PERFORMANCE EVALUATION OF THE VERTICAL AXIS WIND TURBINE WITH VARIOUS ROTOR GEOMETRIES

Dr. Abdullateef A. Jadallah	Dr. Dhari Y. Mahmoud	Hayder A. Farhan
Assistant professor	Assistant professor	M.Sc. Student; Energy Engineering
University of Technology-Iraq	University of Technology-Iraq	University of Technology-Iraq
dr_abd.allateef@yahoo.com	dhari_yousif1990@yahoo.com	addewanihaider89@yahoo.com

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ABSTRACT:

Performance evaluation of a designed and fabricated vertical axis wind turbine **(VAWT**) are revealed in this work. Six different geometries of the VAWT rotors were designed and manufactured. These geometries are: two straight bladed **(2HB) VAWT**, three straight bladed **(3HB) VAWT**, Savonius rotor **(SI),** Savonius rotor **(SII),** Savonius rotor **(SIII)** and Savonius rotor **(SIIII).** The Blades are manufactured from beech wood using **CNC** machines then they subjected to different processes to improve its aerodynamic performance. Savonius blades are merged with the straight blades rotor to improve the self-starting ability of the **VAWT**. A fan of (0.8 m and 2000 rpm) is installed to blow air with the required speed ranged from (0-12 m/s) A conducting duct is designed and constructed to conduct the flow with reasonable uniformity. All geometries are tested under different operating condition to predict the performance of the designed **VAWT.** Number of blades (**N**), chord length (**c**), radius (**R**), and blade pitch angle (**β**), are studied to evaluate the performance of the **VAWT**. Double multiple stream tube methodology is used to study these parameters. To do so, a computer code written in **Matlab** is built. Results show that the performance is highly affected by the design parameters. Theoretical results are compared with the experimental data. A good agreement is obtained.

Keywords: vertical axis wind turbine; blade design, aerodynamic; DMST, Savonius, Performance coefficient (Cp).

تقييم أدآء التوربين الريحي عمودي المحور بهيكليات دوار مختلفة

د. عبد اللطيف أحمد جاد الله	د. ضاري يوسف محمود	حيدر عبد الكاظم فرحان
أستاذ مساعد	أستاذ مساعد	طالب ماجستير
الجامعة التكنولوجية	الجامعة التكنولوجية	الجامعة التكنولوجية

ملخص

تناول البحث تقييم أدآء توربين ريحي مصمم ومصنع بستة هيكليات وهي بريشتين مستقيمة (2HB), ثلاثة ريش(3HB), وتوربين سافينس بثلاثة هيكليات: تقليدي, بريشتين وبثلاثة ريش. تم تصنيع الريش باستخدام ماكنة ال CNC ووضعت مروحة بقطر 80 سم وسرعة دوران 2000 د/دقيقة لتامين السرع المطلوبة. لايصال الرياح بشكل منتظم تم اضافة منفث.

أختبرت الهيكليات من حيث تأثرها بعدد من المتغيرات الحاكمة مثل عدد الريش, طول الريشة وزاوية الخطوة. أنشئ برنامج بلغة ال **Matlab** لحساب الاداء. قورنت النتائج النظرية والعملية واظهرت تقاربا جيدا.

Nomenclature:

A:	Turbine Swept Area
a:	Interference Factor
c:	Chord Length
C:	Force Coefficients
Cp:	Power Coefficients
Ct:	Torque Coefficient
N:	Blades Number
p:	Pressure
P:	Power
r:	Local Radius
Re_b:	Local Reynolds Number Of The Blade
T:	Torque
V:	Velocity
X:	Tip Speed Ratio
I :	Current
v:	Voltage

Greek symbols

$\Delta\theta$:	Azimuth Angle Change
β:	Pitch angle
α:	Angle Of Attack
θ:	Azimuth Angle
ρ:	Air Density
ω:	The Angular Velocity

Sub-scripts

t:	Tangential
n:	Normal
av:	Average
u:	Up stream
d:	Down stream
o :	Free stream
e :	Equilibrium
R:	Relative

