Improvement of Vertical Savonius Wind Turbine Performance

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ABSTRACT

This work presents a study of the vertical Savonuis wind rotor, including design, construct, and test, with a new configuration parameters, to improve its performance.

The new rotor's parameters consist of two stages-four blades (main and secondary). The blades are arranged such that, leaving a separation gap between the inner ends of the blade to get the benefit of the air flow reaction energy in the bucket on the exit side, The secondary stage height equals 1/4 of the rotor height. The blades of the second stages are shifted by 45 degrees from main stage on the same axes.

It is expected that the secondary stage assists the starting of the rotor and prevents the counter torque to appear in the static and dynamic torque cycle.

This Savonius rotor turbine was tested on the subsonic wind tunnel model AF100 made by TecQuipment Ltd., with the range of wind velocities (U=0 to 20 m/s), on no load, it is found that the rotor started rotation at wind velocity of 1.2 m/s. The test of static torque Ts was done under constant velocity of 12 m/s, and dynamic torque T was performed under air velocities of (U=10, 12, 14, 16, and 18 m/s).

Testing results show that the Savonius rotor turbine can start at low wind velocity from any position. The static torque coefficient Cts was improved, with peak to peak value of (17.2 – 39) % in the positive range during cycle of α=180º. The maximum power coefficient approach to (Cp=16% at λ= 0.8). Comparing the performance of this turbine with the others show that the power and torque coefficients are improved.

Keywords: Savonius; VAWT; Wind turbine; Efficiency; power coefficient.

تحسين أداء توربين الهواء العمودي سوفينيس

الخلاصة

اجري هذا البحث لدراسة توربين الهواء العمودي نوع سوفينيس بمواصفات ومحددات تصميم جديدة، وتم بناءه واختباره لتحسين الأداء. أن دوار التوربين الجديد يتكون من مرحلتين (رئيسية ، وثانوية) إذ تحتوي كل مرحلة على أربع ريش، مركبة بوضعية تركت في نهايات الريش الداخلي فجوة تسمح لمرور تيار الهواء من الريشة الأمامية المقابلة للهواء إلى الريشة الخلفية المعاكسة، لغرض الاستفادة من طاقة رد فعل جريان الهواء عند الخروج من الريشة الخلفية. إن ارتفاع المرحلة الثانية يساوي 1/4 ارتفاع التوربين الكلي وان ريش المرحلة الثانية منحرفة عن وضع ريش المرحلة الرئيسية بزاوية 45 درجة على نفس المحور. يتوقع إن تساعد المرحلة الثانية في شروع التوربين في بداية الدوران، وكذلك تمنع حدوث العزم العكسي من الظهور خلال دورة العزم السكوني، والحركي.

اجري اختبار توربين الهواء سوفينيس على جهاز نفق الهواء تحت الصوتي نوع AF100 made by TeQuipment Ltd. تحت مدى سرع هواء من 0 إلى 20 م\ثا، بدون حمل فوجد إن الدوار

بدأ بالشروع بالحركة عند سرعة هواء1.2 م\ثا ، واجري اختبار العزم السكوني على سرعة هواء 12 م\ثا ، واختبار العزم الحركي على سرع الهواء (12،10، 14، 16، 18) م\ثا.
أظهرت نتائج الاختبارات إن توربين الهواء سوفينيس يمكن إن يبدأ الدوران من أي وضع كان وفي سرع الهواء البدية. كما قد ظهر تحسن في معامل أداء العزم السكوني Cts بمدى تتراوح قيمته (17.2 – 39)% وبالاتجاه الموجب خلال زاوية دوران $\alpha=180^{o}$ ، وان أقصى معامل قدرة Cp وصل إلى 16% عند نسبة السرعة الخطية لطرف الريشة $\lambda= 0.6$. وبالمقارنة أداء هذا التوربين مع الآخرين تبين إن معاملا القدرة والعزم قد تحسنت .

INTRODUCTION

The shortage in the storage of conventional fossil fuels has given us the scope to think about their unavailability in the future. Furthermore the environmental pollution mainly caused by using the fossil fuels. Then the usage of this fuel must be reduced or replaced. Renewable energy, especially the wind energy is very good option for this purpose. Among all renewable energies present in the word, the wind energy is known to have the highest potential and is environmentally friendly too. It has been roughly estimated that roughly 10 million MW of energy is continuously available from the earth's wind [1].

The vertical and horizontal wind machines had used to convert the wind energy to power. The simplest of the modern types of the wind energy conversion system is a Savonius wind turbine rotor. This conversation system is very useful for Iraq and Arabian area which are very rich with renewable energy of wind.

Savonius rotor invented by S. J. Savonius in 1929 – 1931, is a kind of drag type vertical axis wind turbine. The basic configuration of this rotor has an "S- shaped " cross- section constructed by two semicircular buckets with small overlap between them, and the principle of operation is based on the difference drag between convex and concave parts of the buckets [1,2].

