DEVELOPMENT OF A RECIPROCATING AEROFOIL WIND ENERGY HARVESTER

By

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A thesis submitted in fulfillment of the full requirements for the degree of

DOCTOR TECHNOLOGIAE: ENGINEERING: MECHANICAL

In the Faculty of Engineering, The Built Environment and Information Technology at the

Nelson Mandela Metropolitan University

December 2008

Promoter

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ABSTRACT

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Cross flow wind turbines are not unique. The performance of Savonius and Darrieus turbines is well documented. Both share the advantage of being able to accept fluid flow from any direction. The Savonius is drag based and hence has poor power output while the Darrieus is lift based. Due to the fact that the Darrieus has fixed blades the fluid flow through the rotor does not result in optimal lift being generated at all points in the rotation circle. A drawback of the Darrieus system is that it has to operate at a high tip-to wind-speed ratio to obtain reasonable performance with the fixed blades. Deviation from a small optimal range of tip speed ratios results in poor performance. The Darrieus also has poor starting torque. The research conducted in this project focused on overcoming the shortcomings of other turbines and developing an effective cross flow turbine capable of good performance. A number of different concepts were experimented with, however all were based on a symmetrical aerofoil presented to the actual relative airflow at an angle that would produce the highest lift force at all times. The lift force was then utilized to generate movement and to do work on an electrical generator. All concepts contemplated were researched to ascertain their appropriateness for the intended application. During development of the final experimental platform and after lodging of a provisional patent (RSA 2007/00927) it was ascertained that the design shared some similarities with an American patent 5503525

dated 28/4/1994. This patent employed complex electronic sensing and control equipment for control of blade angle. This was thought to be overly complex and costly, particularly for small scale wind energy generation applications and a simpler mechanical solution was sought in the design of the final experimental platform used in this project. The design of the mechanical control system was refined in an attempt to make it simpler, more durable and employ the least number of moving parts. Literature studies and patent searches conducted, suggested that the mechanical control system as developed for the final experimental platform was unique. The enormous variation in the power available from the wind at the different wind speeds likely to be encountered by the device necessitated some means of control. In high wind conditions control of the amount of wind power into the device was deemed to be the preferable means of control. A number of different concepts to achieve this were devised and tested. The final concept employed limited the tail angle deflection and hence the lift produced by the aerofoils. This resulted in a seamless “throttle” control allowing the device to be used in any wind strength by adjusting the control to a position that resulted in the device receiving a suitable amount of power from the wind. The outcome of performance tests conducted indicated that the device has the potential to be developed into a viable wind turbine for both small and large scale applications. The ability to control the power input from the wind to the machine from zero to a maximum is considered to be one of the most beneficial outcomes of this project and together with the quiet operation and low speed, are considered the main advantages of the device over existing wind turbine designs. The possibilities of using the device to compress air for energy storage are exciting avenues that warrant further research.

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GLOSSARY OF TERMS

A

Aerofoil – curved surface designed to create lift.

Angle of Attack – angle between the chord line of a wing and the relative airflow.

AC – Alternating current.

B

Bellshion Blades – A type of aerofoil employing upturned tips.

Betz, A – German aerodynamicist who found that an ideal wind machine could extract 16/27 the total power in the wind. (Betz limit / Betz Law).

C

Chord – Distance from leading edge to trailing edge of an aerofoil.

C_L – Coefficient of lift. Non dimensional coefficient used in calculation of lift force of an aerofoil. A function of the wing attitude to the relative airflow.

Critical angle of attack – The angle of attack at which the lift coefficient is a maximum. Any further increase in angle of attack usually results in the aerofoil stalling.

D

Darrieus, GJM – Inventor of the vertical axis Darrieus rotor wind turbine turbine in 1929.

DC – Direct Current.

F

Feathered – Rotation of a blade about its longitudinal axis until the chord line is parallel to the RAF.

H

HAWT – wind turbine employing a horizontal axis rotor, driven by lift forces.

Hellman's Formula – A formula for calculating wind velocity at various heights in the atmosphere using a known velocity at a known height.

HTD – A type of toothed belt whose teeth are semi circular in cross section.

K

Kevlar – light, strong para–aramid synthetic fibre developed by DuPont in 1965 used in composite components and ropes.

L

Laddermill – A concept for a windmill that consists of a long string or loop of kites supported by the lifting force of the kites. The top intended to reach 10000m altitude.

Lift Force – Aerodynamic force created when airflow passes over an aerofoil. The direction of the force is perpendicular to the RAF.

M

Magnus effect – Thrust created by the wind passing over a spinning cylinder. The spinning cylinder acts as an aerofoil.

N

NACA - National committee on aeronautics (USA).

P

Pitchable Tips – Overspeed control mechanism common among early Danish wind turbines where a portion of the blade tip was rotated about its longitudinal axis during overspeed events.

Power Coefficient (Cp) – The quotient of the power extracted by a wind turbine to the power in the wind. A measure of the rotor's aerodynamic efficiency. Also referred to as "coefficient of performance".

R

RAF – The actual airflow experienced by an aerofoil. In the case of a wind turbine blade it is the resultant of the airflow due to rotation and the actual wind. Also known as "apparent wind" or "relative wind".

Reciprocating – motion that regularly reverses its direction.

S

Savonius – Simple drag based device with high starting torque invented by SJ Savonius. Also referred to as S-rotor.

Span – The overall length of the aerofoil in the direction perpendicular to the cross section.

Spoilers – A long narrow panel on the upper surface of an aerofoil that when raised destroys or spoils the lift and increases the drag generated by an aerofoil. Method of overspeed control on wind turbine rotors.

Sprag Clutch – A type of mechanical coupling allowing transfer of torque in one direction only.

Stall – A condition of an aerofoil in which an excessive angle of attack causes separation of the flow over the aerofoil, resulting in loss of lift and an increase in drag. Used in wind turbines for regulating power output.

Symmetrical aerofoil – an aerofoil shape whose cross section is mirrored about the chord line.

T

Teetering hub – Rotor hub that permits 2 blade rotors of HAWT's to move as a rigid body several degrees perpendicular to the plane of rotation.

Tip Brakes – Means of overspeed control incorporating a plate located at the end of a wind turbine blade such that when deployed a dramatic increase in drag is caused.

Tropopause - The border between the troposphere and the stratosphere.

Troposphere – The lowest portion of the earths atmosphere approximately 11km in depth.

TSR – Tip speed ratio. The ratio of the blade tip speed to the wind speed.

V

VAWT – Vertical axis wind turbine. Wind turbine whose rotor spins about a vertical axis.

W

Wortmann – Aerodynamicist after whom the wortmann family of aerofoils is named.

ACKNOWLEDGEMENTS

I wish to thank the following:

- Prof Danie Hattingh for his support, advice and encouragement throughout the duration of the project
- Gideon Gouws for assisting with the manufacture of the final experimental platform
- Stewart Clegg for many hours of assistance with the testing
- Karl du Preez for his support and for arranging some relief from lecturing duties
- My family for the many hours of "family" time that this project has occupied

AUTHOR'S DECLARATION

I declare that this thesis is my own, unaided work. This thesis is submitted for the degree Doctor of Technology (Mechanical Engineering) at the Nelson Mandela Metropolitan University. It has not been submitted before for any degree or examination at any other tertiary institution.

R.L.Phillips

CHAPTER 1

PROJECT SCOPE

1.1 INTRODUCTION

The harvesting of wind energy dates back hundreds of years. The majority of devices used over the years have employed blades rotating on a horizontal shaft. Whilst these devices have proved to be effective, they possess certain inherent limitations and problems. These problems often affect their viability. The aim of this research is to address these problems and develop a wind energy harvester not subject to these problems at all or subject to them to a far lesser degree. The term “viability” in this context will refer to acquisition cost, running cost and acceptance by the community of the proposed system / device.

1.2 PROBLEM STATEMENT

To develop a reciprocating aerofoil wind energy harvester platform and to analyze and compare its feasibility as an alternative method for harvesting wind energy.

Problems associated with conventional horizontal axis wind turbines (HAWT) are:

1) High acquisition costs
2) High maintenance costs
3) Noise (due to high blade tip speed)
4) High frequency shadows – annoyance to community
5) Hazard to birds
6) Unsightly tall structures
7) Poor storm resistance

1.3 SUB-PROBLEMS

The sub problems listed below will be handled in a chronological order and successive steps will only be conducted upon successful completion of previous steps.

The *first step* will be to build a working model/s of the proposed device to ascertain the practicality of the concept. The model/s will be tested in actual wind conditions and their practicality and functionality verified. Changes will be made to the models until they function in a satisfactory manner.

The *second step* will be to establish the force output capacity of the device. Predictions of power output will be made from this based on the envisaged speed of movement. This will be quantified in units similar to those used for conventional horizontal axis turbines. This step will involve theoretical calculations verified by experimentation. An accurate correlation between the two values will be sought and equations derived to simplify future power calculations.

The *third step* will be to develop a reliable means of using the reciprocating motion / force of the aerofoil/s to generate electrical power. The major challenge here will be to accommodate short term wind speed variations (gusts) and the reciprocating motion of the aerofoils and to convert this to a steady rotational speed for the generator/s. The possibility of generating power directly from reciprocating coils passing through a magnetic field will also be investigated as an alternative to conventional alternators employing rotary motion.

The *fourth step* will be to develop a control system for the machine which will allow control under all expected environmental conditions.

The *fifth step* will be the detailed design, development and manufacture of a research platform that will form the basis for evaluating the feasibility of this concept.

The *sixth and final step*

It is envisaged that the research platform will have a power output capacity of approximately 1kW. This platform will be used as an optimization tool for maximizing the power output at various points in the oscillation cycle. Data obtained from this research platform will be used to optimize the design for larger capacity reciprocating aerofoil wind energy harvesters if proven to be feasible.

1.4 HYPOTHESIS

It is envisaged that the proposed reciprocating aerofoil device will compare favourably with current systems in the areas of power output and cost effectiveness. The ratio of power output from the device to the total wind power in the cross section occupied by the device will be used as the basis of comparison when comparing the proposed system to others currently in use.

1.5 METHODOLOGICAL JUSTIFICATION

In order to justify the proposed method of approach the following points are briefly discussed:

- **Experimental Setup and Monitoring**

During testing of the preliminary test model/s certain parameters will be monitored and recorded. Some of these will be:

- Wind speed
- Aerofoil angle of attack
- Force output
- Torque output
- Reciprocating velocity

- **Design of Experiments for accurate data analysis**

Since many of the above parameters are variables and influence each other during the process, it will be necessary to follow the best experimental array/matrix in order to recognize and develop significant correlations.

- **Power output Optimization**

It is envisaged that it will be possible to greatly improve the power output of the system by experimenting with changes in parameters during each oscillation of the aerofoil. The inertia of the reciprocating components and the acceleration and deceleration thereof as well as the angle of attack of the aerofoils will all be variables necessary for consideration. The elastic energy absorbed and released by the aerofoil will also require consideration.

1.6 DELIMITATION OF THE RESEARCH

The following limitations are expected.

- That the size of the final working system be capable of an output of 1 kW. This limitation is imposed due to cost implications. The results obtained however will be such that they can be scaled up for predictions regarding larger systems.
- That the research will only cover one type of mechanical system, namely the proposed reciprocating aerofoil setup – no other types will be researched except for comparative purposes.
- That the only types of power output to be considered will be electrical and hydro. The system may be able to output power via pneumatic or other means but these will not be considered.

It is expected that more limitations will arise as the project develops and these will be addressed when they arise.

1.7 ASSUMPTIONS

It is expected that optimum results will be obtained by operating the aerofoil close to its critical angle of attack for most of the operating stroke with a rapid change to negative angle of attack for the deceleration period and return stroke.

1.8 SIGNIFICANCE OF THE RESEARCH

In certain developed nations wind energy is used on a large scale, however this energy is currently generated at a price higher than that of fossil fuel derived energy. This energy is state subsidised and hence not a viable option for developing nations without the necessary resources for such a subsidy scheme. The proposed research is based on using a unique principle to harness wind energy that could prove to be more cost effective than traditional methods. If this is achieved it could result in wind energy becoming viable even for developing nations.

The proposed system can also be used for desalination of sea water by means of the reverse osmosis process. The reciprocating action of the device (or rotation) can be used to pump water to the high pressure required by the reverse osmosis process.

The NMMU has been involved in a number of alternative energy research projects in the past and this project will help to strengthen this field of expertise.

The research will provide “spin offs” of other associated projects and will generate an alternative research avenue at the NMMU.

CHAPTER 2

OVERVIEW OF ENERGY GENERATION FROM WIND

2.1 EARLY HISTORY OF WIND TURBINES AND WINDMILLS

The first recorded use of windmills was in 900 AD by the ancient Persians. The device used had a vertical axis and force was derived by means of the aerodynamic drag generated by flat plates in the wind[1]

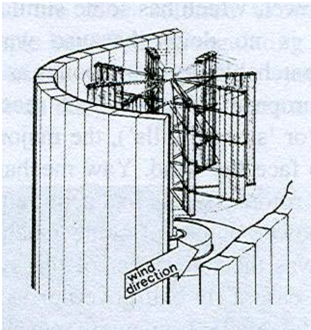

Figure 2.1:Early Persian windmill [1]

Many drag based devices similar in concept to the Persian windmill have been proposed since. Some of these had a vertical axis and some a horizontal axis of rotation. In terms of energy output all of these devices are somewhat limited in that their blades, paddles or cups cannot exceed the wind speed and the wind force on them is as a result of aerodynamic drag and not lift.