1. INTRODUCTION:

Energy is a fundamental characteristic in the development of the society and growth of economic for any country. The use of wind energy can be traced back thousands of years to many ancient civilizations**.** It has been reported that the Babylonian emperor Hammurabi planned to develop the idea of using wind energy for his ambitious agricultural and irrigation project in the (17^{th}) century **B.C**. Hero of Alexandrian who lived in the (3^{rd}) **B.C**., introduce a horizontal axis wind turbine with four sails which was used to blow an organ **(Gary 2010).** Wind energy is implemented for different functions falling in the range from electrification to water pumping and sailing boats. Small scale wind turbines are used to power homes, small businesses and to meet the energy requirements of villages, cottages, street lightening and telecommunication facilities in remotes locations without access to the grid around the world, especially in developing countries **(Eriksson 2008). (Woods 2013)** developed a **MATLAB** model to study the performance of vertical axis wind and hydrokinetic turbines. Simulation results showed that pitch articulation allowed vertical axis wind turbines to start from rest. The ratio of tip to wind speed was found to increase rapidly, carrying the turbine into very fast rotational velocities. **(Omijeh 2013)** investigated the behavior of a **VAWT** with permanent magnet generator (**PMG**) under low and unsteady wind speed. A **PMG** is modeled and simulated using Matlab. Results obtained showed a good system performance. In addition, the cost of design and the cost of maintenance are reduced, making it economical and affordable. **(A.Y. Qasim 2012)** Designed a **VAWT** with movable vertical location of its vanes. The torque is increased in the left side of the turbine by increasing the drag coefficient in this design, and reduction of the negative torque of the frame that rotated contrary to the wind in another side. Two models of different shapes (flat vane and cavity shape vane), were fabricated. The effect of shape, weight and number of frames on **Cp** was studied in the wind tunnel with variable wind velocity. Results showed that as the drag factor was increased the output power increased too, and the vane type wind turbine can be highly efficient. In cavity shape frame, angular velocity decreases with the increasing of the frames number. **(Mateusz 2012)** designed a generator for a **VAWT** with power rated to 20kW at a wind speed of 10m/s. the designed generator fulfills all specifications such as efficiency above 95%, 20kW output power also it has a relative low amount of hard magnetic material. A Matlab program was built to study the generator performance. **(Abdul Hamid 2012)** presented an experimental investigation to evaluate the performance of two **VAWT**s configurations; straight bladed and curved bladed **VAWT**. The number of blades is also varied as two and three blades. It has been found that the magnitude of drag coefficient increases as the angle of attack increased and the magnitude of lift coefficient decreases as the wind velocity increased. Furthermore, the lift coefficient of curved blade increases and becomes less influenced by the wind velocity for the straight-bladed as the angle of attack was increased. **(Rachman 2013)** presented an experiments investigating **HAWT** and **VAWT** incorporated with rounded shroud devices. The experiment was conducted in a vehicle to simulate the effect of the flow of wind. For the vertical axis turbine, the incorporation of the shroud devices showed that both nozzle and diffuser, has no effect on the performance. This study also presented the discussion for the reasons behind the experimental results related to the condition of the turbine rotation and the wind velocity inside the shroud devices.

(Animesh 2013) reviewed the design and performance of an H Darrieus and combined (Savonius Darrieus) **VAWTs** experimentally. Results showed that the combined (Savonius Darrieus) turbine was the best of all the investigated turbines in terms of **Cp**. Therefore, the combined Savonius Darrieus turbine can be used for small scale applications. **(Brusca 2014)** analyzed the evaluation of turbine **CP** under variable aspect ratios of a straight-bladed **VAWT**. A code based on the Multiple Stream Tube Model was used. It was highlighted that the power coefficient was influenced by both rotor solidity and Reynolds number. **Cp** increases with the increase of Reynolds number of the blades. By analyzing the factors which influence the Reynolds number, it was found that the aspect ratio influences the Reynolds number and as a consequence on **Cp.**

2. DESIGN OF THE SMALL VAWT:

Particularly, from the design aspects straight bladed **VAWT** has a simple geometry because its blades are neither twisted and nor tapered. **VAWT** can release wind from any direction regardless of orientation and it is relatively inexpensive in cost and quiet operation. Studies recorded that **VAWT** can attain a significant efficiency improvement. **VAWT** can work in very unstable wind magnitude and direction this is leading them to be suitable for small scale applications in urban areas, i.e. they can obtain energy if the turbulence is high there **(Brusca 2014).** Moreover, the straight bladed **VAWT** has better self-starting capability than the other **VAWTs (Animesh 2013).** The components of the full scale **VAWT** in **figure (1)** are explained below.

Rotor may be considered as the heart of the wind turbines. Blades have an airfoil cross section and extract wind by a lift force caused by a pressure difference between blade sides. Blades can be made from different materials such as Glass Fiber Reinforced Plastics (**GRP**), Carbon Fiber Reinforced Plastic (**CFRP**), Aluminum, and Wood **(Ahlstr¨om 2004).**

The straight blades were built of solid cross sections of Beech wood using three axes **CNC** machine as shown in **figure (2).** Aluminum sheet plate of 0.9 mm thicknesses was folded around a wooden template cutting to form the desired curvature of Savonius buckets. Savonius turbines operates on the drag force which has the advantages of simple and low cost design, its ability to operate at a high wind speeds due to its low rotational speed operation and having high starting torque which enables to operate at low wind speeds (low cut in speed). This design is combined with straight bladed **VAWT** to improve its starting ability at low wind speed operation field by connecting the Savonius blades to the shaft of the straight bladed **VAWT. Figure (3)** shows the designed rotor geometries.

The necessary accessories like (**PM** generator, gears, battery and other electric components) were provided and are housed at the base of the turbine**.** The **PM** generator was reaches over 12v DC below 150rpm and good for 12 volt batteries charging applications.

3. CALCULATIONS OF THE COEFFICIENT OF PERFORMANCE:

The designed six rotor configurations of the **VAWT** were tested using the constructed duct under different wind speed ranged from 0 to 10 m/sec. Wind velocity (V_o), angular velocity (ω); current (I) and voltage (v) were measured to calculate the experimental **Cp** for the **VAWT**. **Cp** can be calculated as follows:

$$C_p = \frac{P_m}{P_{wind}}$$

Hence it can be written as: (1)

$$C_p = \frac{T\omega}{0.5\,\rho A V_o^3}$$

As the wind turbine is run to specified wind velocity, the current and voltage will be recorded. Thus:

$$P_e = I * v$$

It also may be given as (2)

$$P_e = P_m * \eta$$

$$A = 2 * R * L \qquad (3)$$

The tip speed ratio is a decisive factor especially in the control process of the **VAWTs.** So**,** it may be computed as:

$$X = \omega * \frac{R}{V_o} \qquad (4)$$

This parameter serves in determine the performance coefficient theoretically and is considered in controlling the wind turbine.