The Savonius rotor is a vertical machine with high starting torque and reasonable peak power output. It was very efficient in low wind velocity. From the point of aerodynamic efficiency, Savonius wind turbines cannot compete with high – speed propeller and Darrieus type wind turbines. Savonius rotor has a lower power output given size, weight, and cost, thereby making it less efficient, the coefficient of performance is in order of 15%. On the other hand, the savonius rotor is slow running vertical wind machine (λ=1.0) has a rather poor efficiency [3, 4].

O. O. Mojola [5] studied the performance of the Savonius windmill rotor in order to collecting the test data on the speed, torque, and power of the rotor at a large number of wind speeds for each of seven values of the overlap ratio. The performance data of the Savonius rotor are discussed and design criteria established.

Sezai Taskin ET. al. [6] Prepared hybrid system of a solar and wind combined system. A new model Savonius wind turbine was used in their study, the Savonius turbine has three stages deviated at 120 degrees from each other. Savonius turbine performance tests were realized to determine its experimental parameters, and cost optimization and feasibility of combined system were evaluated. According the result of the optimization, optimum numbers for solar panels, wind turbines, and batteries are computed as 16, 5, and 278 respectively for one km highway illumination.

This project investigated the performance improvement of Savonius rotor wind turbine, to collect wind energy and converts it into mechanical power. In this study a new Savonius rotor was designed of two stages in four blades. The design has been developed and its performance in term of rotational speed and output power has been analyzed against wind velocity and compared with another Savonius rotor design.

PARAMETERS OF ROTOR

The parameters used in the design calculation and performance prediction of Savonius rotor wind turbine are as follow [2];

Geometrical parameters of the rotor:

D = Rotor diameter, m
D′= End plate diameter, m
d = Bucket diameter, m
H = Rotor height, m
h = height of each of the two stages, m
e = Rotor over lap, m
e′ = Separation gap between the buckets, m
OL = Rotor overlaps ratio;

$$OL = \frac{e}{D} \quad \dots (1)$$

As = rotor swept area, m^2

$$As = D.H \quad \dots (2)$$

At = Wind tunnel outlet area, m^2
$\beta = Block\ ratio$;

$$\beta = \frac{A_s}{A_t} \quad \dots (3)$$

AR = Aspect ratio of rotor;

$$AR = \frac{H}{D} \quad \dots (4)$$

Ar = Aspect ratio for each stage of rotor;

$$Ar = \frac{h}{D} \quad \dots (5)$$

Aerodynamic parameters:

U = wind velocity, m/s
ρ = Density of air; kg/m^3
n = Rotor speed, RPM
ω = Rotor angular speed rad/s

$$\omega = \frac{2\pi n}{60} \quad \dots (6)$$

λ = Tip speed ratio;

$$\lambda = \frac{\omega D}{2U} \quad \dots (7)$$

Rotor dynamics Parameters

P = Shaft power, W;

$$P = \frac{2\pi nT}{60} \quad \dots (8)$$

T = Dynamic torque, N.m

Ts = Static torque, N.m
Cts = Static torque coefficient

$$Cts = \frac{Ts}{\frac{1}{4}\rho AsDU^2} \qquad \dots (9)$$

Ct = Dynamic torque coefficient;

$$Ct = \frac{T}{\frac{1}{4}\rho AsDU^2} \qquad \dots (10)$$

Cp = Power coefficient;

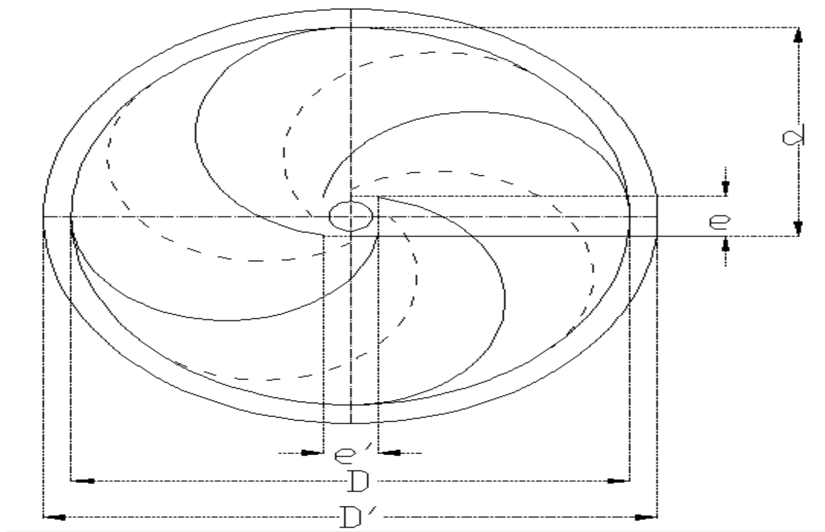
$$Cp = \frac{P}{\frac{1}{2}\rho AsU^3} \qquad \dots (11)$$

