore yawing mechanisms are not needed and the rotor could operate in a gust wind without much efficiency reduction. One disadvantage of lift driven VAWT is its difficulty of self starting. However there are some successful methods proposed to improve this situation. Normally VAWTs are operated in low angular velocities comparing to HAWTs and therefore aerodynamic noise is less. Further, the electrical generator load mountings are easy in VAWTs since the end of its axis is near to the ground level. Nevertheless VAWT has inherent difficulty in theoretical modeling of its performances and more research and developments are needed on this aspect.

2. Performance Characteristics of VAWT Rotors

Several parameters should be considered in designing a wind turbine rotor for a particular type of application. These parameters include solidity of the rotor, length, chord and aspect ratio of the blades, diameter of the rotor, number of blades, surface roughness of the blade, operational range of Reynolds number, blade profile, etc. (see Equation 1). As a result, modeling and design of a rotor become difficult. Moreover, as the requirements differ depend on the type of application, some general design criteria have been established such as high power coefficient, wide range of operation, high self-starting capability, reliability, cost effectiveness, strength and rigidity, optimum rotor inertia etc. One of the difficulties of matching the performance characteristics with the design requirements is the existence of paradox among some design requirements such as high power coefficient versus high self-starting capability, strength and rigidity versus low rotor inertia, reliability versus cost etc. Major challenges in the design of wind turbine rotors include the complexity in the relationships between the performance parameters and the lack of availability of aerofoil data. In particular, the aerofoil of the blade section is subjected a wider range of angle of attack during the operation and aerofoil data is usually available for limited range near the optimum angle of attack. However, a satisfactory performance model could be derived with carefully selection of appropriate techniques and reasonable assumptions.

As there are several parameters involved in the flow around wind rotors, basic approach in theoretical modeling is to use the concept of dimensional analysis. This technique simplifies the initial functional relationship to a lesser number of parameters appeared in non-dimensional forms. For example, the power output of the rotor P_{rotor} could be expressed in non-dimensional form as the power coefficient C_P in the form

$$Cp = g\,(\sigma, c/h, c/D, blade\,profile, \varepsilon, Re, \lambda), \qquad (1)$$

Where $C_P = P/\,(0.5\,\rho A U^3)$ is the power coefficient, P is the power, ρ is the air density, A is the frontal area of the rotor, U is the ambient air velocity. $\sigma = Nc/D$ is the rotor solidity, N is the number of blades and c is the chord length. $D=2R$ is the rotor diameter, ε is the relative roughness of the blade surface, Re is the Reynolds number, $\lambda= R\omega/U$ is the tip-speed ratio, ω is the angular velocity of the rotor, $AR = h/c$ is the aspect ratio, h is the blade length. This equation could be further simplified for the case of relatively high Re as

$$Cp = g\ (\sigma, c/h, c/D, blade\ profile, \varepsilon, \lambda) \ldots\ldots(2)$$

The torque coefficient of the rotor could be derived from above relationships in the form

$$C_T = C_P/\lambda \ldots\ldots(3)$$

Usually the performance characteristics of a wind turbine rotor are represented in non-dimensional form as variation of power and torque coefficients with tip speed ratio at specified values of the other governing parameters. Note that the effect of blade profile on the performance is basically through the variation lift and drag coefficients C_L and C_D with angle of attack α. In other words, C_L and C_D depend on the blade profile and α. Based on experimental data, such relationships could be obtained in the form

$$C_L = lift\ force/(0.5\ \rho A U^2) = h_1\ (blade\ profile, \alpha)$$

$$C_D = drag\ force/(0.5\ \rho A U^2) = h_2(blade\ profile, \alpha),$$

for relatively high Re.
The above relationships basically represent the performance characteristics of a wind turbine rotor.

3. Theoretical Modeling of VAWT Rotors

The aim of a theoretical model is to convert the qualitative functional relationships given in expressions (1), (2) and (3) to quantifiable ones. In the present study, the momentum theory (which considers the rate of change of momentum of the flow in relation to the force acting on the fluid as it passes through the rotor) and the blade element theory (which considers the forces acting on the blades of the rotor in relation to the flow and geometrical characteristics) are applied to a suitably selected elementary flow region around the rotor to quantify the above functional relationships. Among the approaches available, the concept of multiple stream-tubes is employed in the present study, as it is capable of capturing the key design parameters, such as D, N, AR, σ, Re, blade profile, etc. .. This method is described in the following sub-section Software was developed to solve the governing equations derived from momentum theory and blade element theory for selected set of appropriate conditions and the output results were represented graphically. The two set of basic curves, C_P vs. λ and C_T vs. λ, are in non-dimensional form and therefore applicable to series of geometrically similar turbine rotors. But geometrical similarity is only a necessary condition but not a sufficient condition due to the variation of Re. Therefore the effects of Re should also be investigated.