4. THEORETICAL ANALYSIS:

Analysis of vertical axis wind turbines is a difficult task because of its geometry and domain of rotation that has multiple terms of flow analysis that affect its performance. Several methodologies are introduced to analyze **VAWT** in order to predict its performance. Each methodology has its advantages and disadvantages.

(Strickland 1975) introduced the multiple stream tube model (**MST**) to analyze **VAWTs** performance. **MST** model is an extension of the single stream tube model (**SST**). **SST** is developed by **(Templin 1974)** based on the disk actuator theory (**DAT**), which is used in horizontal axis wind turbines (**HAWTs**)**.**

The Double Multiple Stream Tube Model (**DMST**) is chosen for the analysis of the **VAWT** with variable interference factor. **DMST** is enclosed to the category of the momentum models. It is based

on the principle of momentum conservation derived from the second law of motion of Newton. **DMST** was introduced by **(Paraschivoiu 2002)** for determining the behavior of **VAWT**s.
DMST uses the **ADT** twice, first for the upstream and then for the downstream part of the rotor. The **DMST VAWT** is treated as a disc that produces a pressure discontinuity in the wind. Wind speed is decelerated because of this pressure discontinuity. This will lead to produce the induced velocities through the rotor.
The velocity is decelerated two times in the two streams, one for the upstream and the other for the downstream.
The reduction in the induced velocities in the axial streamtube leads to the calculation of the induction factors, thus the induced velocity in the upstream part of the rotor (V_u) is:

$$V_u = V_o * a_u \tag{5}$$

Because of the free stream velocity (V_o) is more than the upstream velocity; (a_u) is less than 1. The equilibrium induced velocity (V_e) is in the midst between the upstream and downstream is:

$$V_e = V_o * (2 * a_u - 1) \tag{6}$$

The downstream velocity (V_d) at the downstream part is:

$$V_d = V_e * a_d \tag{7}$$

Interference factor at downstream (a_d) is smaller than that of the up stream part.
Lift and drag forces may be obtained by calculating the induced velocities at every blade position and then, the torque and power coefficient of the turbine can be predicted.
Resultant air velocity (V_{Ru}) depends on (V_u) and the local tip speed ratio (X_u):

$$V_{Ru} = \sqrt{V_u^2[(X_u - (\sin(\theta))^2)^2 + (\cos(\theta)^2)]} \tag{8}$$

For all geometries, the upstream tip speed ratio is inherently got from:

$$X_u = R * \frac{\omega}{V_u} \tag{9}$$

While the local Reynolds number of the blade may be given as:

$$Re_b = \frac{V_{Ru} * c}{K_v} \tag{10}$$

Considering the flow conditions shown in **figure (5),** the normal and tangential coefficients can be calculated:

$$C_t = C_l \sin\alpha - C_d \cos\alpha \tag{11}$$

$$C_n = C_l \sin\alpha + C_d \cos\alpha \tag{12}$$

According to **(Paraschivoiu 2002)**, the up wind flow conditions are specified by the force coefficient $\boldsymbol{f_{up}}$:

$$f_{up} = \frac{N * c}{8 * \pi * R}\int_{-0.5\pi}^{0.5\pi} |\sec\theta| * (C_n * \cos\theta - C_t * \sin\theta)d\theta \qquad (13)$$

The upstream induction factor is:

$$a_u = \frac{\pi}{F_{up} + \pi} \qquad (14)$$

The tangential and normal forces as function of the azimuth angle (θ) may be got easily after determining $C_n$andC_t:

$$F_n(\theta) = 0.5 * \rho * c * L * W^2 * C_n \qquad (15)$$

$$F_t(\theta) = 0.5 * \rho * c * L * W^2 * C_t \qquad (16)$$

The torque produced by a blade for the **VAWT** is computed as follow:

$$T(\theta) = 0.5 * \rho * c * R * L * C_t * W^2 \qquad (17)$$

The upstream average torque is estimated by averaging the contributions torque of each streamtube:

$$T_{av} = \frac{N}{2 * \pi}\int_{-0.5\pi}^{0.5\pi} T(\theta)d\theta \qquad (18)$$

The non-dimensional average torque coefficient $\boldsymbol{C_t}$ is calculated from:

$$Ct_{uav} = \frac{T_{av}}{0.5 * \rho * V_o^2 * S * R} \qquad (19)$$

Finally, the power coefficient of the upstream half $\mathbf{Cp_u}$ is:

$$Cp_u = Ct_{uav} * X \qquad (20)$$

Similarly, the downstream power coefficient **($\boldsymbol{Cp_d}$)** and average torque ($\boldsymbol{Ct_{dav}}$) of the **VAWT** rotor are obtained.
The overall coefficient of power (Cp_t) for the **VAWT** rotor is the summation of the up wind and down wind power coefficients:

$$Cp_t = Cp_u + Cp_d \qquad (21)$$

To compute the above mentioned parameters, a computer code is built in **Matlab**.