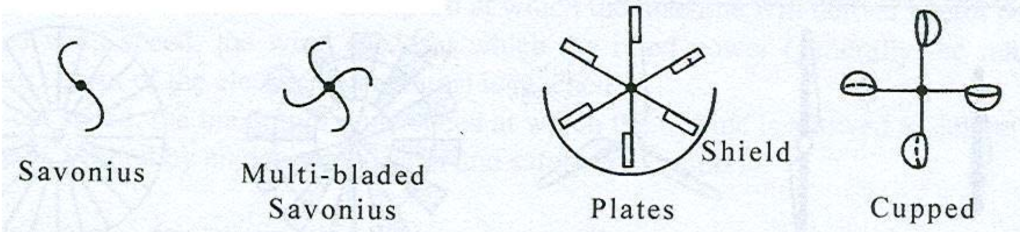

Figure 2.2: Vertical axis drag type windmills [1]

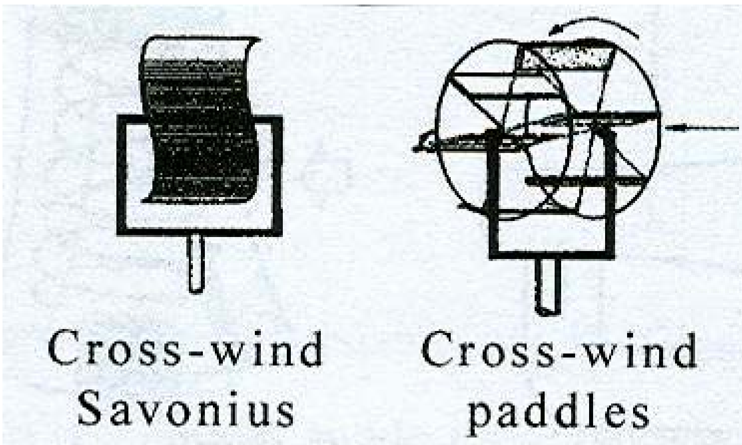

Figure 2.3 Horizontal axis drag type windmills [1]

The first horizontal axis lift based windmills were found in Europe during the Middle Ages. By the time of the Industrial Revolution these windmills had reached a high level of sophistication and some included:

a) Mechanical governors that automatically reduced blade area and hence limited the speed of the windmill in high wind or light load conditions
b) Some blade twist
c) Aerofoil shaped blades
d) Separate yaw rotors that rotated the head of the windmill into the wind

Early research and testing conducted by John Smeaton in the 18th century discovered 3 rules[1]

a) The speed of the blade tips should be ideally proportional to the wind speed
b) The maximum torque produced is proportional to the speed of the wind squared
c) The maximum power is proportional to the speed of the wind cubed

Figure 2.4 Horizontal axis lift type windmill [1]

The “Smock Mill” in Figure 2.4 can be considered to be the forerunner of the modern Horizontal Axis Wind Turbine (HAWT) shown in Figure 2.5. The HAWT is used extensively in many nations for electricity generation.

Figure 2.5 Typical modern HAWT

2.2 ALTERNATIVES TO THE HORIZONTAL AXIS WIND TURBINE

2.2.1 Savonius

Ease of installation, low maintenance and storm tolerance make these attractive when used in remote or inaccessible locations requiring limited power for battery charging or other “non grid” type applications. Their construction is “material / capital intensive”, making them only viable as small scale units. A three stepped, two paddle example is shown in Figure 2.6.

Figure 2.6 Savonius Rotors[2]

According to a technical paper by Menet[3] the optimum geometry for a Savonius rotor should be a 2 paddled, double stepped rotor with end plates which “canalize” the flow inside the rotor. The total height of the rotor should be twice its diameter. Due to the fact that some flow passes between the paddles some lift is generated during a portion of the rotation. This places a well designed Savonius rotor between pure “drag based” machines and “lift based” machines in terms of efficiency. Power coefficients of up to 30% are claimed under ideal conditions.

Number of steps	Number of paddles	End-plates radius R_f	Height of the rotor H	Primary overlap e	Secondary overlap a
2 → ∞	≥ 2	1.1 R	4 R	0.15 d → 0.3 d	0

Table 2.1 Optimal geometry for a Savonius rotor[3]

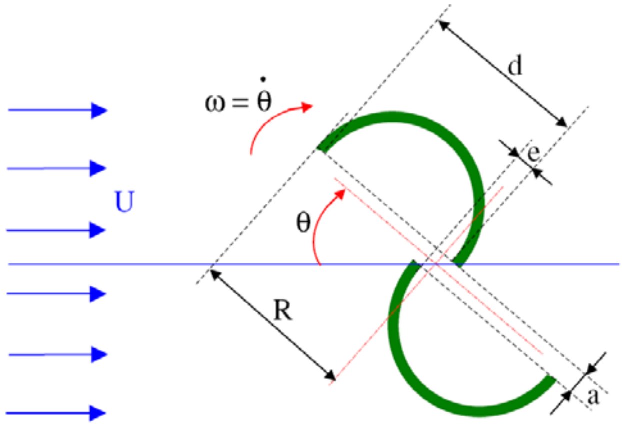

Figure 2.7 Plan view of Savonius paddles[3]

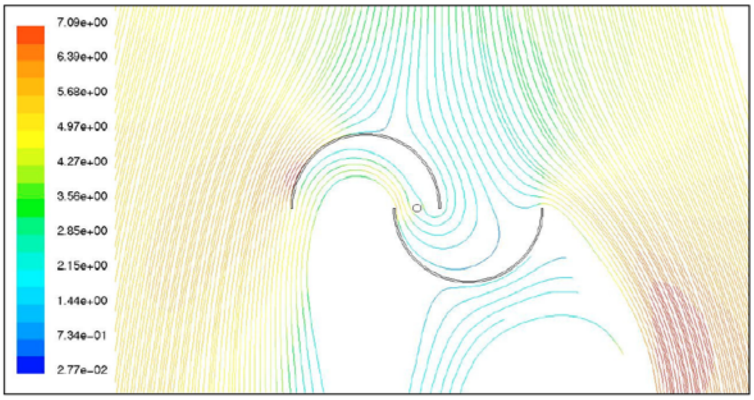

Figure 2.8 Velocity flow field - Savonius paddles[3]

Figure 2.9 shows a velocity flow field simulation by Menet for a Savonius rotor of diameter 0.242m with wind speed of 5m/s.

2.2.2 Madaras and Flettner types

These have revolving cylinders which are mounted on a tracked carriage. The motion of the spinning cylinder causes the carriage to move over a circular track and the carriage wheels to drive an electric generator. Whilst theoretically viable, no large scale units such as these have been installed.

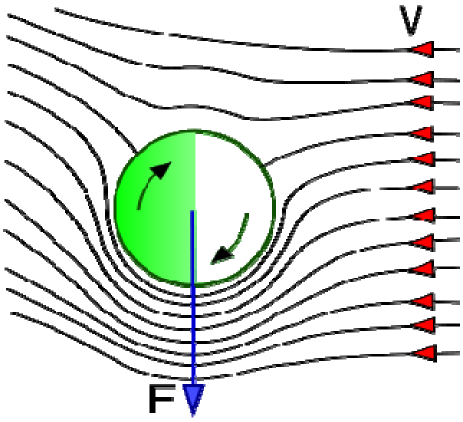

Figure 2.9 Magnus force effect on a rotating cylinder [4]

Equation to determine the Magnus lift force on a rotating cylinder. [4]

$$F = \frac{1}{2}\rho V^2 \, AC_L \qquad (2.1)$$

F = Lift force
ρ = Density of the fluid
V = Velocity of the ball
A = Cross sectional area of ball
C_L = Lift coefficient

The lift coefficient is dependent on the spin ratio[4].

$$S = \frac{\omega \cdot D}{2 \cdot V} \qquad (2.2)$$

S = Spin ratio
ω = Angular velocity of ball or cylinder
D = Diameter of ball or cylinder
V = Linear velocity of ball or cylinder
Typical lift coefficients range from 0.2 to 0.6

2.2.3 Kites

The recent introduction of the sport of kite surfing has resulted in development of "power kites". These are now capable of generating large forces[5] and being controllable through a large angle in relation to the wind – both in the vertical and lateral planes. Another advantage is dynamic sheeting, or the ability to fly patterns in the sky[6] to maintain relative winds at the kite that are several times stronger than the wind on the surface. The wind energy extracted is not so much a function of the kite area, but the entire disc area swept by the kite. In 1981 a 67m freight ship the “Mini Lace” was fitted with a 300m^2 kite sail. Tests on this ship and others revealed that the power from kite sails in comparison to conventional ship sails could be as much as 10 times more. Concepts for harnessing the force from such kites and utilising it for generation of power have been made but as yet no viable solutions are known to be in operation.

2.2.4 Darrieus rotor

The Darrieus concept[7] is one of a high-speed vertical-axis windmill with relatively long, thin, curved blades, which rotate with a tip speed greater than 4 times the wind speed (tip speed ratio). They typically have a low starting torque. The advantages to a Darrieus-windmill are that it can deliver mechanical power at ground level. The generator, gearbox, and turbine components are on the ground, instead of at the top of a tower as in horizontal-axis windmills. The Darrieus rotor is currently one of the few viable alternatives to the HAWT and at one time represented 5% of the installed wind energy in California[8]. The Darrieus rotor shown in Figure 2.10 is of the “phi” or “eggbeater” type with curved blades. Darrieus rotors with straight blades as shown in Figure 2.11 are sometimes referred to as “Giromills” or “Cycloturbines”.

Figure 2.10 Darrieus (phi) windmill [7]

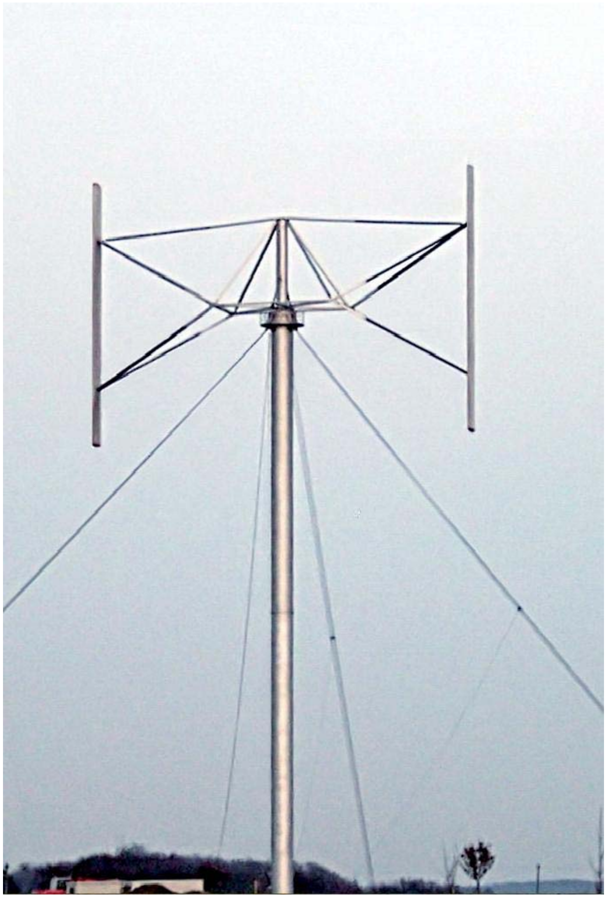

Figure 2.11 Straight blade Darrieus or Giromill[7]

2.3 WIND INDUSTRY GROWTH

Over the past 25 years the size of the largest commercial wind turbines has increased from approximately 50kW to 2MW.[1]

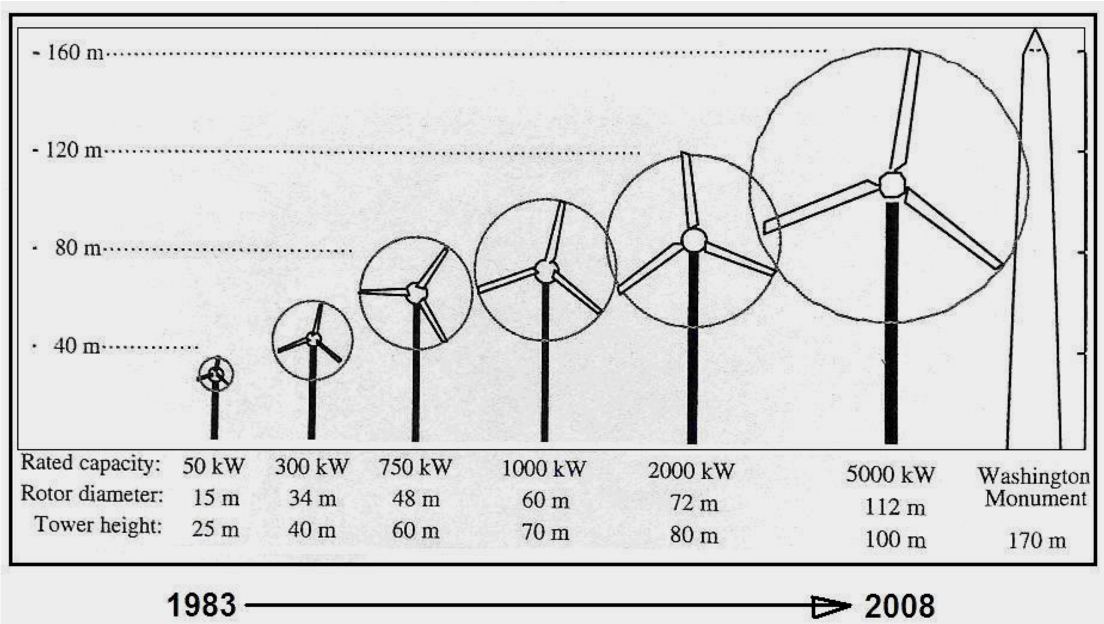

Figure 2.12 Size of the largest commercial horizontal axis wind turbines

The size of horizontal axis wind turbines is unlikely to exceed 5-10 MW as growth beyond this size becomes uneconomical. For wind energy to become a meaningful substitute for fossil fuel derived energy there will however have to be further significant growth. The current growth trend is unlikely to ever achieve more than 20% of the total energy consumption of the USA unless there is a major breakthrough in wind technology. HAWT's require a high mast. Mast heights have reached 100m and are not likely to increase much beyond this due to structural and economic limitations. Using Hellman's equation (2.3) and a 10m height wind speed of 4.73m/s the increase in wind speed up to 200m is as shown in Figure 2.13. The power available per m^2 is shown in Figure 2.14.