EXPERIMENTAL WORK

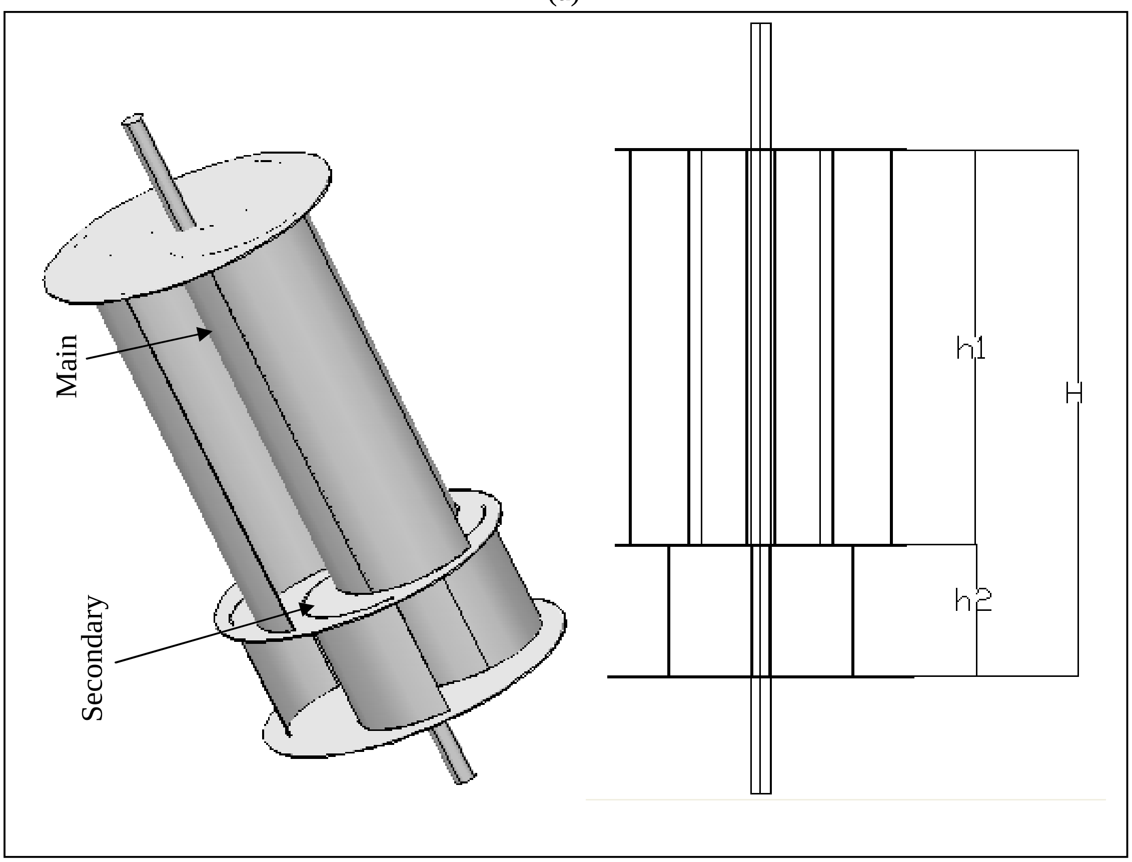
Description of Savonius rotor design

The Savonius rotor studied in this work represents a simple concept that has constructed from two stages (main and secondary) made of thin steel plates, each stage consist of four semicircular buckets blades, as shown in Figure (1).

The rotor has two stages with 45˚buckt phase shift between the adjacent stages, mounted on 10 mm diameter steel shaft. The ends of the rotor shaft are carried by two ball bearings supported on the two side walls of the wind tunnel working area. One end of the rotor shaft is coupled to a friction dynamometer pulley, as illustrated in Figure (2).



(a)



(b)

Figure (1) Savonius wind turbine rotor design.

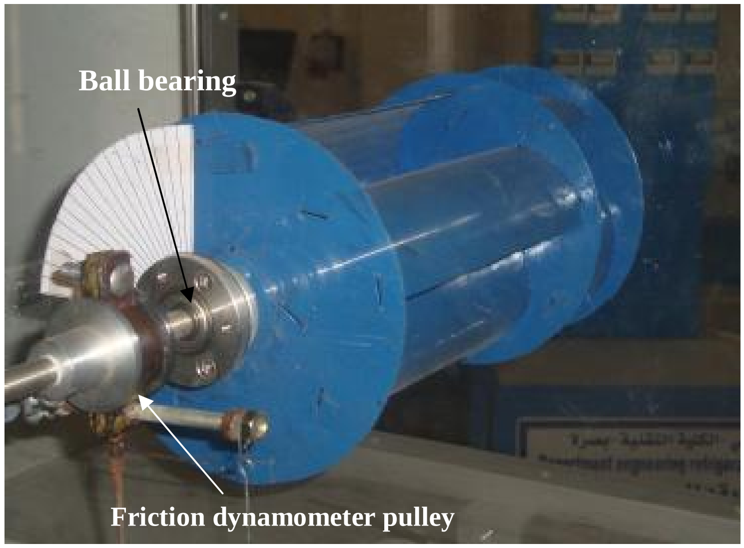


Figure (2) Savonius rotor is mounted in the wind

The whole rotor is turning around vertical axis. The movement is mainly the result of the difference between the drag force in advancing bucket and that in the other one.