5. RESULTS AND DISCUSSION:

A parametric study on the different geometries is presented. The effect of certain parameters such as number of blades, chord length, radius, and blade pitch angle, on the performance of a **VAWT** is studied.
Figure (6) shows the effect of the number of blades **(N)** on the **Cp** of the **VAWT**. As **N** is increased **Cp** increases too. This reveals different starting wind velocities. As the number of blades is increased the inertia of the rotor increases too. This will lead to stable behavior of the rotation rotor and minimize the effect of the turbulence of wind magnitude and direction.

Chord length affects the performance of vertical axis wind turbine. As shown in **figure (7)** chord lengths of (0.09, 0.1 and 0.12 m) are used. As the chord increased, the power coefficient is increased too. This is due to the increase in the lift force that generated by the airfoil section. **Figure (8)** shows the variation of **Cp** for different rotor radii. It is noticed that the power coefficient **Cp** increased accordingly with the increasing of the radius. Effect of the blade pitch angle on the behavior of straight blades H-rotor is presented in **figure (9).** Analysis indicates that the straight-blade H-rotor could generate higher performance at pitch angle of 0. The non-dimensional torque per unit blade span generated at each azimuth angle (**θ**) is shown in **figure (10)** for 10, 15, 20 rpm. Complexity appears when NACA0012 blades stall under steady state flow conditions. For upstream part of the rotational domain, the torque is higher than that of downstream part. This will lead to generate more power in the upstream part.

Variation of the angle of attack with the tip speed ratio for upstream and downstream demonstrated the adversity between them as shown in **figure (11). Figure (12)** and **figure (13)** illustrates the lift and drag coefficient of NACA0012 airfoil profile using **Matlab** code to generalize the value of **Cl** and **Cd** that taken from NACA0012 table.

A comparison between experimental and computed **Cp** for two and three bladed **VAWT** are conducted. A good agreement can be observed between them as shown in **figure (14)** and **figure (15).**

Cp of **SII** is better than that of **SI** because its buckets ability to capture more wind power as shown in **figure (16).** Comparison between **SII** and **SIII** is introduced in **figure (17).** The difference in behavior is due to different in geometry that effects on the rotational speed for the same tip speed ratio. **SIIII** is less efficient than SIII because it has four drag buckets that increased the inertia of the rotating rotor.

Savonius rotor **SII** has the higher value of **Cp** than that of the other geometries. With the wind velocity variation **Cp** increases until velocity reaches a certain value and then it starts decreasing as shown in **figure (19).** The actual produced power by the turbine is extremely lower than theoretical power of the free stream wind as shown in **figure (20).** This is because of the increment in the drag forces of the Savonius buckets. At a certain wind velocity magnitude, reverse drag of Savonius rotor increases too, and the rotor rpm will increase. It will be unable to capture all available power of the wind. This leads to a decrease in the power coefficient.

6. CONCLUSION:

Three bladed **VAWTs** have advantages over two bladed **VAWTs** in some aspects. With three blades **VAWTs** the cyclic variations in the rotor torque and the magnitude and direction of net force due to the combined effects of lift and drag forces on all blades will be reduced. Increasing the chord length leads to increase in **Cp** due to the increase in lift forces. So as the swept area of the rotor is increased, the power extracted will increase dependently and the ratio of the radius of the rotor to blade length is very important factor which affect the power coefficient **Cp** of the **VAWT**. The performance of the **VAWT** was observed to be highly depending on the tip speed ratio. Tip speed ratios affect the behavior and aerodynamics of the blades in accordance of the angle of attack which leads to **Cl** and **Cd** calculations.

High lift value and low drag value mean high performance obtained from the **VAWT** attained from higher lift with minimum drag (i.e. high **L/D** ratio).

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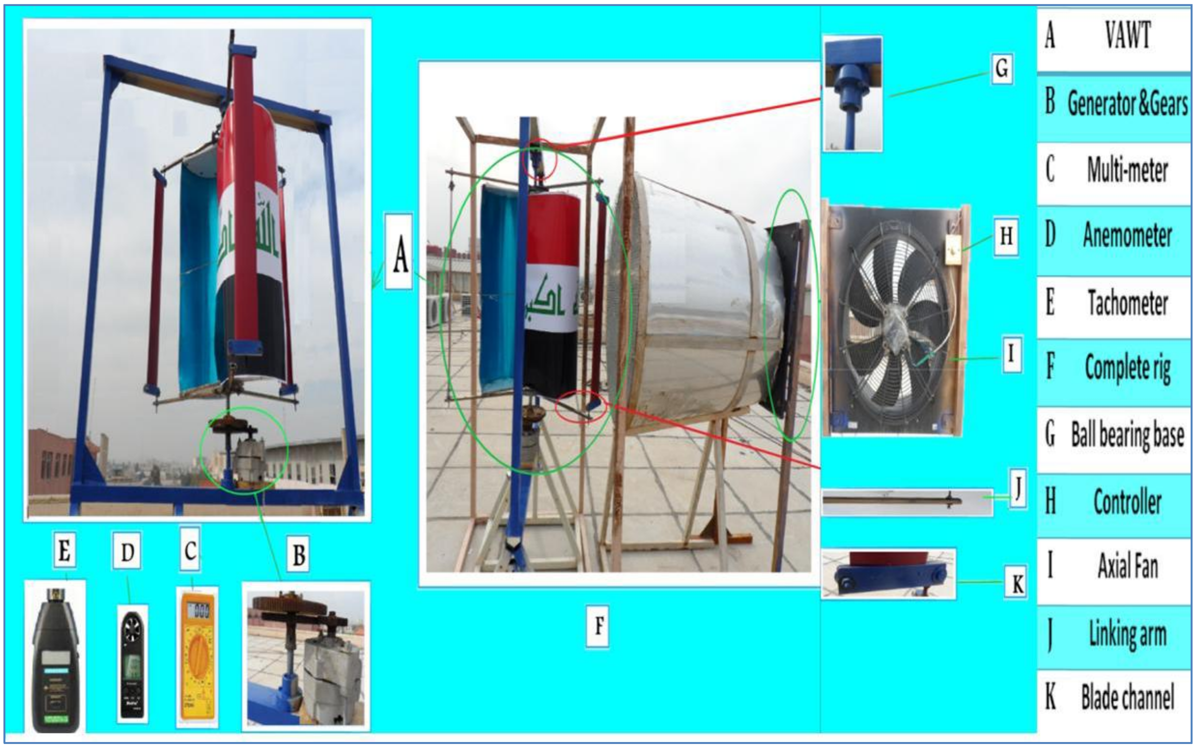