$$V_h = V_{10}(0.233 + 0.656\log(h + 4.75)) \quad (2.3)$$

h = height in metres

V_{10} = velocity at 10 metre height in m/s

V_h = calculated velocity at height h

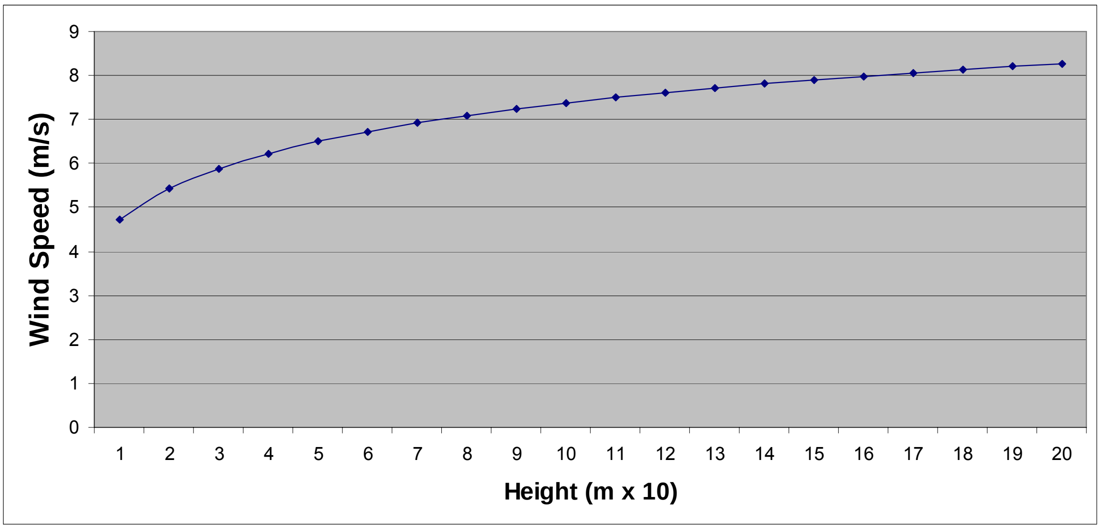

Figure 2.13 Increase in wind speed with height

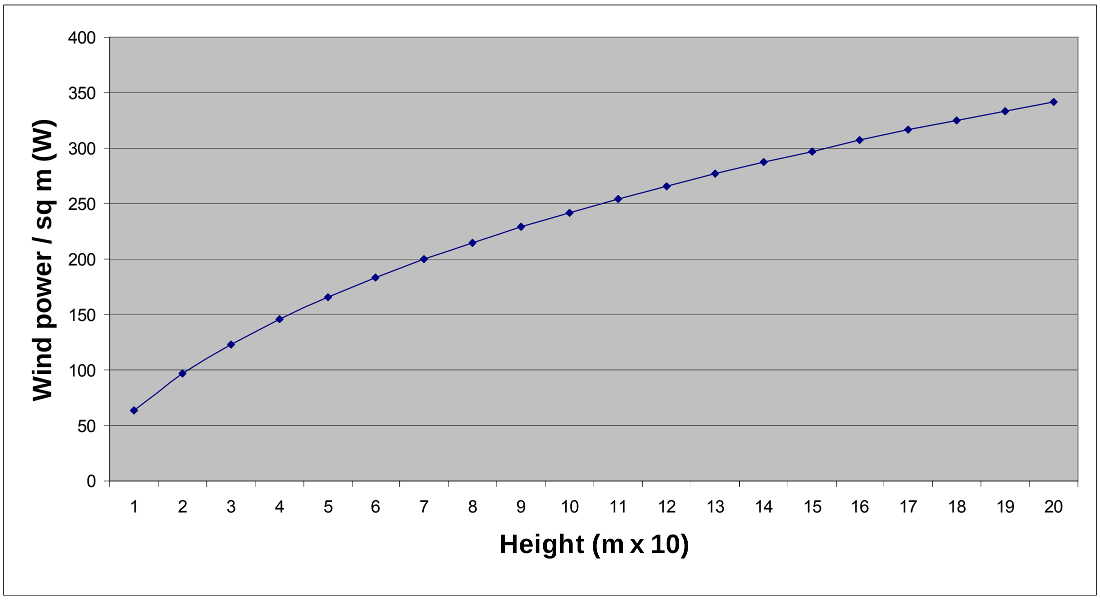

Figure 2.14 Increase in wind power with height

It can be seen that the increase in available wind power grows significantly with altitude. It is reasonable to assume that a device which can exploit this high energy wind without the need for a mast could possibly offer a major breakthrough.

2.4 EXPLOITING HIGH ALTITUDE WIND WITHOUT A MAST

A number of concepts exist which aim to harness high altitude wind without the need for any significant vertical structure. All share a common principle of lifting a type of wind machine to high altitude by means of:

- lighter than air lifting body (helium balloons)[9]

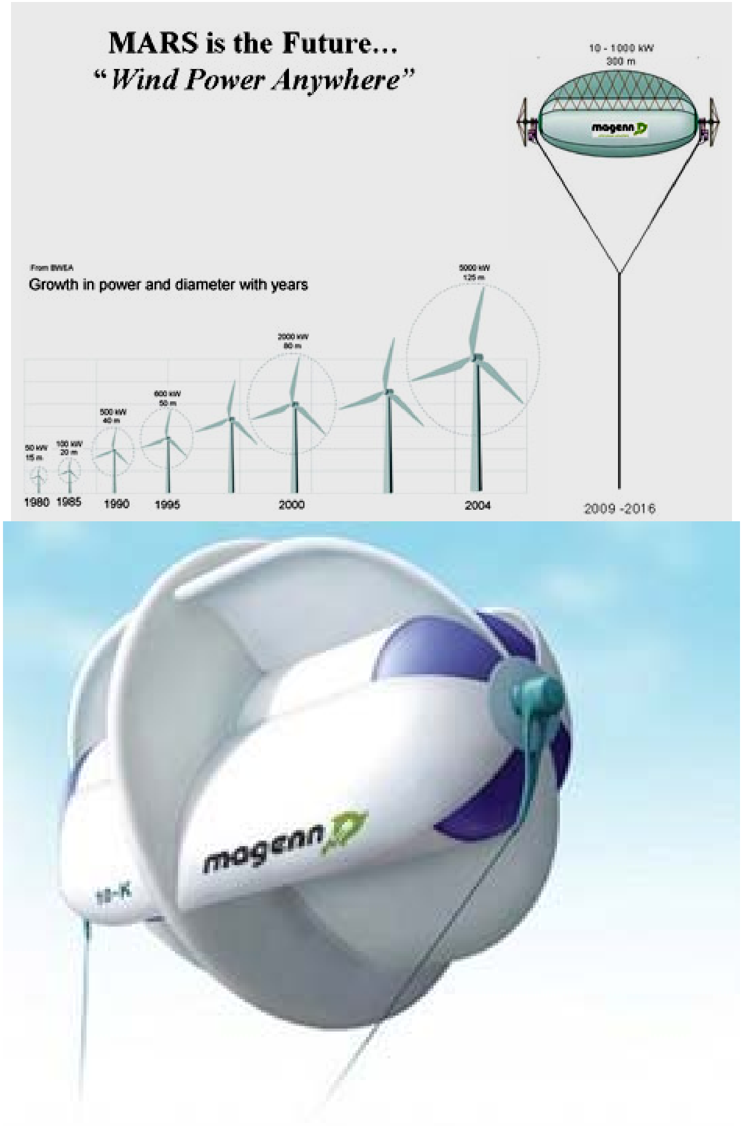

Figure 2.15 Magenn - lighter than air device

- lift producing rigid aerofoils
- non rigid aerofoils (kites)[5,6]

The wind machine then drives a generator which is either also lifted to altitude or remains on the ground. Review of these concepts drew the following conclusions:

- The wind energy is extracted by means of a drag based machine which is unlikely to produce viable amounts of electricity even though it is positioned in high velocity airflow.

- The mass of the generating equipment is a limitation, particularly on large scale units.
- Safety concerns. In the event of a cable failure or sudden loss of wind there exists a potential danger on the ground for loss and injury. It follows therefore that whatever is lifted off the ground should be of lightweight construction and preferably non-rigid.
- The generating equipment should ideally be positioned at ground level with just the wind generating mechanism raised into the high velocity airflow.

2.4.1 Adapted kite concept

Using modern power kites it may be a possible to harness wind energy at altitudes of up to 350m. The growth of the sport of kite surfing has in the last few years resulted in significant advances being made in the field of “power kites”. In the last 2 years kites have been developed which are fully “de-powerable”. Such kites offer greater control of the angle of attack of their aerofoil than previous kites and in so doing are able to regulate their lift force from zero to a maximum. This control is achieved by means of lines to the “power bar” which is held by the operator. Differential control between the left and right lines results in full directional control of the kite. Larger versions of such non-rigid lifting devices have the potential of producing a very large tensile force in the tethering cables. The kite structure has also been improved significantly with the addition of high pressure inflated compression spars allowing for larger spans and more accurate aerofoil sections. Power cannot be generated from a static tensile force unless there is motion of the applied force. Power output is a product of the magnitude of the force and the velocity of motion. A possible way of achieving such motion may be as depicted in Figure 2.16.

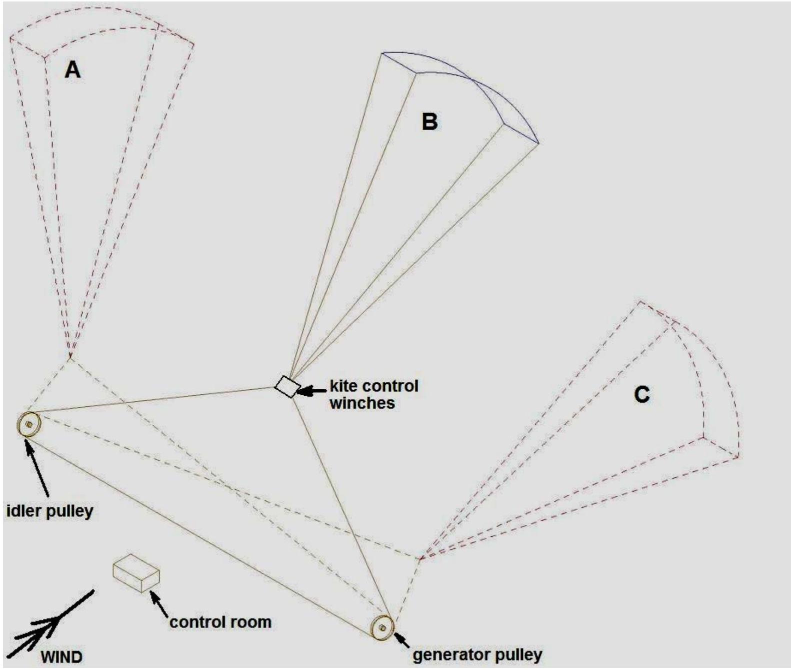

Figure 2.16 High altitude kite concept

The kite (or stacked kites) would be controlled via radio controlled winches run by servo motors. A human controller (kite flyer) would fly the kite/s from a control room positioned with unrestricted view of the kite in all expected positions. The kite would be flown in a pattern which would produce the largest force and highest rotational velocity of the generator pulley. This would more than likely be some form of "figure of eight" path between A and C. This flight pattern is also referred to as dynamic sheeting. The kite lines would ideally be made of kevlar which offers a high strength to weight ratio. The height attained by the kite/s at the highest point in their flight path could be 350m or more. Wind speed data obtained at 10m altitude from the Port Elizabeth weather office[10] for 2006 was converted using Hellman's formula[12] to that expected at 350m altitude. The average annual wind speed at 350m altitude was 9.01m/s. Skilled kite flyers could increase the average speed[6] over the surface of the kite by a factor of 2. The average wind speed over the kite aerofoil could therefore be as much as 18m/s. According to Abbot[12,] the lifting force of the kite could be calculated as follows:

$$F = C_L \frac{1}{2} \rho V^2 A \qquad (2.3)$$

F Lift force (N)

A Aerfoil area (m^2)

C_L Coefficient of lift

V Wind velocity (m/s)

ρ Air density (kg/m^3)

Assuming a conservative lift coefficient of 0.8; kite area of $60m^2$ and ρ = 1.208 kg/m^3

$$F = 0.5 \times 1.208 \times (18)^2 \times 0.8 \times 60$$

$$= 9393N$$

2.4.2 Laddermill

This was a concept developed for harnessing high altitude wind (up to 10km altitude). According to Ockels[13] data from the Dutch Meteorological Institute gathered between 1951 and 1980 indicated that average wind speeds in the troposphere up to the tropopause increased almost linearly with altitude. This trend stopped at approximately 10km altitude. At what is considered to be the maximum practical tower height of a windmill (100m) the power available per m^2 is one sixth of that available at 1000m[14]. Using the 100m reference the power at 5000m is 17 times greater and at 10000m is 30 times greater. The average power density from ground level to 10km is 2.5 kW/m^2 meaning that for a 1km width there is 25 GW of energy available in the troposphere. The Laddermill (Netherlands patent 1004508 1996) aims to extract some of this energy by means of multiple horizontal aerofoils connected to an endless belt rising from the ground to high altitude. The endless belt would run a generator at ground level. The system would be self supporting without the need for any towers. Research conducted indicates that with this device power could be extracted from the wind with a lower acquisition cost and environmental impact than existing horizontal axis wind turbines.

2.5 OPTIMISATION OF LARGE HORIZONTAL AXIS TURBINE EFFICIENCY

More than 95% of large scale wind generators currently installed are HAWT's. Extracting the maximum possible energy[15] from these machines forms the basis of most current wind energy research reviewed. A method of increasing the power output of a HAWT[16] would be to increase the tip speed above the 75 m/s considered to be the current commercial maximum for three bladed turbines. A means of achieving this is proposed to be the use of a two bladed turbine with slender blades attached to a teetering head. The use of the teetering head would reduce bending loads on the blades and allow for larger diameters and hence tip speeds. The operation at higher tip speeds (up to 90m/s proposed) would allow for more power to be produced at a given torque. This would make the turbine more cost effective in terms of power output to acquisition cost. The drawback of such high tip speeds would be noise. Such turbines would therefore probably only be feasible offshore.

According to Johnson[17] the relative performance between various types of wind turbine are as shown in Figure 2.17. It can be seen that the high speed 2 bladed type described above is the type that comes closest to the Betz maximum of 59% power coefficient albeit with a very high tip speed ratio.