The main input parameters of the theoretical model are free stream air velocity, density of air, viscosity of air, number of blades, diameter of rotor, height of rotor, blade profile, chord length and blade pitch angle. Further effect of blade profile is analyzed by considering lift and drag data relevant to four NACA 4 digits aerofoils. These are NACA 0012, NACA 0015, NACA 0018 and NACA 0021.

Implementation of Multiple streamtube model (MSM)

In this method, flow through the entire rotor is separated into adjacent, aerodynamically independent sufficiently high number of parallel stream-tubes (refer Figure 1). This is a better approach for the non uniformity of inflow. It was proved that total decrement of flow velocity in upstream and downstream is same as proved by Bernoulli theorem in the Betz limit. Even though some of the assumptions behind the MSM are contradicted the basic fluid dynamic laws, it simplifies the complex flow pattern of the VAWT and thus makes logical mathematical model for VAWT (Paraschivoiu 2002). This method assumes that cross section of each stream-tube remains unchanged. Path of the inflow is assumed to be a straight line and air velocity of each stream-tube is supposed to be decreased before entering to the upstream circular path. Furthermore on leaving the downstream circular path, velocity of the air flow decreases and settles down in far away. Another assumption used is that the velocity does not change while passing through the circular path (Strickland 1975). Firstly the momentum theory is applied for each stream-tube and dimensionless thrust coefficient is obtained as.

$$C_{thrust} = \frac{momentum\ loss\ rate}{\frac{1}{2}\rho U^2(\text{hR}\Delta\text{esine})} = 4\frac{U'}{U}\left(1-\frac{U'}{U}\right) = 4a(1-a)$$

where $a = U'/U$ is the induction factor U is free wind velocity and U' is air velocity enters to the rotor. This equation is only valid when a is less than 0.5. When a exceeds 0.5, Glauert empirical formula is used. For $0.4 < a < 1.0$

$$C_{thrust} = \frac{26}{15}a + \frac{4}{15}$$

Secondly, the blade element theory is applied to obtain another expression for thrust coefficient and these two set of equations are solved by a root finding algorithm to obtain induction factor for each stream-tube. This leads to the required expressions for torque and power coefficients.

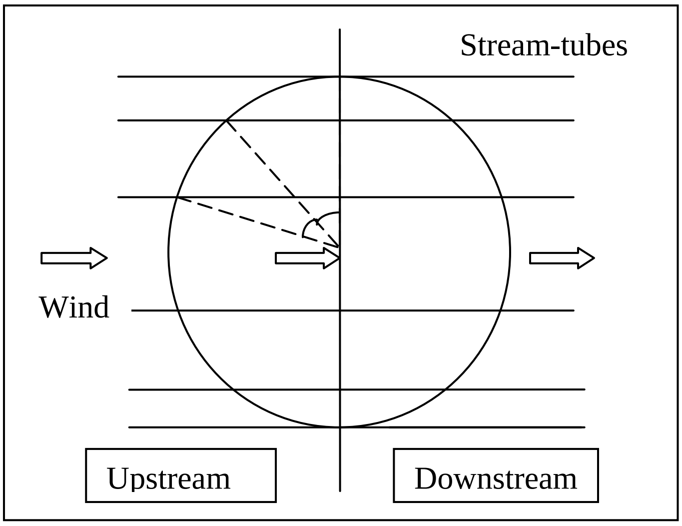

Figure 1 - *A systematic view of multiple stream-tube model*

Finite span effect and Strut losses

To evaluate the finite span effect, modifications and corrections are incorporated to the aerofoil drag and lift coefficients that are relevant for infinite spans. These corrections vary according to the type of coefficients and whether the angle of attack exceeds the stall angle or not. Before stalling, lift and drag coefficients are evaluated by using Lanchester and Prandtl theory (Bertin 2006). After the stall angle, coefficients are evaluated by using Viterna and Corrigan model (Chua 2002). Support arm drag losses are also included with some simplifications. The expressions related to the general element are integrated to obtain the resultant effects. Average torque coefficient loss and power coefficient loss are estimated in the form

$$(C_T)loss = \frac{1}{4}(\lambda^2+1)\frac{n \times A_f}{A_s}c_D$$

$$(C_P)loss = \frac{1}{4}\lambda(\lambda^2+1)\frac{n \times A_f}{A_s}c_D$$

Where n is the number of support arms, A_f is the frontal area of the struts, A_s is the frontal area of the rotor. Here c_D is taken as 0.9.