Figure (1): The designed small vertical axis wind turbine

Figure (2) Utilized CNC Machining

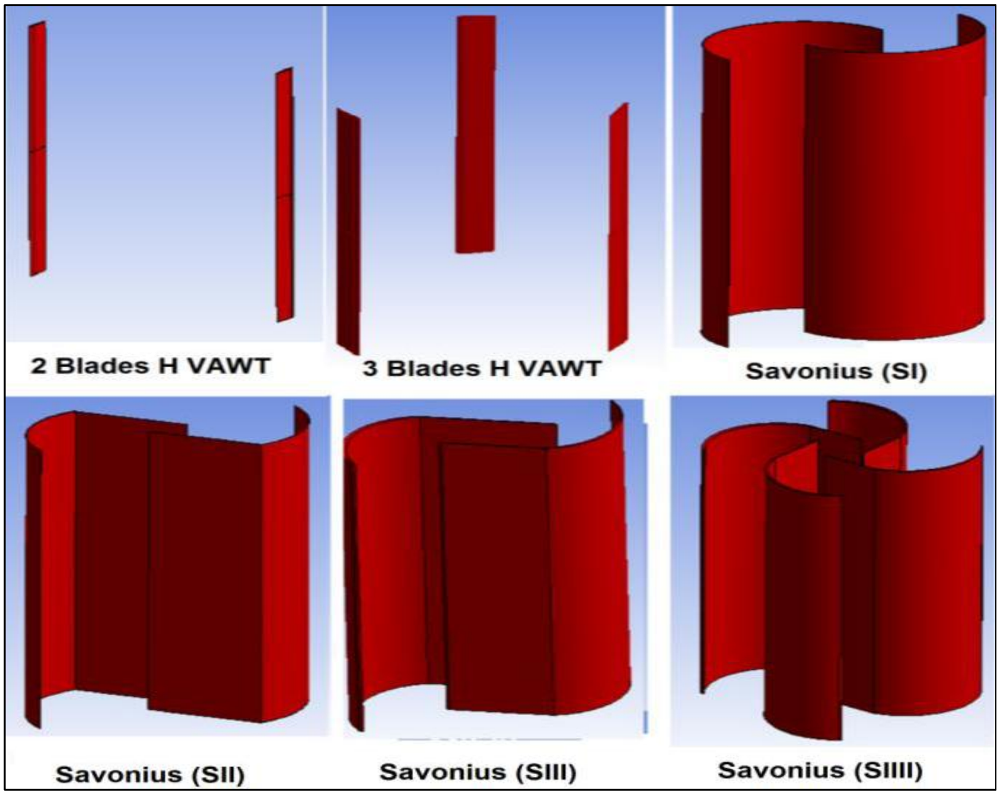


Figure (3) the designed geometries of VAWT rotor

Figure (4) Acecories: the genertor, bearing and Gears

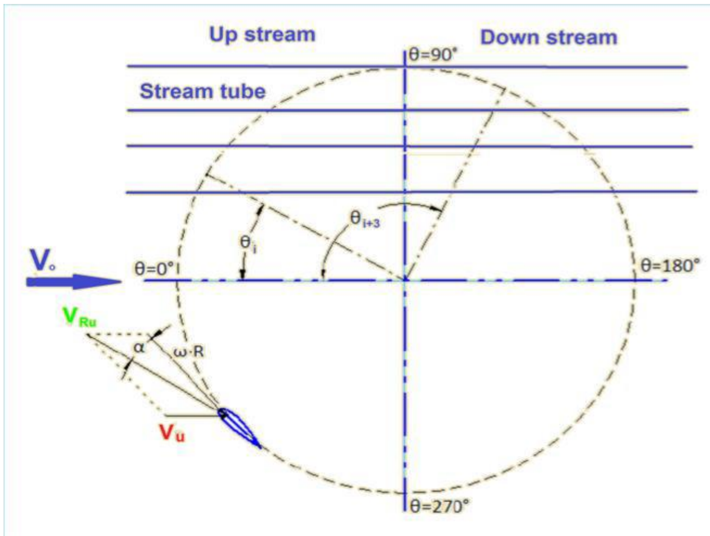


Figure (5) Flow analysis of the DMST [3]