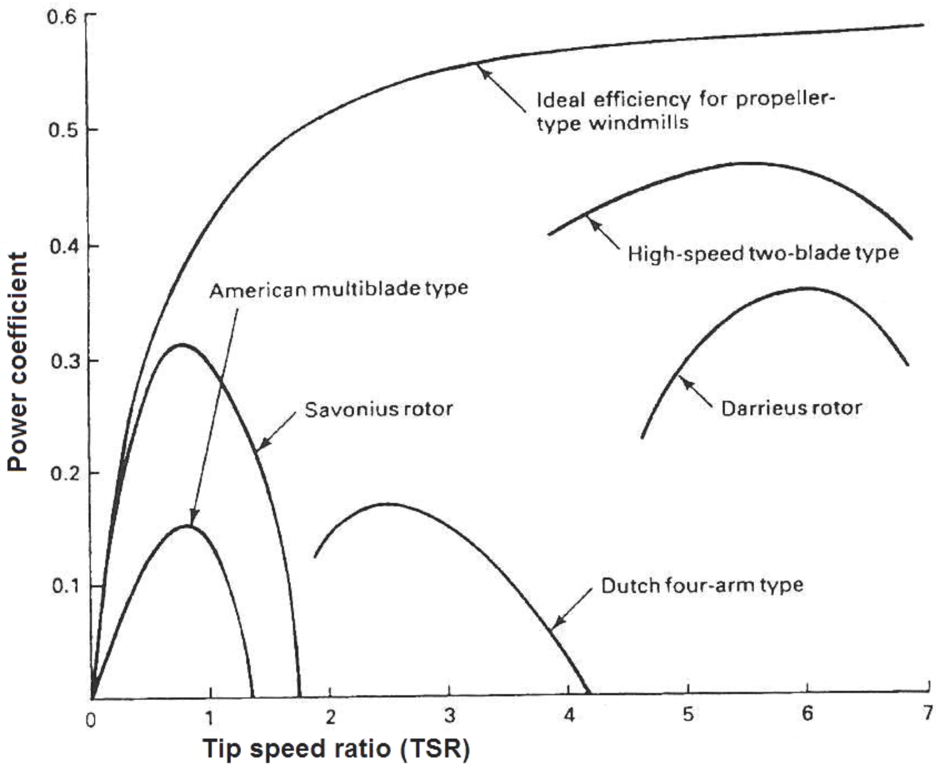

Figure 2.17 Typical performance of wind machines[17]

2.6 CURRENT RELATED RESEARCH KNOWLEDGE

Literature studies conducted indicated that the type of device proposed in this thesis has not been researched and no experimental data could be found. Apart from similarities in American patent 5503525 no other literature has been located. Whilst different in principle of operation, the Darrieus straight bladed “H” rotor shares a few similarities and was thus investigated.

2.6.1 Straight bladed Darrieus - performance prediction by Islam

A technical paper by Islam[18] indicated that mathematical performance prediction models based on the double-multiple streamtube model, Vortex model and Cascade model were appropriate for the Darrieus rotor. Islam stated that power output from a straight bladed Darrieus could be calculated thus:

$$F_{ta} = \frac{1}{2}\pi \int_{0}^{2\pi} F_t(\theta) d\theta \qquad (2.5)$$

$$Q = N \cdot F_{ta} \cdot R \qquad (2.6)$$

$$P = Q \cdot \omega \qquad (2.7)$$

F_{ta} = Average tangential force on each blade (N)
F_t = Tangential force on each blade (N)
Θ = Angular position (rad)
Q = Total torque for N blades (Nm)
R = Turbine radius (m)
ω = Turbine angular velocity (rad/s)
P = Power output (W)
N = number of blades

2.6.2 Optimization of the straight blade Darrieus

A technical paper by Jiang[19] investigated the effects of number of blades, solidity, wake effect and TSR on the overall performance of the straight bladed Darrieus.

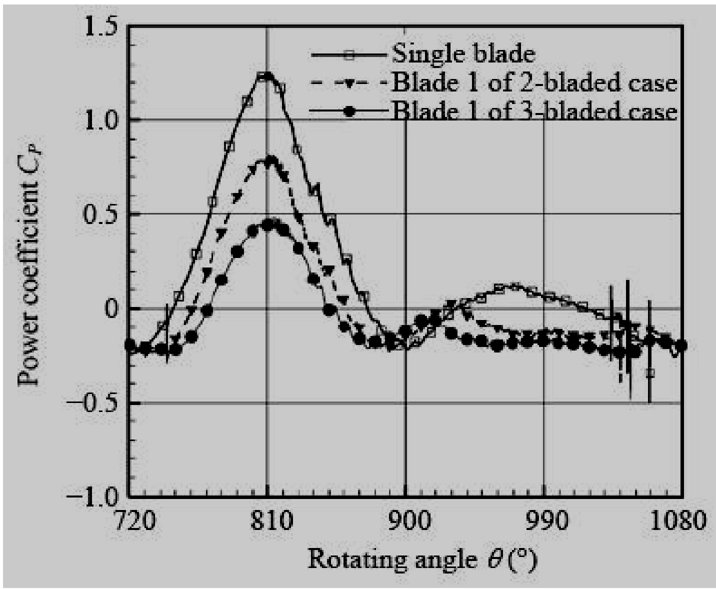

Figure 2.18 Power coefficient versus rotation angle for single and multi blade Darrieus[19]

Figure 2.18 indicated that solidity had a large influence on power output, particularly with machines running at high TSR.

2.6.3 Recent performance tests – Straight blade Darrieus

Suzuki and Taniguchi[20] conducted recent testing (2008) on various Darrieus type VAWT's. Their turbine enjoys improved performance over traditional Darrieus types due to the Bellshion blades. The blades have inwardly turned wingtips which reportedly improve performance. As at date of writing this type of device was believed to be the most efficient type of small scale VAWT in existence and hence was used for comparison purposes. Its claimed performance exceeds that shown in Figure 2.18 for Darrieus machines significantly. It is also claimed that maximum power occurs at a significantly lower tip speed ratio than most Darrieus machines.

Figure 2.19 Two blade Darrieus with Bellshion blades

The following test results were published[20] for the machine depicted in Figure 2.19. Specifications were given as; Radius 0.4m; Blade length 0.8m; Two blades; Swept area 0.64m^2

Wind speed	Rotor speed	Tip speed ratio	Power output	Power coefficient
m/s	rev/min	TSR	W	Cp
4	163	1.7	5.9	0.25
6	253	1.8	22.26	0.278
8	320	1.7	55.29	0.292
10	412	1.7	109.6	0.297
12	499	1.7	192.8	0.302
14	554	1.7	313.9	0.31

Table 2.2 Test Results (smaller machine)

The machine was run at various tip speed ratios and it was determined that maximum power was produced at a TSR=1.7. Table 2.2 indicates the absolute maximum power output possible by the device at the various wind speeds considered. The reduction in power coefficient above and below the optimum of 1.7 is evident in the Figure 2.20 which shows power coefficient on the vertical axis plotted against TSR on the horizontal axis.

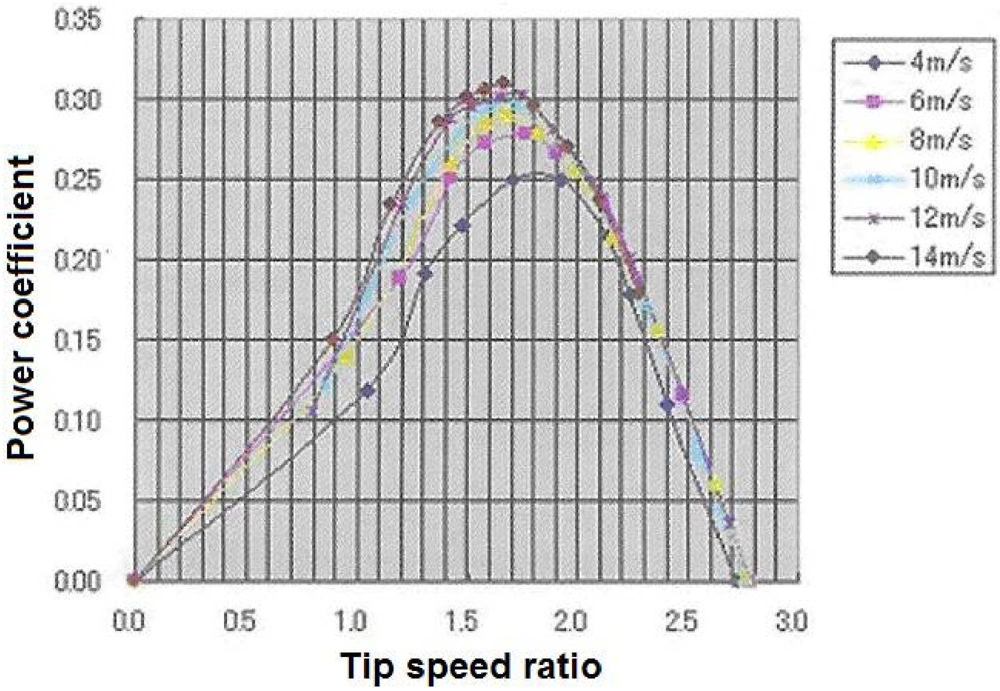

Figure 2.20 Power coefficient (Cp) plotted against Tip speed ratio (TSR)[20]

Performance testing was also conducted on a larger machine with specifications: Radius 1m; Blade length 2.5m; Two blades;Swept area $5m^2$

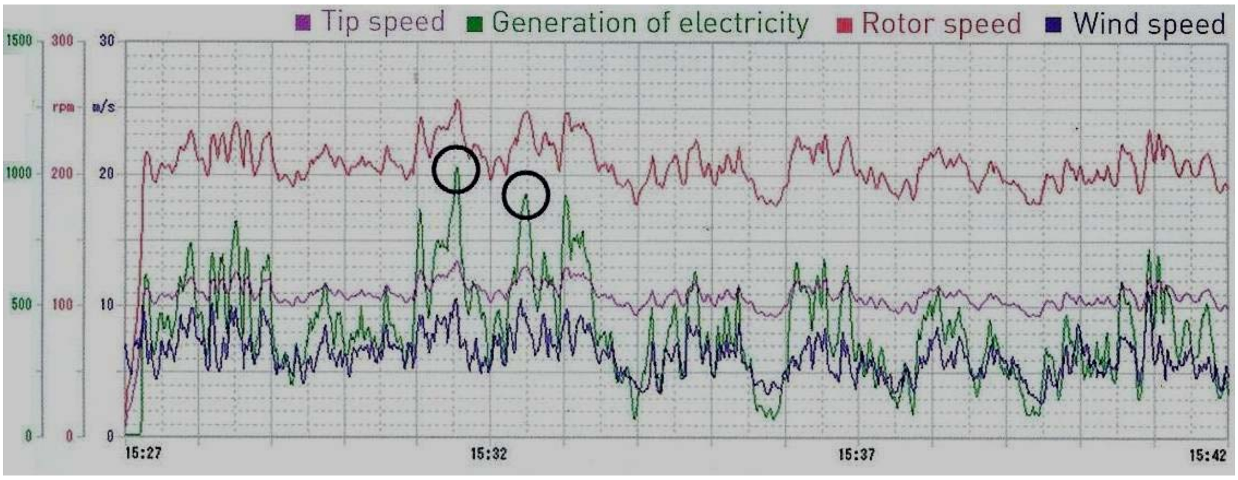

Figure 2.21 Performance test results (larger machine)[20]

2.7 SUMMARY

Most wind machine performance literature reviewed focused on the optimization of either high speed modern HAWT's or Darrieus rotors. As these are the only 2 types in wide scale use this was a logical outcome. Both types are used for generation of electricity and their high rotational speed is well suited to electrical generators which are often driven directly to minimize losses[21]. Very little literature was found regarding optimization of low speed machines. Low speed, high torque machines are not well suited to the generation of electricity. They are however well suited to the pumping of water and compressing of air, both of which can be useful methods for storing energy. Many developing nations do not have a “feed in” policy to the national electricity grid, necessitating some form of cost effective energy storage if wind energy is to be utilized by the private sector. Possible methods being:

- Pumping water to high ground during windy periods and running it back through hydro electricity turbines later
- Compressing air[22] and running an electrical generator off the compressed air when electricity is required.

It is therefore the opinion of this author that a gap exists in wind energy research for the development and optimization of a low speed, high torque device. Such a device should ideally have good public acceptance to allow it to be installed close to people and property. Acceptance would be easier to achieve if the device was quiet running and held minimal risk in the event of catastrophic failure. The device researched in the remainder of this thesis was based primarily on these criteria.

CHAPTER 3

DEVELOPMENT OF THE RESEARCH PLATFORM

3.1 INTRODUCTION

The preliminary research into an alternative type of wind machine started with the placement of an aerofoil in the wind and the investigation of ways of extracting power from it by using its lift force. The placement of the aerofoil was always such that all parts of it experienced the same air velocity at the optimal angle to the aerofoil to produce maximum lift force. It was the opinion of the author that this principle held advantages over devices such as the HAWT, which have varying velocities and angles of attack across the span of their blades. This fundamental principle was retained throughout the various concepts researched. Due to the fact that power is the product of force and velocity, the force from the aerofoil had to be combined with motion to extract power. Various types of motion were considered, however due to the constraints set regarding flow over the aerofoils it was necessary to reverse the angle of attack at some point in the motion cycle. The aerofoils were therefore required to produce lift force equally in both directions. This required the use of symmetrical aerofoils as shown in Figure 3.1.