In the present study the Savonius rotor was designed and fabricated from straight blade type, and buckets overlap ratio Eq. (1), was selected to be as 0. 2. Because the power coefficient was found by previous studies to be maximum of 0.2 overlap ratio [1, 2, 7, 8, 9].

In order to allow air flow to pass from front bucket to the opposite one, leaving a separation gap at the inner end of blades, to get benefit from the airflow reaction energy in the bucket in the exit way.

The rotor was divided into two stages shown in Figure (1). The main stage received a major amount of wind energy, and converted it into rotating shaft power. The shifting phase of blades in the secondary stage will assist the starting of the rotor.

The rotor was equipped with two end plates, and separating plate between the stages which canalize the flow inside the rotor. The end plates also lead to better hydrodynamic performance. The influence of the diameter of these end plates D' relatives to the diameter of the rotor D has been experimentally studied. The higher value of the power coefficient was obtained for a value of D′ around 10% more than D [7, 9, and 10].

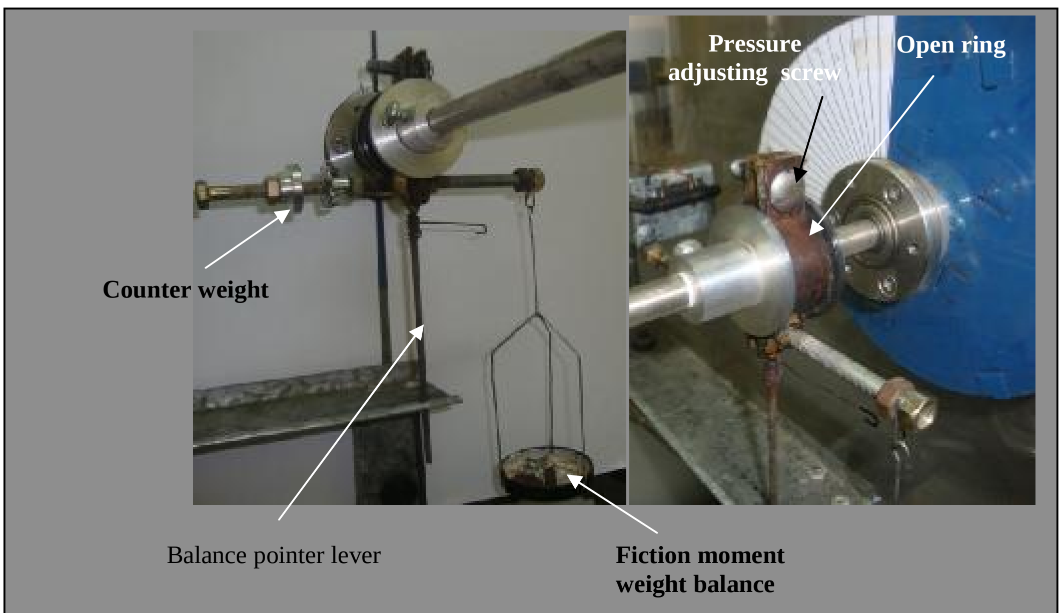
The Aspect Ratio AR is the height of the rotor H divided by its diameter Eq. (4). This is very important parameter for performance of Savonius rotor. In this work, AR was taken as 2, because the value of AR more than 1.0 seems to be improving the efficiency for a conventional Savonius rotor [7, 9, 10]. The parameters of Savonius wind turbine rotor which tested in this study are listed in Table (1).

Table (1) Parameters of Savonius wind turbine rotor.

Parameters	D, mm	D', mm	d, mm	H, mm	h1, mm	h2, mm	e, mm	e', mm	OL	As, m^2	AR
Dimension	130	143	72	260	195	65	14	14	0.20	33800	2.0

FRICTION DYNAMOMETER

Energy produced by the wind turbine is absorbed by friction resistance of dynamometer and transformed it into heat. The dynamometer used in this study is designed and built in the simplest form of an absorption type as shown in Figure (3). It consists of an open ring of the steel plate strip, which cladding by cloth as frictional layer. The pulley of dynamometer is surrounded by the open ring. The pulley is mounted on the end of wind turbine power shaft. The Pressure between open ring and pulley remains constant. A bolt and nut were fixed between two ends of open ring to adjust the pressure as required. The lower part of the open ring has three levers attached to it, one of them carries a weight W at its outer end. The magnitude of the weight can be adjusted so that its moment can balance the moment of friction resistance between the open ring and pulley. A counter weight is placed on the other lever which balances the dynamometer when unloaded by changing the length of lever arm by turning the weight of the screw bolt. A third lever was used as the balance pointer is perpendicular on the past levers moves in the slot are provided to limit the motion of the lever.