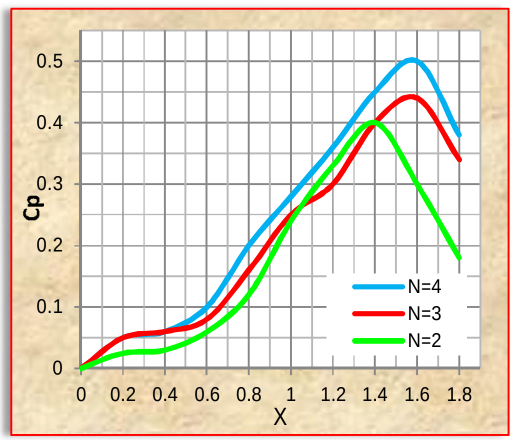


Figure (6) Blade number (N) effect on Cp

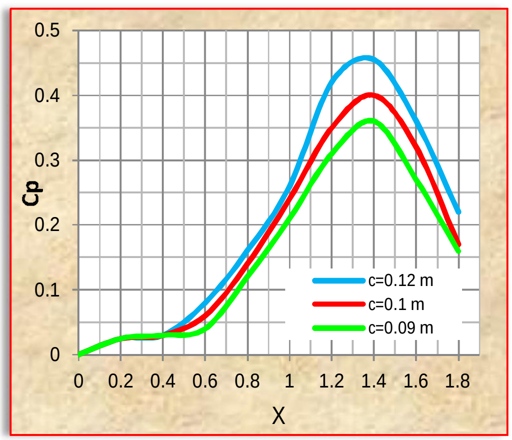


Figure (7) Chord (c) effect on Cp

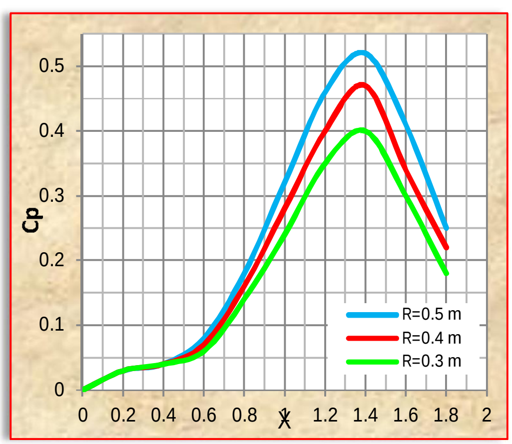


Figure (8) Radius (R) effect on Cp

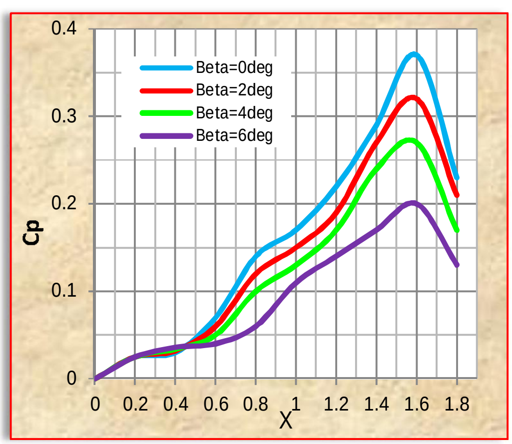


Figure (9) Blade pitch angle (β) Effect on Cp

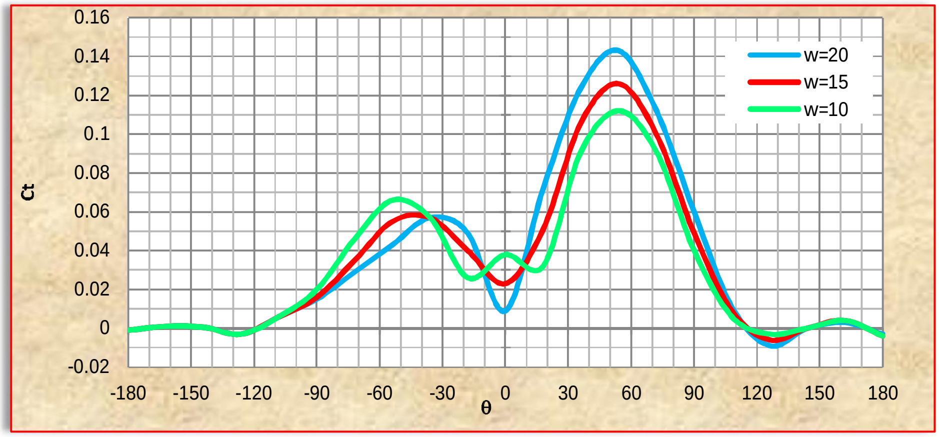


Figure (10) Torque coefficient as a function of blade azimuth angle (θ) for different angular velocity (ω)