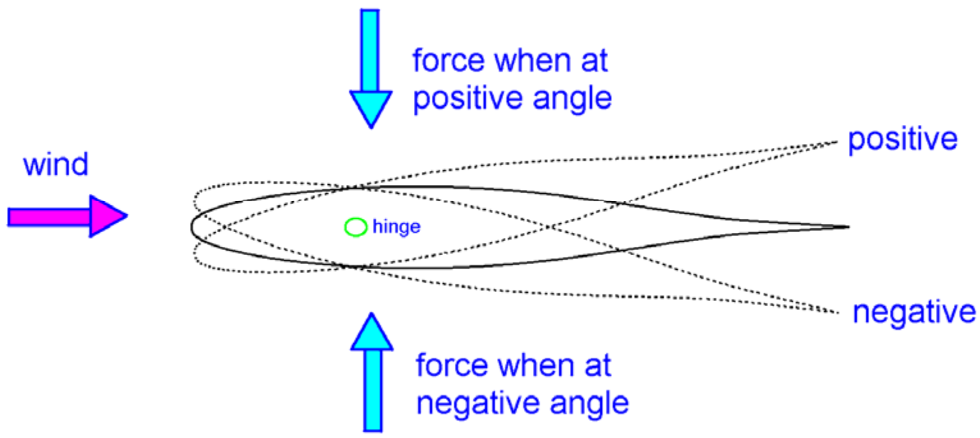

Figure 3.1: Basic principle of operation

The simplest concept considered was one where a symmetrical aerofoil was placed horizontally in the airflow and its angle of attack controlled so as to produce a reciprocating motion. The aerofoil was to be hinged to a wheeled carriage as shown in Figure 3.2. The wheeled carriage system was discarded due to its complexity and replaced by the hinged arm setup shown in Figure 3.3.

3.2 POSSIBLE ARRANGEMENTS CONSIDERED

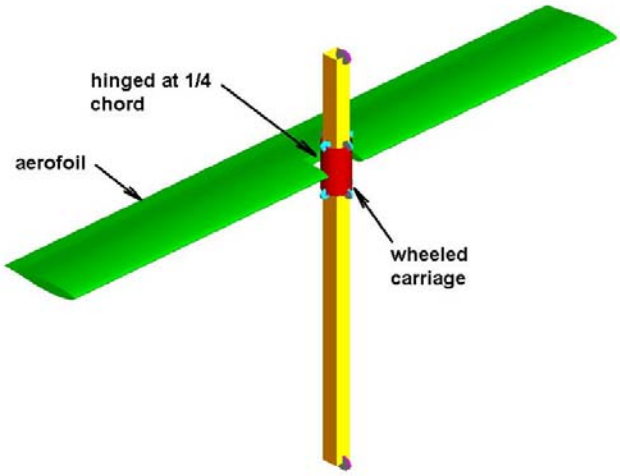

Figure 3.2 Initial concept – wheeled carriage

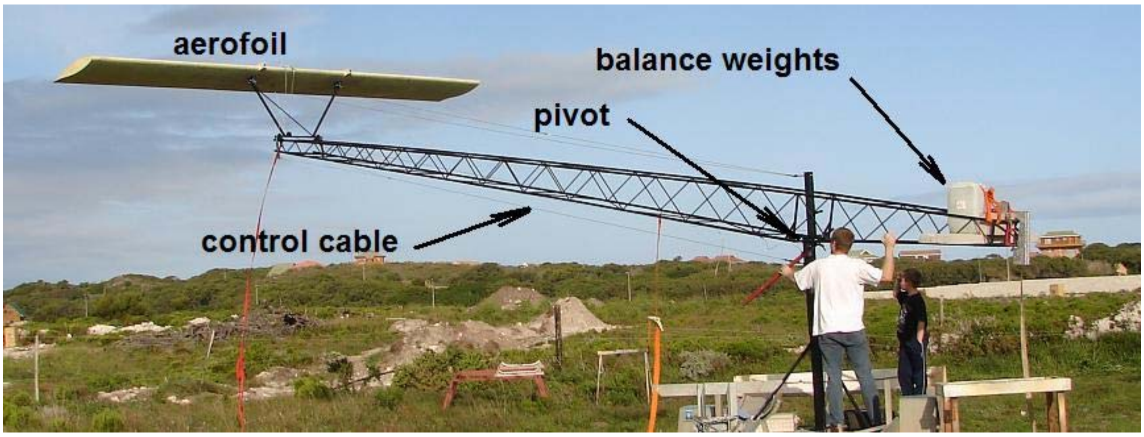

Figure 3.3 Horizontal aerofoil on hinged arm – aerofoil directly controlled

The arrangement shown in Figure 3.3 employed a 6m span aerofoil mounted at the end of a 9m arm of truss type construction. The system was counter-balanced and the angle of attack of the aerofoil controlled by cables.

By means of a spring loaded "over centre" mechanism the angle of attack of the aerofoil was automatically reversed just before the arm reached the end of its travel range. It was envisaged that electrical power would be extracted from the system by linear generators or conventional rotating generators driven in one direction via a ratchet or "sprag" clutch arrangement. Other possibilities considered for power extraction were pumping of water or compression of air with positive displacement pistons. According to Riblett [23] the torque produced (pitching moment) on a symmetrical aerofoil hinged at its ¼ chord should be zero at all angles of attack less than stall angle. Even with the aerofoil hinged at 25% of its chord it was found that the initial force required to alter/reverse the angle of attack of the aerofoil was in excess of 200N. This was due mainly to the mass and hence inertia of the components. For this reason a secondary smaller aerofoil was added to control the main aerofoil. The aerofoil section used throughout was a Wortmann FX71L-150.

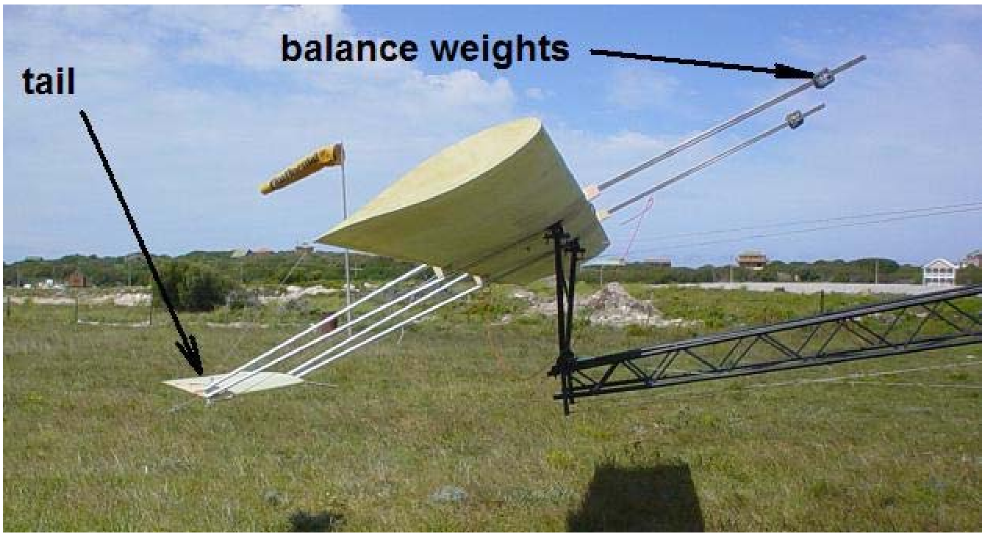

Figure 3.4 Horizontal aerofoil on hinged arm-indirectly controlled

It was found that a force of less than 10 N was required to control the smaller aerofoil and that the small aerofoil possessed adequate leverage to control the larger aerofoil even in light wind conditions. The small aerofoil was hinged at its ¼ chord and it was of symmetrical section. The main aerofoil was counterelativer balanced so that the small aerofoil did not have to overcome any weight effects.

The smaller aerofoil was controlled by a spring loaded "over centre" mechanism operated by cables that actuated the mechanism once the arm approached its travel limits. The arrangement shown in Figure 3.3 was able to automatically reciprocate the arm. The unit operated well provided that adequate resistance was provided to limit the reciprocating speed. To date no power has been extracted from the device, however this may be attempted once a suitable linear to angular motion device has been developed.

An alternative means of retaining the reciprocating aerofoil system, yet driving a shaft in one direction was considered next. An aerofoil was mounted vertically in the airflow and attached to a radial arm. The radial arm was connected to the main central shaft.

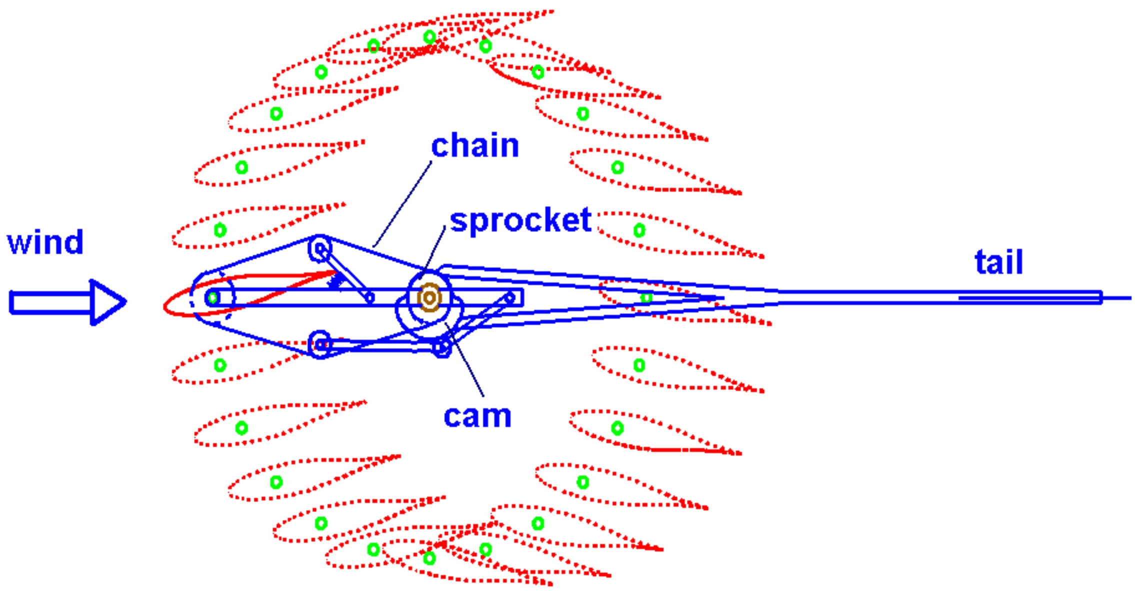

Figure 3.5 principle of operation – vertical axis with directly controlled aerofoils

The central sprocket was directly connected to the tail. The central sprocket therefore remained fixed in relation to the direction of the prevailing wind. The angle of attack of the aerofoil was made to change by means of two chain tensioners. One tensioner (primary) was controlled by a roller follower / arm arrangement running on a cam. The cam was coaxial and fixed to the central sprocket. The secondary tensioner was spring loaded to oppose the primary tensioner. The cam profile was designed such that follower lift and fall caused the aerofoil to be at a positive angle of attack in relation to the wind direction for half of the rotation circle and at negative angle of attack during the other half of the rotation circle thereby causing torque on the main shaft in one direction (anti-clockwise for Figure 3.5). Figure 3.6 shows the device constructed.

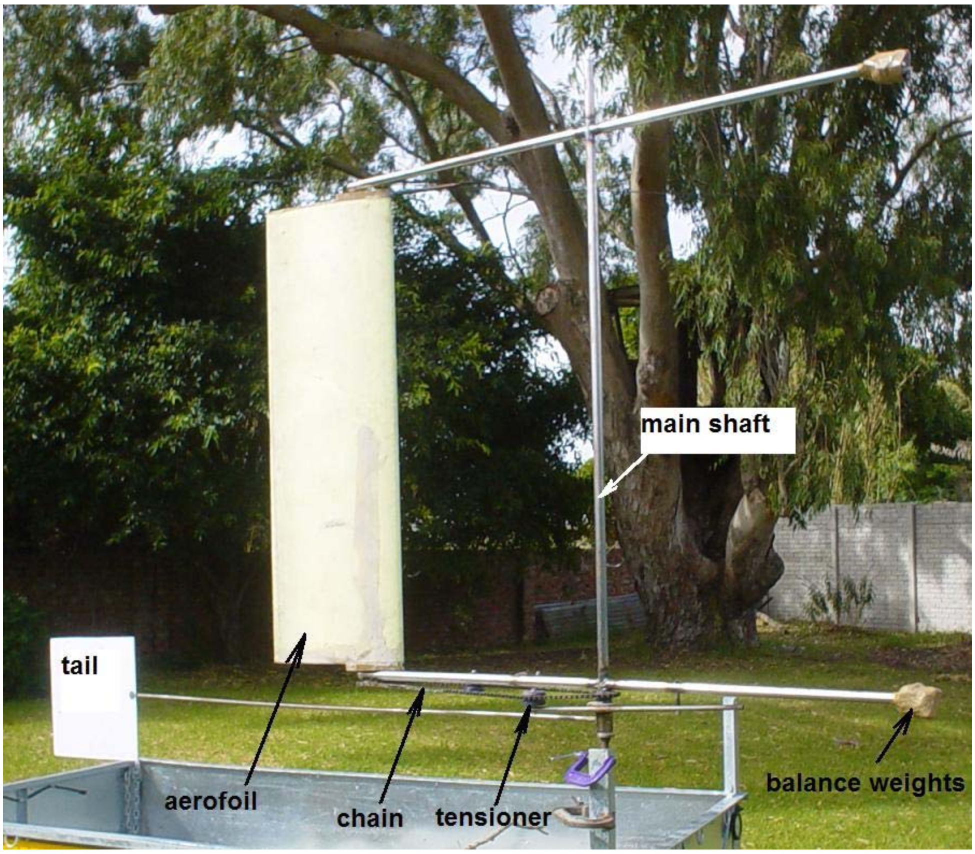

Figure 3.6 Vertical aerofoil revolving about a vertical axis – aerofoil directly controlled

The unit was run with a single aerofoil and balance weights. At slow rotational speeds (regulated by applying resisting torque) the unit demonstrated reasonably stable operation and high torque output. Starting torque was high, provided that the single aerofoil was in the front or rear half of the rotation circle and not at the point where angle of attack was changing (change over point). It was learnt in subsequent tests on other devices that the smoothness of operation and stability could have been greatly enhanced by adding a second or preferably third aerofoil. This would also have ensured that the unit was self starting from all positions. An analysis of the relative angle between the aerofoil and the relative airflow at varying wind and rotational speeds showed that a cam profile could be optimized for a small range of wind speeds and rotational speeds but not for the entire expected range. This lead to the development of the freely pivoted aerofoil arrangement described next and favoured for the rest of this project. The device described above may have lacked the ability to operate through a wide range of tip speed ratios however the stability resulting from the direct control of the aerofoils render it ideal for use in slow speed, high torque applications such as water pumping. Whilst not pursued any further in this research it was felt that this concept possessed merit for further research.