4. Results and Discussion

Aerofoil's lift and drag coefficients are obtained corresponds to the infinite blade or a bounded blade (Sheldahl and Klimas 1981). Aerodynamic characteristics of finite span blades are different from those of infinite span blades or bounded blades. When the blade span is finite, high pressure air spills out to the low pressure region and circulation along the span is not uniform. This alters the lift, drag and moment coefficient of the aerofoil and there should be adjustments for data taken from bounded blade (Anderson 2007). Figure 2 presents the effects of aspect ratio on the power coefficient of the rotor. NACA 0021 profile is used for the analysis and the rotor diameter is kept at 2 m. Wind velocity is taken as 6 m/s and chord length is kept at 0.2 m. Note that the chord length is kept constant in order to omit the effects of change of Reynolds number and only the blade height is changed. As *AR* is increased, the maximum power coefficient is also increased and the operating range becomes wider. Furthermore it was seen that the self starting ability is improved as the aspect ratio increases.

Solidity is influenced by three design parameters of the rotor that are number of blades, chord length and rotor diameter. Eventhough turbines cannot be strictly classified as low, medium and high solidity, for electrical generation lower solidity turbines are very usable. The main reason is that electrical generation applications normally deal with lower torque. In addition high maximum power coefficients can be achieved and electrical unit cost may be lower owing to lower construction and material cost. Moreover high solidity results for narrow operating range of tip speed ratios and it effects of performance reduction in gusts and variation of wind. However higher solidity improves the self starting performance, and therefore is better for VAWTs (Kirke 1998). The effect of rotor solidity is presented in Figure 3. The profile selected for this analysis is NACA 0021 and chord length, blade height, wind speed and number of blades are selected as 0.2 m, 1.8 m, 6 m/s and 3, respectively. Comparing values of the Solidity are 0.6, 0.4, 0.3 and 0.24 and it is varied by changing the value of rotor diameter. Variation of the power coefficient with the tip speed ratio is demonstrated and unlikely to maximum power coefficient (C_{Pmax}), maximum thrust coefficient (C_{Tmax}) increases when solidity lowers. When solidity increases, it can be easily seen a drop of C_{Pmax} and optimum λ. But range of operating tip speed ratios is high for low solidity. However, there is an increment of self starting ability with high solidity. Number of blades primarily affects the solidity (σ) of the rotor. Two blades or three blades are frequently used in wind turbines. Number of blades affects not only power coefficient but also structural stability. As illustrate in Figure 4, four graphs are drown using NACA 0021 aerofoil and keeping blade diameter, chord length, blade height and ambient air velocity as 2 m, 0.2 m, 1.8 m, 6 m/s respectively. Torque performance is presented and it is apparent that higher torque can be achieved by increasing turbine blades. Furthermore that average torque of two bladed rotors is lower than the three bladed ones (DeCoste, et al. 2005). Also it was noted that as number of blades decreases, range of operating tip speed ratios increases and tip speed ratio correspond to the maximum power coefficient shifts towards to higher values. But it should be noted that there is no visible difference of value of C_{Pmax} when the turbine consists with one blade, two blades or three blades. These facts were confirmed in literature (Kirke 1998) by compareing one bladed rotor with two and three bladed rotors. However there is a slight drop of value of C_{Pmax} if the turbine consists of four blades. Moreover there is an improvement of self starting ability, when number of blades increase and it is also confirmed in literature (Kirke 1998).

The frequently used aerofoils for standalone VAWTs are NACA 0012, 0015, 0018, and 0021. These are preferred due to its simplicity for manufacturing and availability of performing data (Claessens 2006). The basic difference in these blade profiles are variation of thickness. A thick aerofoil improves the self starting capability of VAWT and there is another benefit for the structural strength. But there is no apparent change in C_{pmax} and tip speed ratio (λ) where $C_{p\ max}$ occurs. Even though most of the researchers argued that thicker the aerofoil, higher the self starting capability, some of them show it is not relevant to low Reynolds number applications such as small scale vertical axis wind turbines (Kirke 1998). In Figure 5, ambient air velocity, number of blades, rotor diameter, chord length and blade height are kept as 6 m/s, 3, 2 m, 0.2 m, 1.0 m respectively. Improvement of self starting ability can be identified while profile goes to higher numbers that is thickness of the aerofoil increases. But there is no significant variation of rang of operating λ. Eventhough gradual increment of C_{Pmax} and decline of optimum λ can be seen in blade profile NACA 0012, NACA 0015, NACA

0018 respectively, NACA 0021 behaves in a slightly different way. Its C_{Pmax} is less than the C_{Pmax} of NACA 0018 and optimum λ is slightly higher than the optimum λ of NACA 0015 blade profile.