Figure(3) Friction dynamometer

Figure(4) Savonius rotor wind tunnel system

TESTING PROCEDURE

The experimental apparatus used in the present investigation is shown in Figure (4). It consists of the rotor assembly and the bearing housing to hold the rotor shaft in the side wall of working section of the wind tunnel. Although the Savonius rotor is a kind of vertical axis wind turbine; Considering the convenience of measurement, the rotor axis were set-up horizontal. The test rotor was placed in the center of the working section of the wind tunnel. The rotor torque was measured by frictional dynamometer located on the shaft as shown in Figure (3). The rotor was tested on the subsonic wind tunnel model AF100 made by TecQuipment Ltd, It's technical data is listed in the Table (2).

Table (2) Technical of the wind tunnel.

Total length of apparatus	3700 mm
Total depth (Front to back)	1065 mm
Total height	1900 mm
Working section	(305x305x600) mm
Air velocity	0 to 36 m/s
Fan motor	AC three phase axial variable speed.

The rotor was operated with a constant wind velocity (U= 10, 12, 14, 16, and 18 m/s) to measure the performance at different speed. The torque was measured during rotation. The digital stroboscope (Tachometer) was used to measure the rotation speed of the rotor.

The rotor shaft was fixed stagnant by the friction dynamometer during the static characteristics measurements by tightening the adjustable pressure bolt and nut to prevent rotation the of rotor. The static torque was measured fixed bucket rotation angle under steady wind speed. This static measurement was repeated every 5 degrees of bucket rotation angle α for a specific condition wind speed of (U= 12 m/s).

All these tests are performed in the Fluid Mechanic Laboratory of Technical College of Basrah.

CALIBRATION OF AIR VELOCITY OF WIND TUNNEL

The wind tunnel air velocity must be calibrating and adjusting at the inlet working section before the experiment is performed. The pitot tube and static wall tapping measure the stagnation pressure and the static pressure at the wall as shown in Figure (5). Referring to Bernoulli's equation, the difference between the stagnation and static pressures gives the dynamic pressure from the velocity can be found.

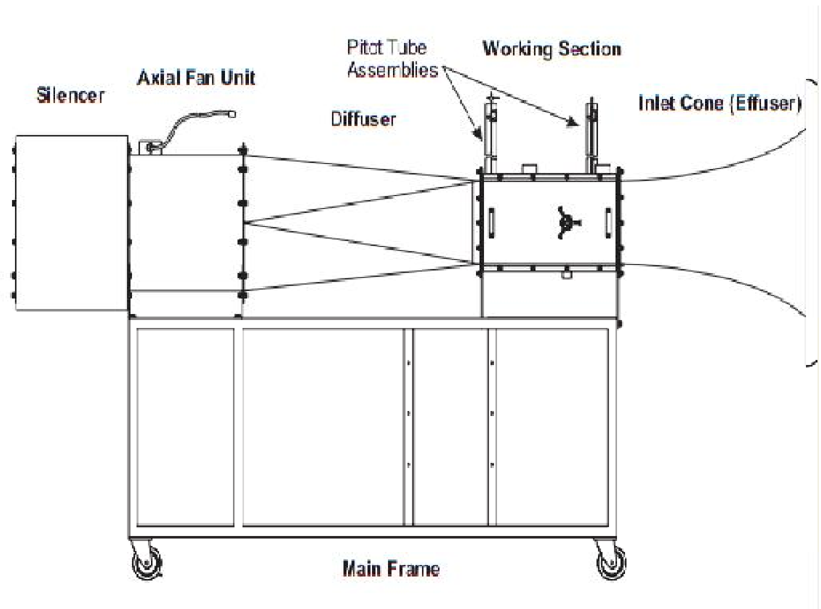


Figure (5) Schematic of wind tunnel.

The velocity at the point of measurement is given by:

$U = \sqrt{\frac{2\times\Delta P\times 9.81}{\rho_a}}$ and $\rho_a = \frac{P_a\times 100}{RT_a}$

Where:

ΔP=Dynamic pressure (mm H_2O)

U=Velocity(m.s^{-1})

ρ_a=Local air density(kg/m^3)

T_a=Ambient air temperature(K)

P_a=Ambient atmospheric pressure (millibar)

R= Gas constant=287m^2/s^2K

To calibrate the air velocity through working section of the wind tunnel, perform the following procedure.

i. Ensure that the Pitot Tube is fitted to the front position (nearest the inlet). Check that the mechanism allows the probe to traverse the inter section.
ii. Connect the pitot tube to the manometer ΔP. Connect the wall tapping to the let limb and the pitot tube to the right limb.
iii. Zero the manometers and take reading of the ambient air temperature and barometric pressure. The position of the pitot tube in the center of the tunnel.
iv. Start the fan and run it at full speed. Take a reading from the manometer. Reduce the fan speed and take another manometer reading. Continue to take manometer reading for a range of fan speeds.
v. Plot a graph of manometer reading versus reference velocity, see Figure(6).