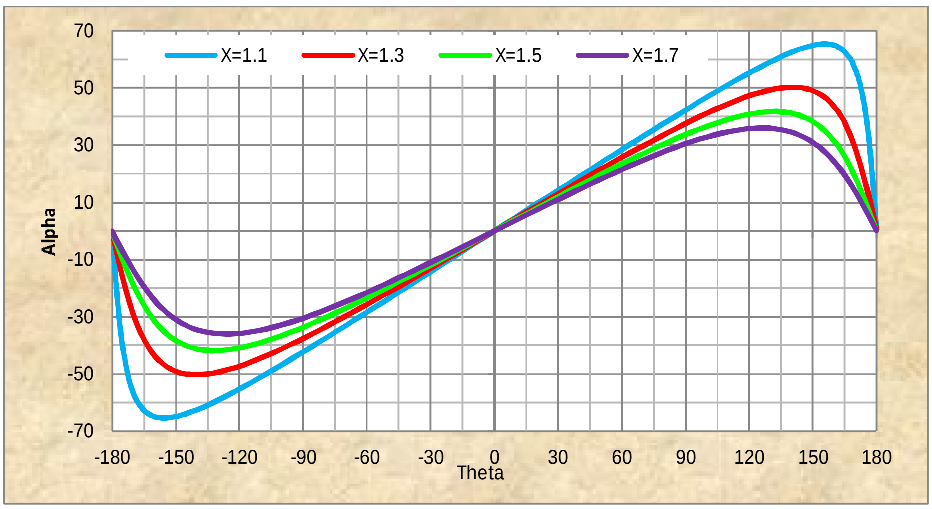


Figure (11) Effect of tip speed ratio on alpha

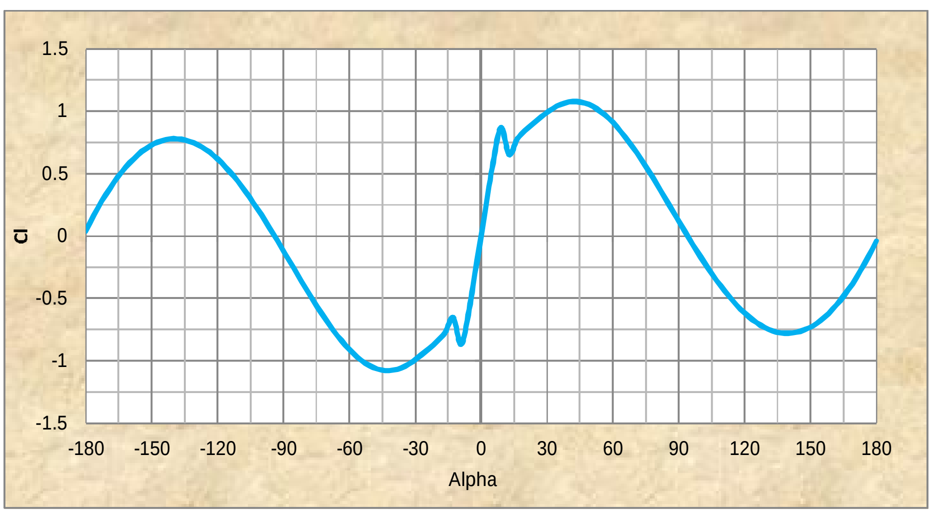


Figure (12) Lift coefficient vs. angle of attack

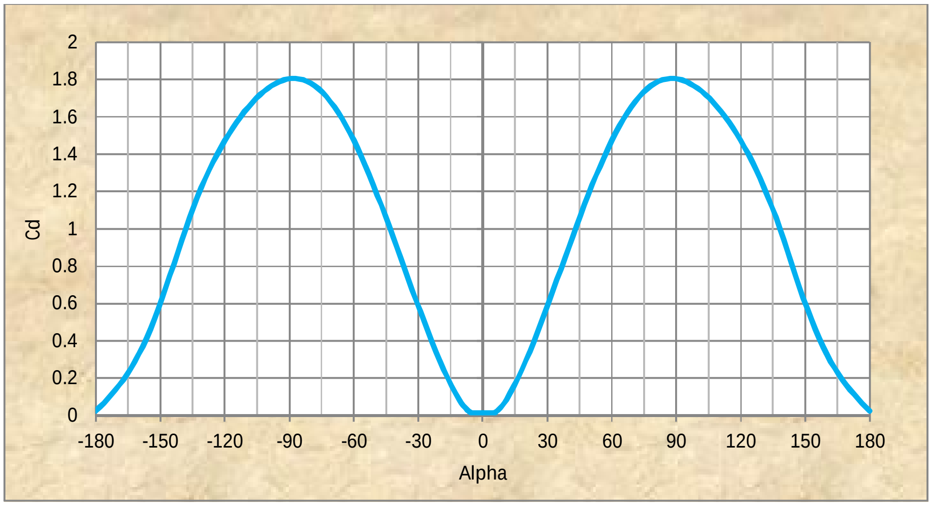
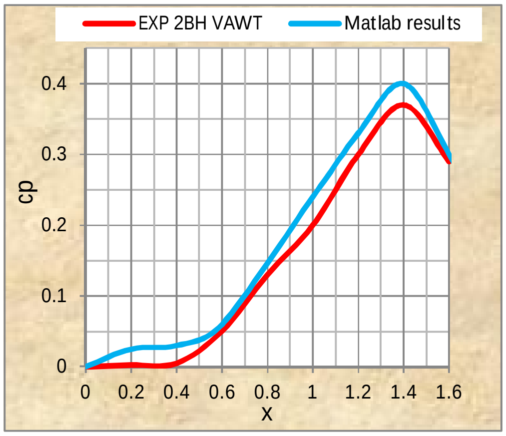