The most influential geometrical parameter for the Reynolds number is chord length which influences solidity, flow curvature and aspect ratio further. Ratio of C_L/C_D is high for higher Reynolds numbers and it effects for better performance of the turbine. Hence high torque and power performance can be achieved. But contribution of the Reynolds number for the self starting is controversial and still it is not completely solved. In Figure 6, NACA 0021 is selected and ambient air velocity, rotor diameter, blade height are kept as 6 m/s, 2 m, 1.8 m respectively. Effect of Reynolds number for the performance of the turbine is examined by omitting variation of solidity and without including finite span effect. Thus variation of chord length only cause for variation of Reynolds number. By Figure 6, it can be easily seen that higher Reynolds numbers cause for higher C_{Pmax} and shifting of optimum λ towards to low tip speed ratios. Moreover self starting ability increases and operating range of tip speed ratios increases.

Combined effect of Reynolds number and solidity is evaluated without including finite span effect. Here only chord length is changed. Although there can be seen a gradual increment of optimum λ, it cannot be seen a gradual increment of C_{Pmax} when chord length is increased. But it was noted a gradual increment of C_{Tmax} as chord length is increased. Moreover it is apparent that self starting ability is increased with increasing chord length. In Figure 7, diameter is varied by keeping swept area constant. Decline of C_{Tmax} can be noticed with increasing rotor diameter. Increment of turbine diameter results decline of C_{Pmax} and shifting of optimum λ toward low speed ratios. Nevertheless there is a slight increment of range of operating tip speed ratios with the turbine diameter. There can be seen an enhancement of self starting ability with decline of diameter.

5. Conclusion

Major factors needed to be concerned for designing small scale VAWTs for battery charging applications and influence of dimensionless parameters for the major factors are concluded.

Ability to self start

From the theoretical modeling, means and their success on improving ability to self start can be evaluated. It is hard to see any influence of aspect ratio on self starting. But When the number of blades of the turbine is increased, it can be seen an apparent improvement of self starting. But going for more than four blades is not feasible and there are number of factors such as power performance, economy, rotor inertia etc. need to be considered. Even though higher solidity and Reynolds number improve self starting, economic aspect of these factors has to be considered. Moreover, Blade profile has significant effect on self starting that is thickness improves it. Constructing aerofoils with camber is difficult task and due to the lack of data on lift and drag coefficients, mathematical prediction is difficult. But implementing thicker aerofoil is easy and another benefit of thick aerofoil is high strength. Even so, blade inertia increases owing to thicker blades.

Power performance

C_{Pmax} is the most important value in power performance and it can be easily achieved by increasing aspect ratio. But higher solidity lowers the C_{Pmax} and high Reynolds numbers give high C_{Pmax}. Although increment of chord length increases Reynolds number, it as well causes for higher blade inertia. Effect of number of blades on C_{Pmax} is not subtle and when turbine consists with one, two or three blades, it is hard to notice any change of $C_{Pmax.}$ Under the topic of power performance, width of the power curve is crucial inasmuch as it measures sensitivity for short term changes of wind speed. Peaky power curve causes for extreme sensitivity for changes of wind speed and it should be avoided. As number of blades lower, wider the power curve and one bladed turbine gives widest power curve. But implementing one bladed turbine is not possible due to unbalanced centrifugal forces and three bladed turbines are more appropriate than two bladed turbines for it gives more stability.

Optimum tip speed ratio

The tip speed ratio which gives C_{Pmax} is also significant in designing small scale VAWTs in that it affects for noise and life of the turbine. High tip speed ratio means high rotational speed and it causes for aerodynamic and structural noise. Furthermore vibrations can be high since unbalanced centrifugal forces develop with rotational speed and it may reduce the life of the turbine. Normally optimum tip speed ratio shifts towards low tip speed values with number of blades.

Torque performance

Consideration of torque performance of the turbine is crucial with respect to the load and transmission system. Normally load can be classified according to the stating torque and variation of torque with respect to the rotational speed. Normally turbine connected with multi pole generator requires low stating torque. Thus it can be seen a convergence with the turbine and the multi pole generator. Most influential dimensionless parameter for the torque characteristic of turbine is solidity. Turbines with one blade and two blades shows low torque characteristics and three bladed turbine gives sufficient torque characteristics for small scale VAWTs.