The graph of reference velocity versus manometer reading produce is valid only for the temperature and pressure at time of measurement since the ambient conditions may vary. To produce a more comprehensive graph that can be used at any time, the values should be corrected to account for ambient conditions.

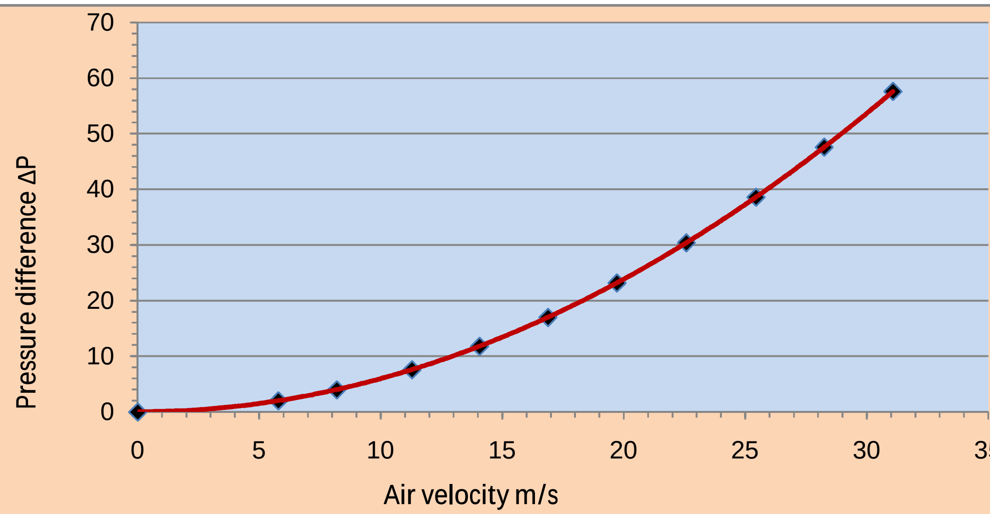


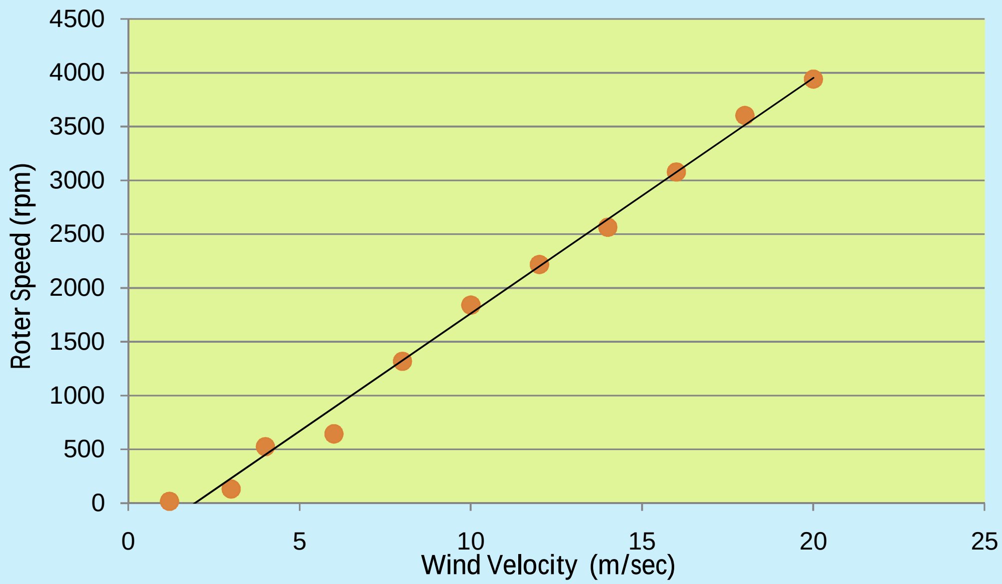
Figure (6)Calibration for air velocity of wind tunnel

RESLUTS AND DISCUSSIONS

Variation of rotor speed with wind velocity

In the tested ranges of wind velocities (U=0 to 20 m/s) on the present rotor with no load, found that the rotor was started rotation at wind velocity of 1.2 m/s. Then the speed increased continuously with increasing wind velocity as shown in Figure (7).