Earlier tests on the horizontal aerofoil system showed that effective control of the main aerofoil could be achieved by means of a smaller aerofoil mounted downwind of the main aerofoil at a suitable distance. It was decided to experiment with this system on the vertical rotating aerofoils. The same symmetrical aerofoil section as used on the larger aerofoil was used for the smaller aerofoil with the hinge point at ¼ chord for both aerofoils initially.
Tests were conducted with the smaller aerofoil (referred to as the tail in future) parallel to the main aerofoil. The unit was positioned in a 5m/s wind and the main shaft was rotated at various speeds. The aerofoils were balanced such that their mass centre was on the pivot axis so that centrifugal effects would not cause any rotation of the aerofoils. As predicted the aerofoil remained aligned into the wind at very slow rotational speed. At higher speeds it remained aligned with the local relative airflow (RAF). At rotational speeds which resulted in a tip speed exceeding the wind speed the aerofoil would attempt to turn around when on the down wind side of the rotational circle. For this reason it was envisaged that the unit would always be limited to a tip speed slightly below wind speed. Once it was established that the tail was capable of effectively aligning the aerofoil with the local airflow, various methods of altering the tail angle during rotation were explored so as to produce torque from the device. Figure 3.7 shows the aerofoil and tail at four positions in the rotation circle. As an example a wind speed of 16m/s was used together with a rotational speed of 87 rev/min with an arm of 840mm radius. The resultant relative airflow (RAF) is shown in magnitude and direction as a vector drawn to scale. Visual observation confirmed that the tail effectively aligned the main aerofoil as predicted in Figure 3.7.

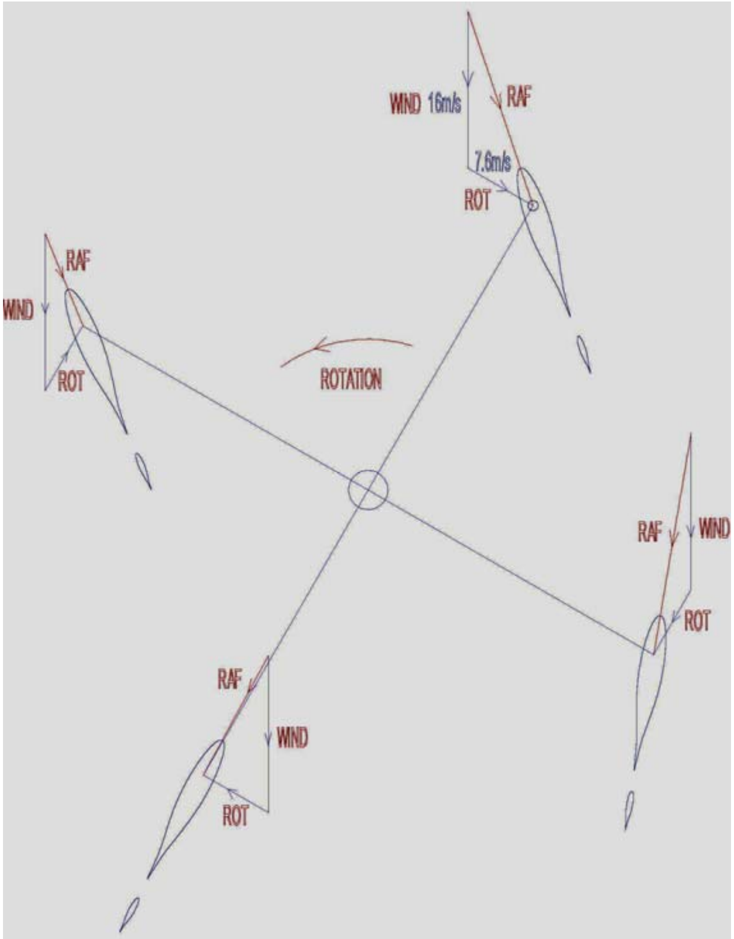

Figure 3.7 Alignment of the main aerofoil to the relative airflow by means of the tail

Using servo motors, a radio controlled receiver, battery pack and radio control transmitter it was possible to manually control the tail (at slow speed) and produce torque. The experimental setup utilized is shown in Figure 3.8 and 3.9. It was evident that deflection of the tail in relation to the main aerofoil by any angle less than approximately 10^0 caused the main aerofoil to deflect by a similar amount in relation to the local wind direction (RAF).

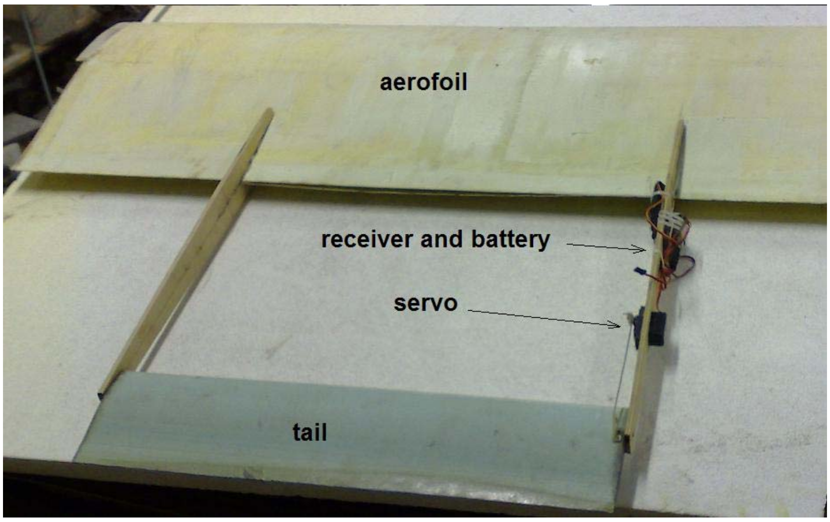

Figure 3.8 Remote controlled tail setup - details

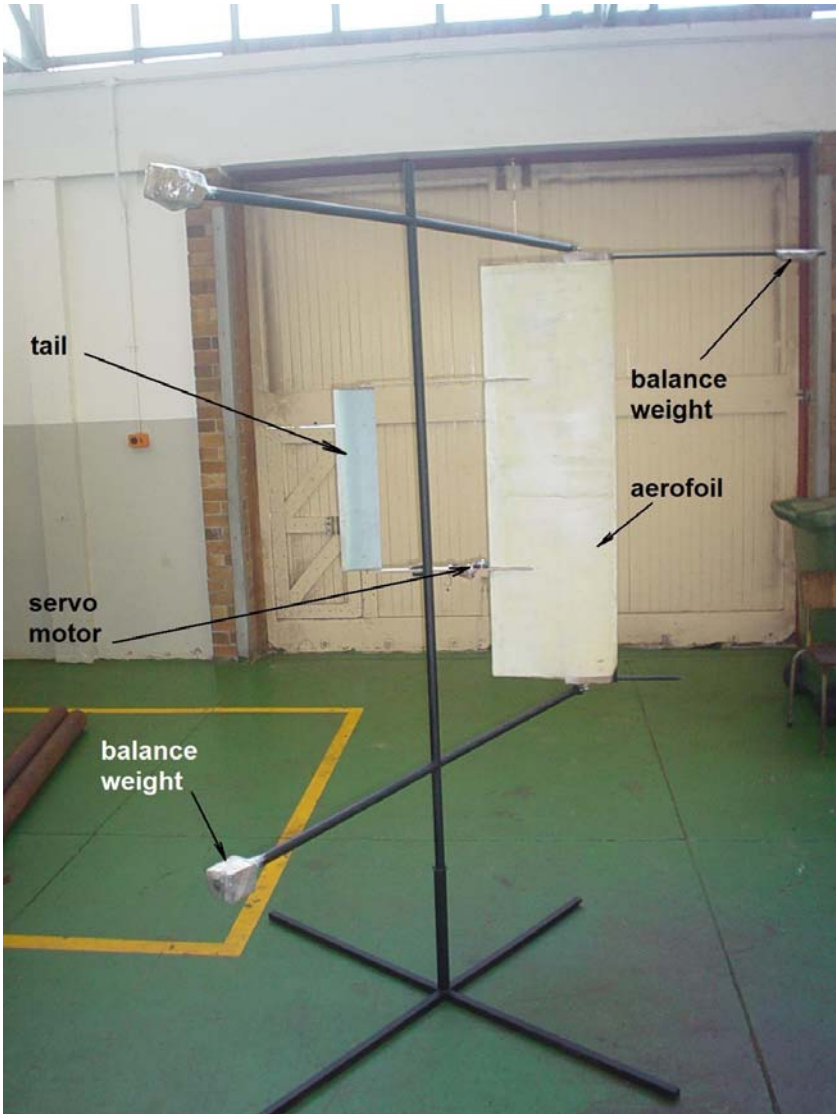

Figure 3.9 Remote controlled tail setup

The conclusion of this experiment was that if it were possible to develop a device which would be able to present it's aerofoils to the local wind direction at the optimum angle of attack at all rotational positions and hence produce maximum force from the wind, the greatest possible torque would be achieved in the main shaft. Review of the coefficient of lift versus angle of attack graph[12] for the aerofoil showed that maximum lifting force would occur at approximately 12^{o}. It was also concluded that the direction of the lifting force should be directed such that it produced the maximum possible turning moment about the main shaft. Control of the tails via a remote electronic control system was considered to be feasible and would be the preferred means of control for large scale units. For simplicity and cost effectiveness of small scale units such as the experimental platform envisaged it was decided to initially develop a purely mechanical means of controlling the tails.

It was determined from the previous experiment that the tail needed to be deflected to a pre-determined positive angle in relation to the main aerofoil during half a revolution and then to the same but negative angle during the remainder of a revolution. The change over point should occur when the radial arms of the machine were perpendicular to the wind. Sensing of the wind direction no longer required a separate tail as in Figure 3.6 due to the fact that each aerofoil had its own tail. Furthermore the tails in this setup sensed local relative airflow (RAF) and not wind direction. The first mechanical system researched utilized a spring loaded pushrod running on a plate as shown in Figure 3.11. The spring loaded pushrod was made to run on a semi circular flat plate. During half of the revolution the tail was deflected against a stop (in the positive direction) by a light spring force. During this half of the revolution the lever was off the plate. During the remainder of the revolution the lever ran on the plate and deflected the tail in the negative direction. It was found that excessive friction occurred on the entry ramp of the semi-circular plate as the pushrod was made to rise against the spring force. An improved setup was fabricated as shown in Figure 3.13 to alleviate this problem. The primary reason for using the semi-circular plate system was the potential to control the amount of tail deflection. By raising or lowering the plate the amount of tail deflection would be limited, thereby controlling the amount of wind power entering the device. This was not utilized on the experimental setup, however the plate system would have this potential.