Figure (13) Drag coefficient vs. angle of attack



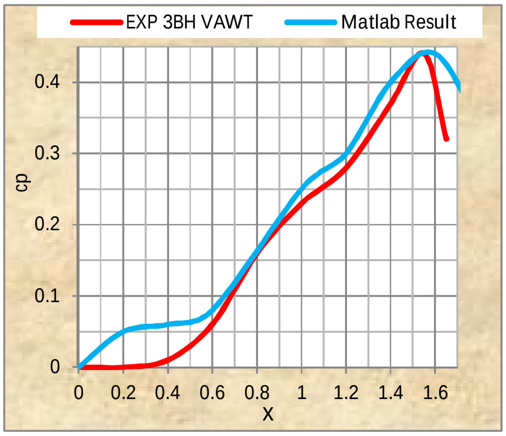
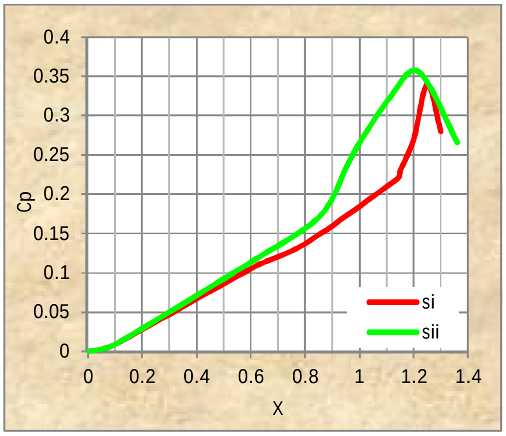


Figure (14) Cp for two blades VAWT Figure (15) Cp for three blades VAWT



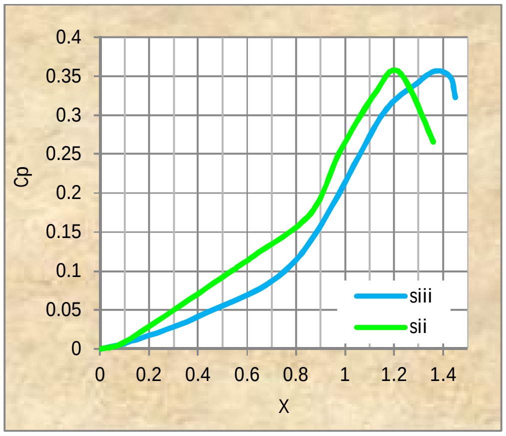


Figure (16) Cp for SI and SII

Figure (17) Cp for SII and SIII

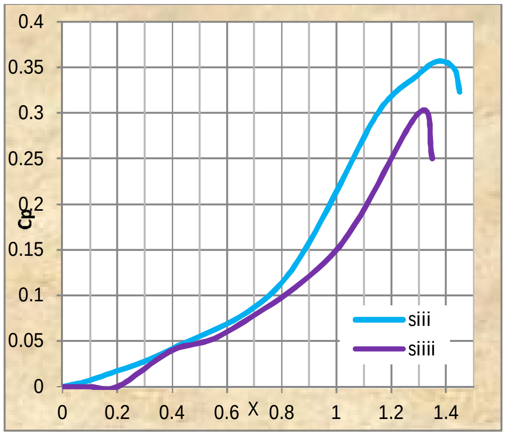


Figure (18) Cp for SIII and SIIII

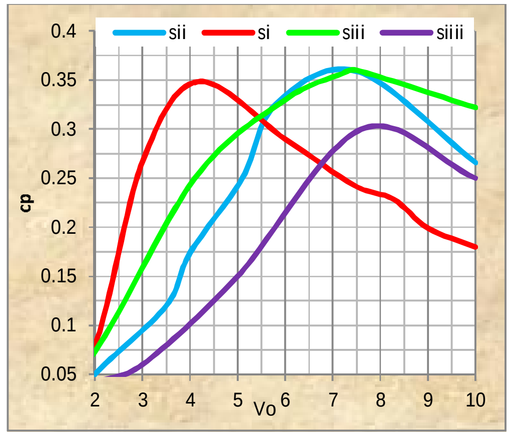


Figure (19) Cp vs wind velocity

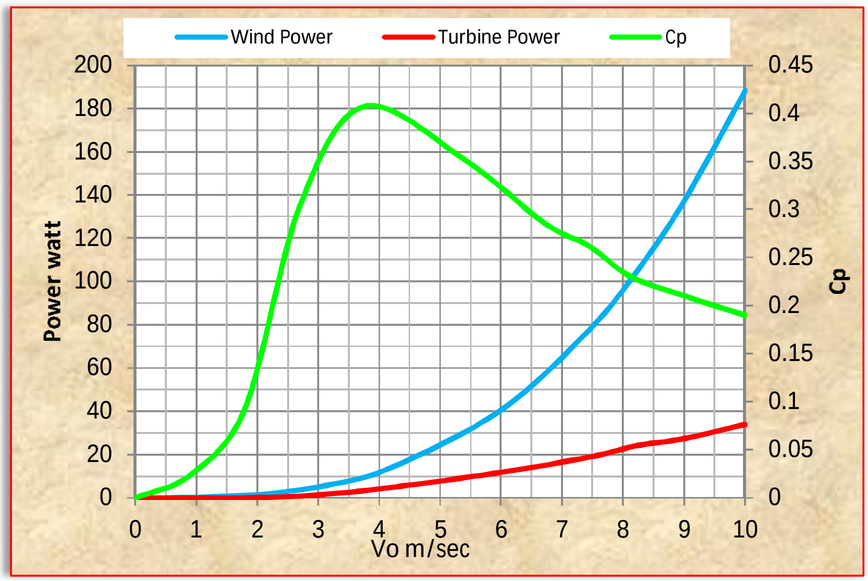


Figure (20) Power of the wind and turbine power for (SI) with three blades