The rotating speed of rotor via the wind velocity has linear proportional behavior until the rotor high speed of 3903 RPM at wind velocity of 20 m/s, the proposed design is very sensitive to the variation wind velocity because of the number of packets which affected by the momentum of the wind stream in the same time.



Figure(7) Rotor speed with wind velocity

Static torque coefficient

The static torque coefficient Cts in Eq. (10) the variable for one revolution of the test rotor at 12 m/s wind velocity has a cycle of 90 degrees according to the buckets number of the Savonius rotor as shown in Figure (8). It is found that the Cts during the 90 degrees has small variation, that was because of the drag difference effect between the convex – concave parts of the buckets in the secondary stage buckets which shifted by angle of 45dgress from main stage buckets, added to the effect of the main stage, so the variation of Cts was minimum in first quarter part of the revolution.

As shown in Figure (8), Cts variation during the rotation degree range of (90 – 180), had large variation, that because of the effect of convex – concave drag difference subtracted from the effect of main stage through the last 45 degrees during the second part of this cycle. This behavior is repeated in the second half for one rotor revolution.

Generally Cts is varied in the range of (0.172 – 0.39), with a difference value of 0.128. It is clear from Figure (8), that all the variations were in the positive range, which help the rotor starting at any position of α. These Cts variations range in this work is better as compared with Cts difference of two bucket one stage Savonius winder rotor and the peak value of Cts in this work is higher than of three stage rotor. The Cts variances obtained from this work were improved compared to the results given by [2]. The peak value of Cts illustrated in Figure (9), is higher when compared with the value of three stages rotor presented by [2].

Figure (8) Static torque coefficient for present rotors in on revolution

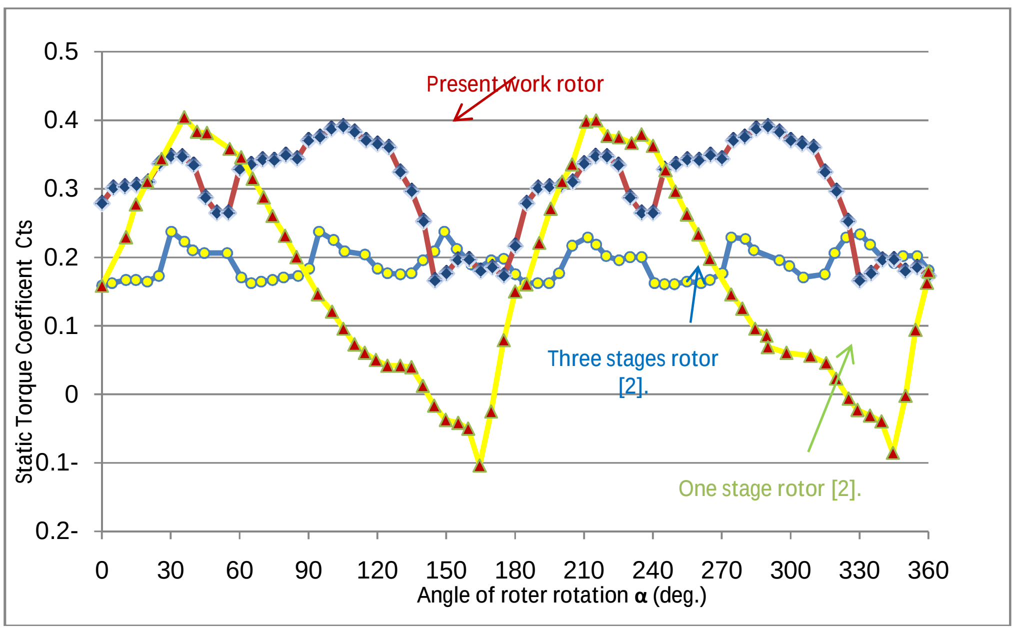


Figure (9) Static torque coefficient for deferent rotors design in on revolution

Dynamic Torque coefficient Ct, Power coefficient Cp

Figure (10) shows the vertical axis as torque coefficient Ct, Eq. (11), of test rotor, where the horizontal axis is the tip speed ratio, and the data measured under wind velocities of U= 10, 12, 14, 16, and 18 m/s respectively.

From Figure (10), the torque coefficient has inverse proportional relation with tip speed ratio, where the Cts value was reduced with increasing of λ. This indicates that the tested rotor can produce high torque under low rotation speed. The Figure (10), shows also the increase of power coefficient Cp, Eq. (2.3.5), with λ. The peck Cp = 0.16 at the tip speed ratio of $\lambda = 0.8$ and maximum Ct = 0.28 at $\lambda = 0.2$. When λ increases more than 0.8 the Cp reduces until λ= 1.02, where at the rotor speed higher than the wind speed in this situation the Cp = Ct.

The performance factors of the Savonius wind turbine tested in this work is illustrated in Figure (10). As the power output increased with increasing of λ, the torque is reduced, therefore the relation of Cp, Ct with respect to λ in the Figure (10) are very useful to predict the wind machine turbine power for field application.