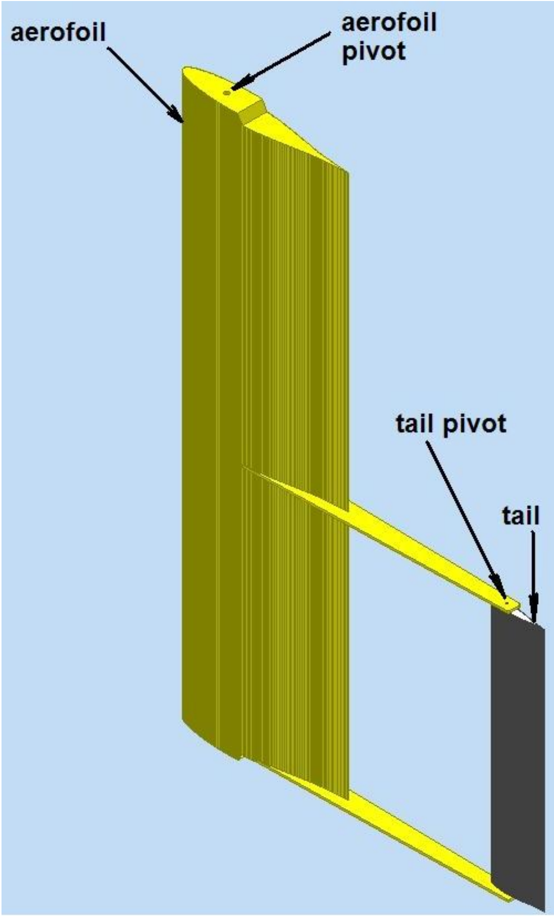

Figure 3.10 Aerofoil and tail assembly

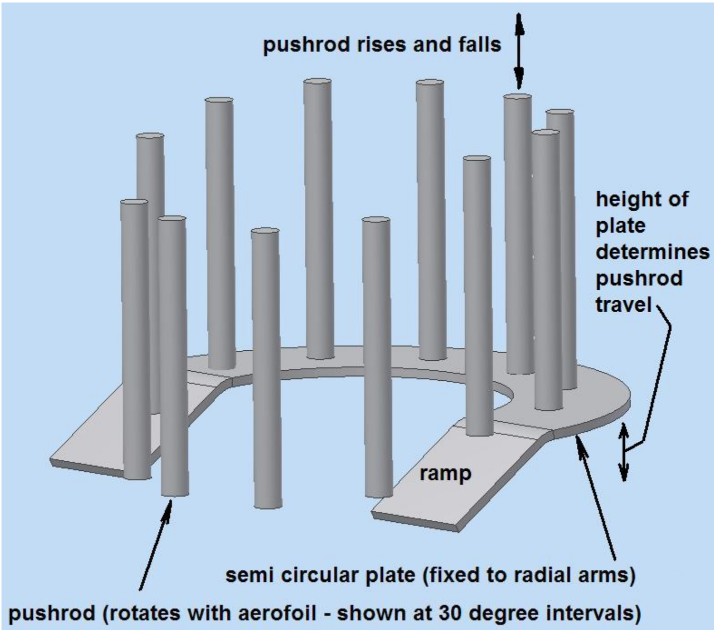

Figure 3.11 Initial mechanical tail control setup – pushrod running on plate

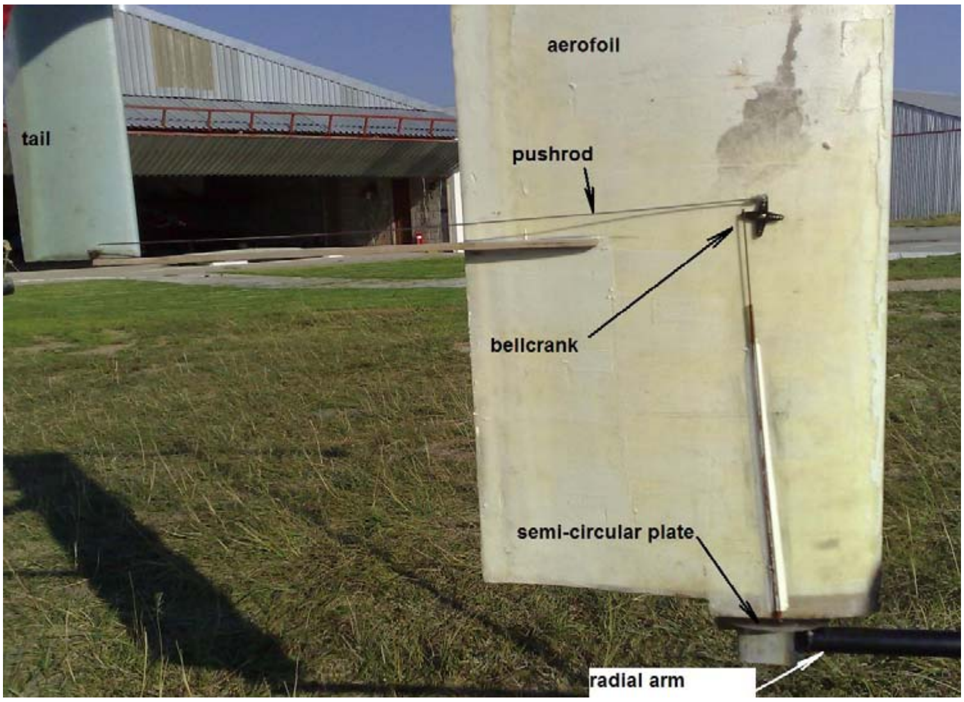

Figure 3.12 Initial setup showing tail control

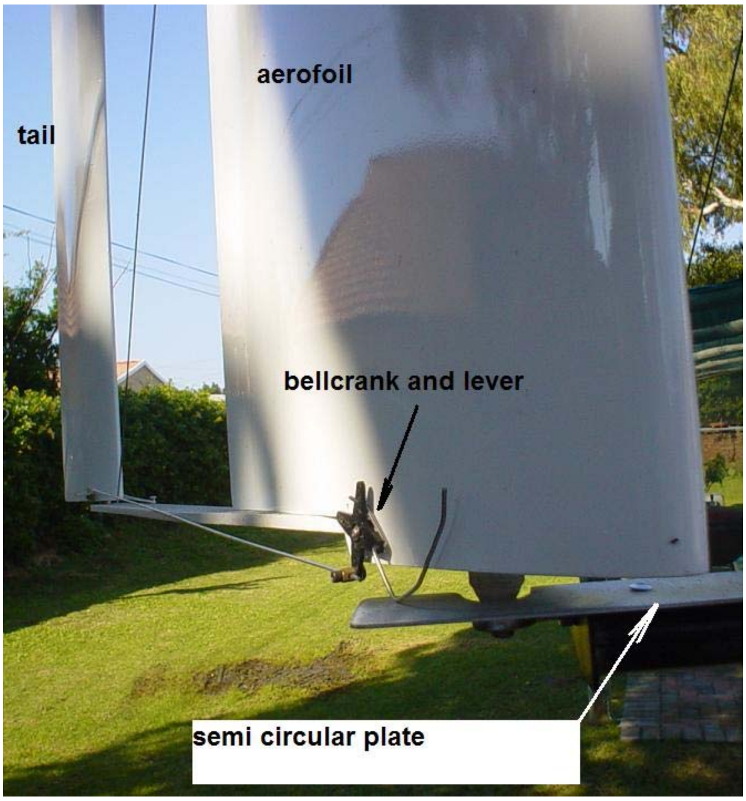

Figure 3.13 Improved mechanical tail control setup – lever running on plate

The second mechanical system researched, utilized a cam and roller follower. The roller follower was made to run on a cam affixed to the radial arms. When the follower ran on the cam's base circle (for half of the revolution) the tail was deflected by a light spring to a stop (max positive deflection). When the follower ran on the raised portion of the cam the lever to which the roller follower was attached pulled the tension linkage connected to the tail, causing it to deflect to the maximum negative angle.

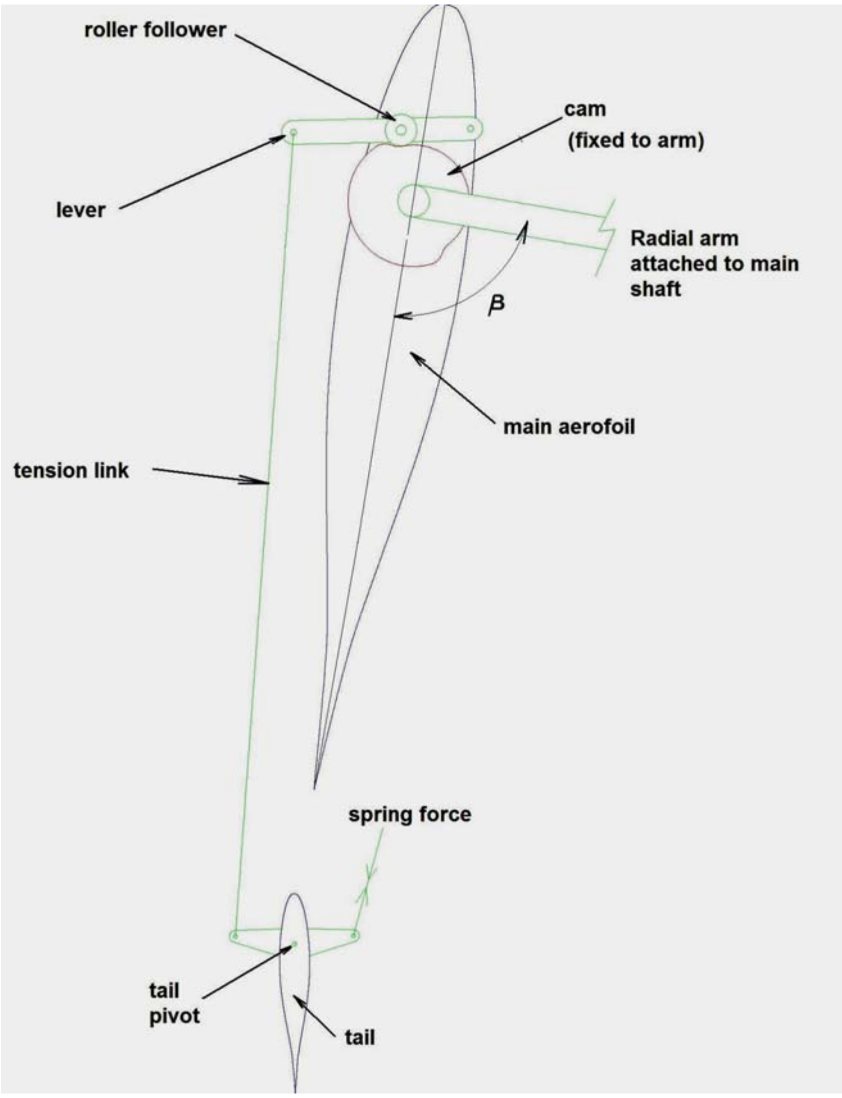

Figure 3.14 Cam/roller follower arrangement

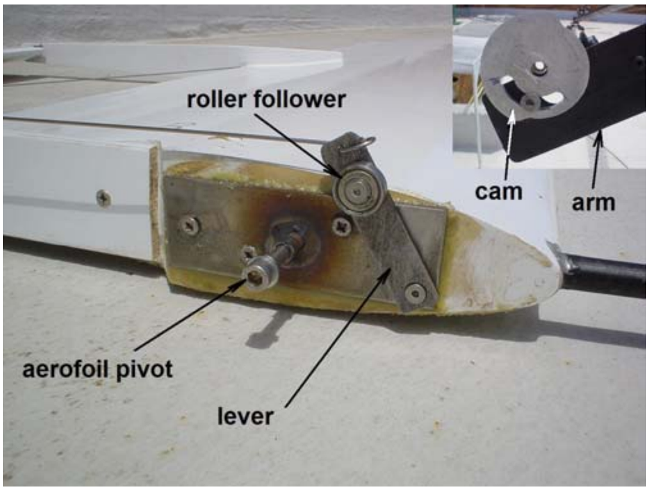

Figure 3.15 Mechanical tail control setup - cam and roller follower system

This system proved to be the most practical of the various mechanical systems experimented with and hence was the one chosen for the final experimental platform.

Figure 3.16 Cam and roller follower controlled system with 2 blades

The system shown in Figure 3.16 was adjusted such that the tails deflected to 10^0 positive and negative in relation to the main aerofoils. The change over point occurred when the aerofoils reached an angle of 90^0 to the horizontal arms. (Denoted by angle "β" in Figure 3.12). The system possessed adequate starting torque provided that it was initially positioned with the arms not at 90^0 to the wind. If at this position the aerofoils were at the change over position between positive and negative angle of attack and produced little or no force. Their effective crank radius at this point was also nil meaning that no torque was produced at this position. Provided that an adequate flywheel was fitted it would have been possible to get the two bladed system to operate reasonably well, however the more effective solution was to add a third aerofoil. With the aerofoils arranged at 120^0 to each other the unit would be able to start from any position and produce continuous torque with little need for a flywheel.

3.3 FINAL EXPERIMENTAL PLATFORM

The final configuration decided upon was a device consisting of a hollow tubular steel main shaft of outside diameter 46mm. This was mounted to a dual taper roller bearing arrangement at the top of the 4m high mast. The shaft was made to run true and the bearings and structure possessed adequate rigidity such that the main shaft did not require a top bearing and stay wires. Clamped to the main shaft were two brackets to which the six radial arms were bolted at 120^0 to each other. The design philosophy used was that the platform should easily be able to accommodate changes required during testing such as gear ratio, balance mass, tail deflection angles, tail pivot positions etc.

Specifications:

- Three aerofoils of 1.3m span and 400mm chord (Wortmann FX71L-150 section). Aerofoils manufactured with foam core and fiberglass skin.
- Three mechanically controlled tail aerofoils for control of the main aerofoils as per Figure 3.12.

- Kestrel 300 generator type 0501 driven from the main shaft via a two stage speed increasing drive capable of accommodating various combinations of sprocket and pulley size.

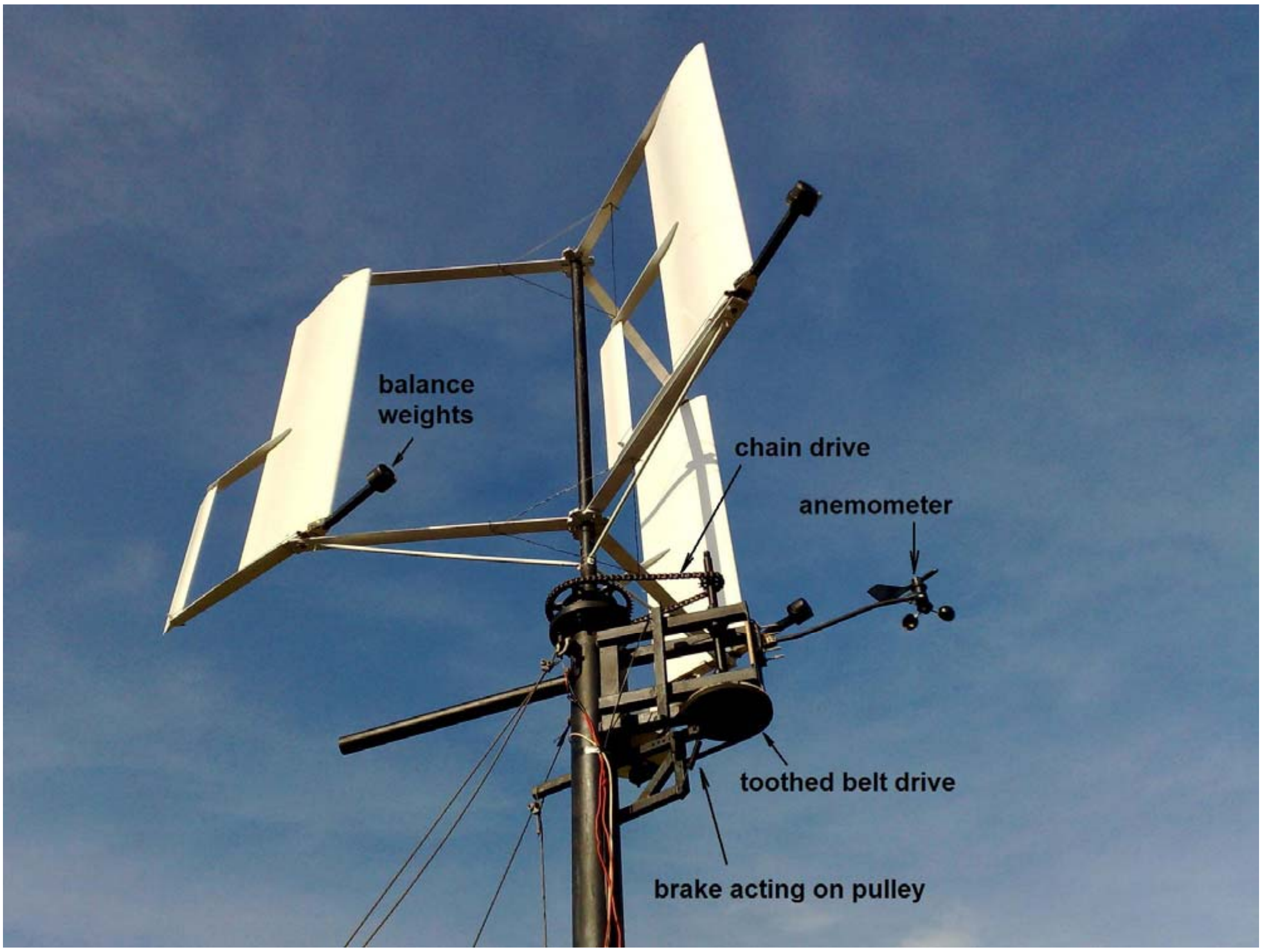

Figure 3.17 Final experimental setup

Note: In Chapter 1 (Project Overview) It was assumed that the inertia of the reciprocating components and the acceleration and deceleration thereof would require consideration. Due to that fact that the final platform employed aerofoils which revolved rather than reciprocated, this aspect was considered to have negligible influence and was ignored. The elastic energy absorbed and released by the aerofoils was also neglected due to the fact that the aerofoils used in the final platform were of low aspect ratio which resulted in little or no bending deflection occurring.