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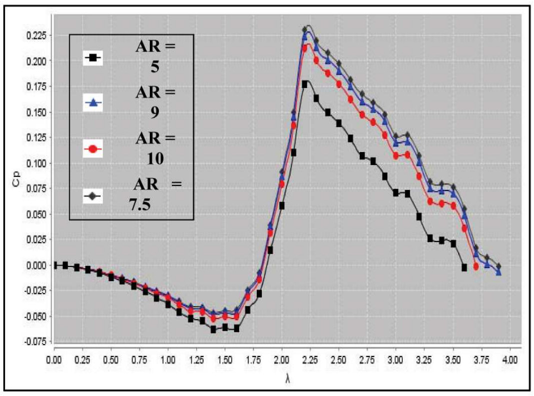

Figure 2 - *The effect of aspect ratio*

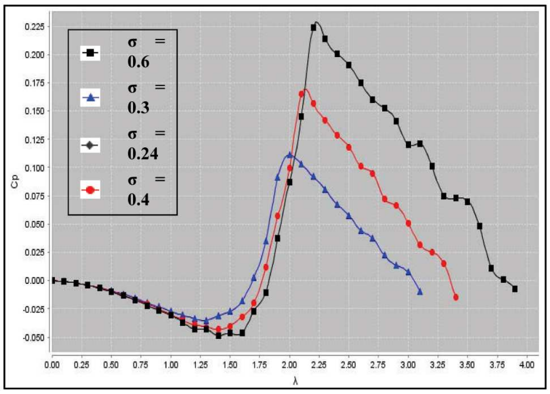

Figure 3 - *Effect of solidity*

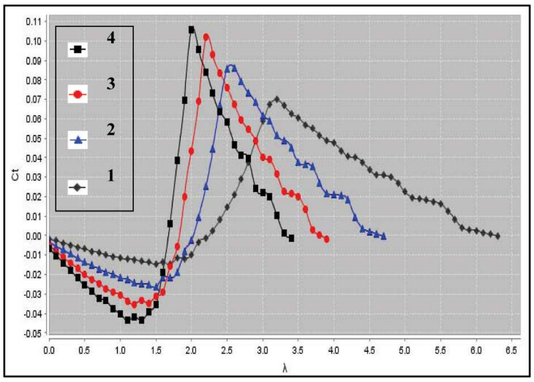

Figure 4 - *Effect of number of blades*

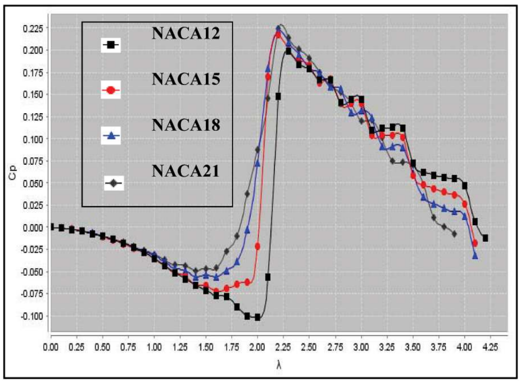

Figure 5 - *Effect of blade profile*

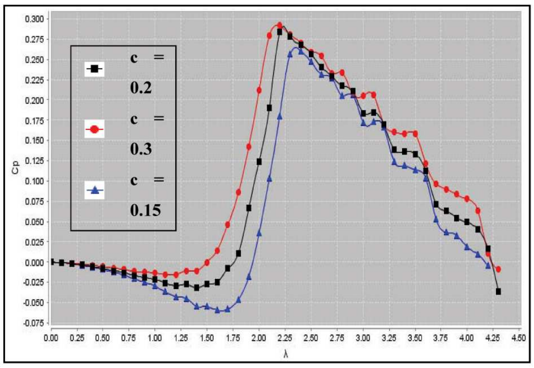

Figure 6- *Effect of Reynolds number*

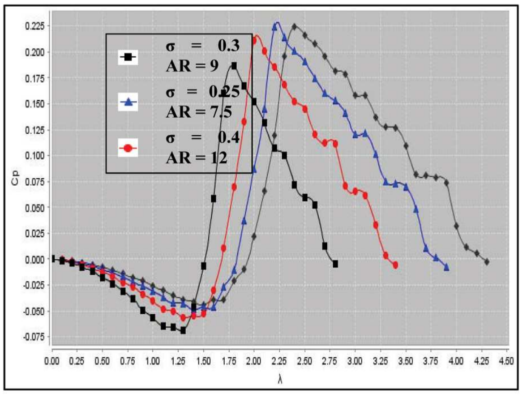

Figure 7 - *Changing aspect ratio while keeping chord length as a constant*