Table (3) shows the performance coefficients of the present rotor values comparing with rotors studied by [2].

Table (3) Performance coefficient of rotor comparing values.

Performance Coef.	Present work rotor	One stage rotor	Three stages rotor	
$Cts_{max.}$	39%	40%	24%	U=12 m/s
$Cts_{(Peck-Peck)}$	(17.2 – 39)%	(-11 – 40)%	(16 – 24)%	
$Cp_{max.}$	16%	16%	11%	$\lambda = 0.8$
Ct	21%	14.5%	17%	
$Ct_{max.}$	28%	24%	16.1%	$\lambda = 0.2$

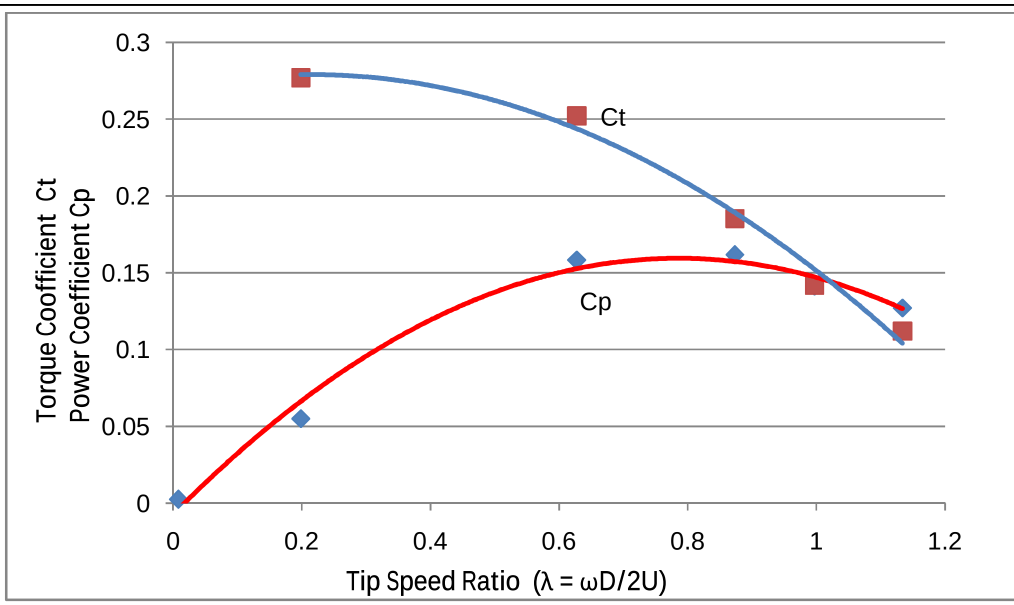


Figure (10) Dynamic Torque Coefficient, Power Coefficient

CONCLUSIONS

From the presents test results of this rotor design it was found that the following performance developments can be presented as follows:

1. The static torque coefficient Cts is improved, with peak to peak value of (17.2 – 39) % in the positive range during cycle of α=180º. So that the rotor had the ability to get started at low wind speed from any position α .
2. The rotor performance has a maximum power coefficient approach to Cp=16% at λ= 0.8. Where the Cp of traditional rotor does not exceed 15%, so the Cp of tests rotor depend on the tip speed ratio. When the rotor operated at a tip speed ratio more than 0.8, produced poor performance.
3. The rotor produced high torque coefficient Ct at low speed, that is useful to operate in tip speed ratio range from 0.6 to 0.8. Because the rotor had highest performance coefficients in this range.
4. The rotor had very good self starting ability at low wind speed velocity with the ability of smooth running, high torque and high RPM.
5. The rotor design in this investigation is suitable for water pumping, electricity generation and could be used with gear train to increase the RPM, because of the high torque at low speed of rotor rotation.

NOMENCLATURE

Sample	Definition	Unit
AR	Aspect ratio of rotor	
Ar	Aspect ratio for each stage of rotor	
As	Rotor swept area	m^2
At	Wind tunnel outlet area	m^2
Cp	Power coefficient	
Ct	Dynamic torque coefficient	
Cts	Static torque coefficient	
D	Rotor diameter	m
d	Bucket diameter	m
D'	End plate diameter	m
e	Rotor over lap	m
e'	Separation gap between the bucket	m
H	Rotor height	m
h	Height of each of two stages	m
n	Rotor speed	RPM
OL	Rotor over lap ratio	
P	Shaft power	W
Pa	Ambient atmospheric pressure	bar
R	Gas constant	m^2/s^2K
T	Dynamic torque	N. m
Ta	Ambient air temperature	K
Ts	Static torque	N. m
U	Wind velocity	m/s
ΔP	Dynamic pressure	mmH_2O
β	Block ratio	
ρ, ρ_a	Air density	Kg/m^3
ω	Rotor angular speed	rad/s

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