3.4 DATA LOGGING

Two different data loggers were utilized:

- Pace Scientific XR5-SE

Figure 3.18 Pace Scientific XR5-SE

The XR5 logger[31] was configured to record wind speed, wind direction, generator rotational speed, amperage and voltage. A DC100A current sensor was utilized in conjunction with the XR5 logger to allow logging of amperage output of up to 100A. Voltage logging of up to 60V was achieved by the addition of a INP/12 voltage scaling cable. Rotational speed was sensed with an externally powered 12mm proximity switch and logged by the XR5. Wind speed and direction were sensed by means of the WSD 100[32] and logged in the XR5.

Figure 3.19 WSD 100 Wind speed and direction sensor

- Eagle Tree e-Logger V3

Figure 3.20 Eagle Tree e-Logger V3

The Eagle Tree logger had the advantage of the display panel which was useful during initial optimization of the device “on site”. Real time display was possible without the need for a computer. The Eagle Tree logger however required constant voltage supply from the generator. During light wind conditions this proved to be a problem as the logger would reset if the machine stopped rotating. Wind direction and speed data could not be logged on the Eagle Tree logger and this data had to be obtained from the XR5 logger and the data merged.

The XR5 system was the preferred system and the one utilized for gathering the data on which the outcomes of this project are based.

3.5 SUMMARY

The experimental platform evolved significantly during the research and development process outlined in Chapter 3. The evolution involved a number of distinct stages and each subsequent stage came about as a direct result of improvements and deficiencies identified at that stage. The final configuration of the experimental platform was not as it was envisaged at the outset. The end result was a unique device which showed potential as a low speed, quiet means of extracting energy from the wind. At this point the device still required refinement and this lead to further research and functionality testing as described in Chapter 6 and Chapter 7.

CHAPTER 4

AERODYNAMIC PRINCIPLES AND PERFORMANCE PREDICTIONS

4.1 INTRODUCTION

In the absence of any available literature regarding the expected performance of a device such as that described in Chapter 3, it was necessary to work from basic principles. The few similarities to the Darrieus concept and HAWT were also investigated in this chapter.

4.2 FORCES AND TORQUES EXPERIENCED BY BLADE IN AIRFLOW

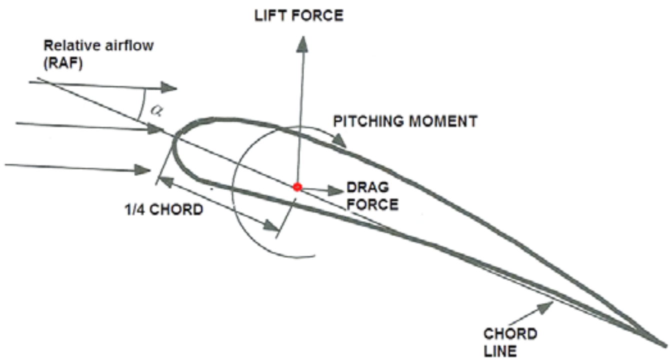

Figure 4.1 Forces and torques experienced by blade in airflow(1)

According to Abbott[12], lift and drag forces on an aerofoil can be calculated using:

$$F = C_L \frac{1}{2} \rho V^2 A \qquad (4.1)$$

$$D = C_D \frac{1}{2} \rho V^2 A \qquad (4.2)$$

F Lift force (N)

D Drag force (N)

A Aerofoil area (m^2)

C_L Coefficient of lift

V Wind velocity (m/s)

ρ Air density (kg/m^3)

The total force experienced by the aerofoil is resolved into two perpendicular components (lift and drag). The lift force is perpendicular to the RAF and the drag force is parallel to it.

4.3 VARIATION OF C_L WITH CHANGES IN ANGLE OF ATTACK

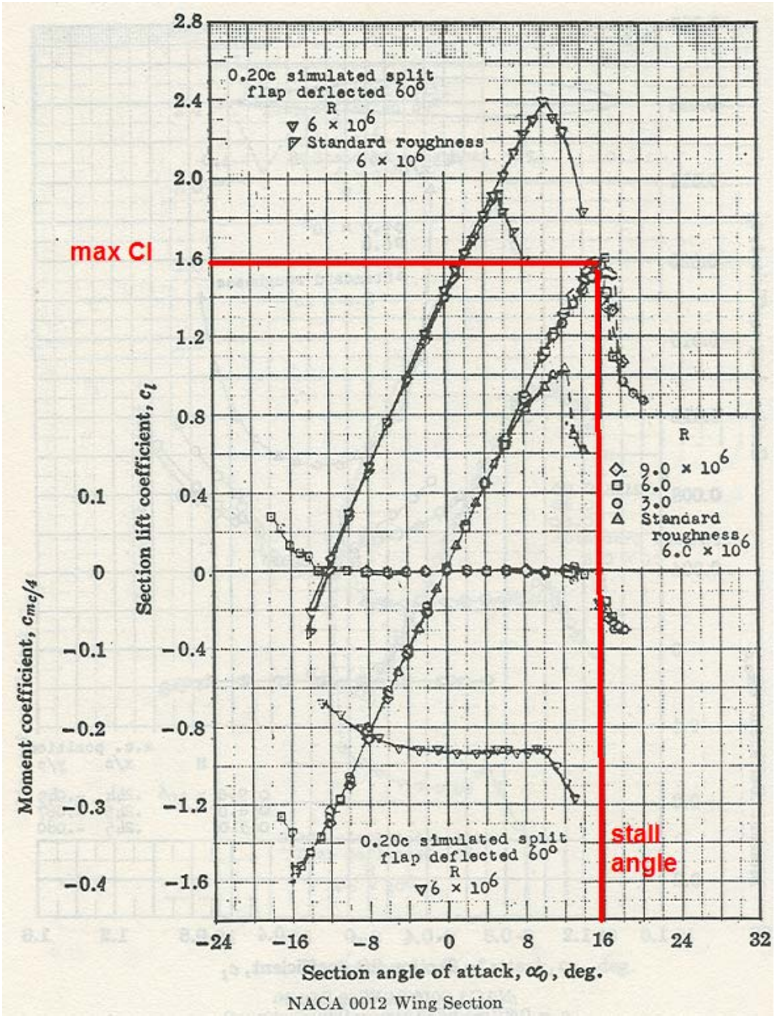

Figure 4.2 Variation of C_l with changes in angle of attack NACA 0012 aerofoil [12]

Figure 4.2 shows the relationship between the lift coefficient and the angle of attack for a NACA 0012 symmetrical aerofoil.

4.4 DETERMINING THE DIRECTION OF THE RELATIVE AIRFLOW (RAF)

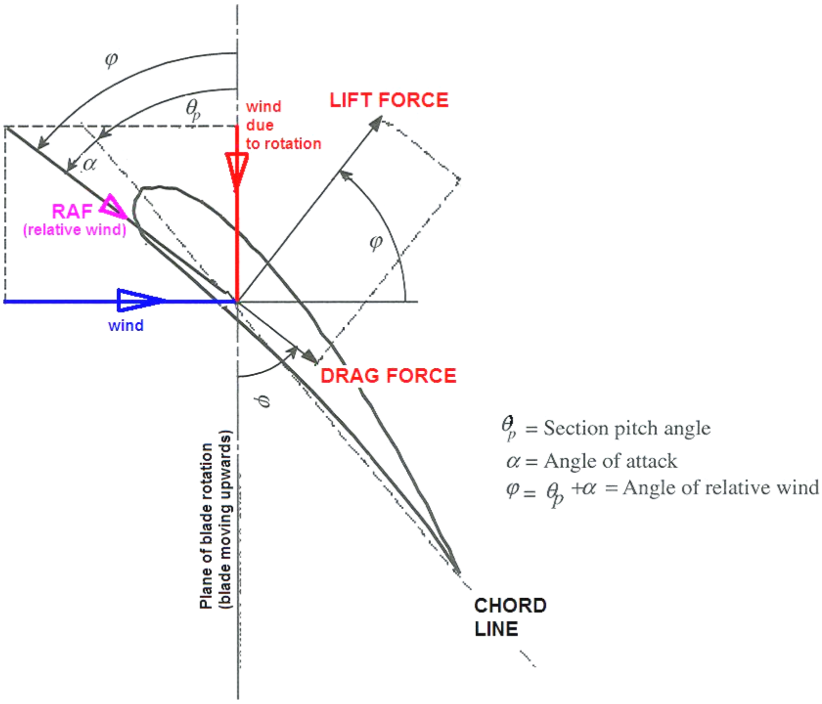

Figure 4.3 Determining the RAF direction[1]

A cross section through a blade of a HAWT is shown Figure 4.3. The direction of the relative airflow is obtained by summing the wind vector and the velocity vector due to blade movement (rotation). The angle of attack is the angle between the aerofoil chord line and the RAF. The angle of attack is added to the blade pitch angle to obtain the total angle of the RAF. The sketch refers to a single cross section of the HAWT blade. Different cross sections have different pitch angles due to blade twist. The wind due to rotation also differs due to the change in radius at different cross sections and increases proportionally with radius.

4.5 DETERMINING THE ANGLE OF ATTACK OF A HAWT

Equations 4.3 to 4.6 were used in Figures 4.4 and 4.5 to determine the actual airflow parameters at various stations along the blade of a typical HAWT under various wind speeds and rotational speeds.

$$V_{rot} = \frac{\Pi \times dia \times RPM}{60} \qquad (4.3)$$

$$RAF = \tan^{-1}(\frac{wind}{V_{rot}}) \quad (4.4)$$

$$AofA = RAF - bladeangle \quad (4.5)$$

$$V_{tot} = \sqrt{(V_{rot})^2 + (wind)^2} \quad (4.6)$$

$$pitch = \frac{(60 \times wind)}{RPM} \quad (4.7)$$

The variables are defined as:

V_{rot}	(m/s)	component of linear velocity due to rotation
dia	(m)	diameter of blade station considered
wind	(m/s)	ambient wind velocity
RAF	*(deg)*	angle of relative airflow measured from rotation plane
AofA	*(deg)*	angle of attack of aerofoil
V_{tot}	*(m/s)*	velocity of air over aerofoil (m/s)
bladeangle	(degrees)	angle between rotation plane and chord line
RPM	(rev/min)	angular speed of turbine blades

The spreadsheet in Figure 4.4 was used to calculate the ideal blade angles required by a HAWT (third column). When the HAWT is operated under its ideal design parameters it is possible to achieve an ideal angle of attack along the entire blade (ninth column). In this case 0^o was used as an example, however this would vary depending on the actual aerofoil section used. Columns 5 to 8 indicate the angle of attack experienced at various non ideal rotational speeds. Assuming a stall angle of 12^o it can be seen that large portions of the blades are stalled, particularly at low rotational speeds (shown in red).

Wind speed		15	kts		7.716	m/s		
Ideal rotational speed		500	rev/min					
Required pitch		*0.93*	m					
Diameter		6	m	Deviations from ideal conditions				
			wind (m/s)	7.75	7.75	7.75	7.75	7.8
			wind(kts)	15.066	15.066	15.066	15.066	15.066
			RPM	1	50	100	250	500
% rad	dia(mm)	blade angle	Vrot(m/s)	0.3	15.7	31.4	78.5	157.1
100	6000	*2.8*	*RAF(deg)*	87.7	26.3	13.9	5.6	2.8
			AofA(deg)	84.9	23.4	11.0	2.8	0.0
			Vtot(m/s)	7.8	17.5	32.4	78.9	157.3
			Vrot(m/s)	0.3	14.1	28.3	70.7	141.4
90	5400	*3.1*	*RAF(deg)*	87.9	28.7	15.3	6.3	3.1
			AofA(deg)	84.8	25.6	12.2	3.1	0.0
			Vtot	7.8	16.1	29.3	71.1	141.6
			Vrot(m/s)	0.3	12.6	25.1	62.8	125.7
80	4800	*3.5*	*RAF(deg)*	88.1	31.7	17.1	7.0	3.5
			AofA(deg)	84.6	28.1	13.6	3.5	0.0
			Vtot	7.8	14.8	26.3	63.3	125.9
			Vrot(m/s)	0.2	11.0	22.0	55.0	110.0
70	4200	*4.0*	*RAF(deg)*	88.4	35.2	19.4	8.0	4.0
			AofA(deg)	84.4	31.2	15.4	4.0	0.0
			Vtot	7.8	13.5	23.3	55.5	110.2
			Vrot(m/s)	0.2	9.4	18.8	47.1	94.2
60	3600	*4.7*	*RAF(deg)*	88.6	39.4	22.4	9.3	4.7
			AofA(deg)	83.9	34.8	17.7	4.7	0.0
			Vtot	7.8	12.2	20.4	47.8	94.6
			Vrot(m/s)	0.2	7.9	15.7	39.3	78.5
50	3000	*5.6*	*RAF(deg)*	88.8	44.6	26.3	11.2	5.6
			AofA(deg)	83.2	39.0	20.6	5.6	0.0
			Vtot	7.8	11.0	17.5	40.0	78.9
			Vrot(m/s)	0.1	6.3	12.6	31.4	62.8
40	2400	*7.0*	*RAF(deg)*	89.1	51.0	31.7	13.9	7.0
			AofA(deg)	82.1	44.0	24.7	6.9	0.0
			Vtot	7.8	10.0	14.8	32.4	63.3
			Vrot(m/s)	0.1	4.7	9.4	23.6	47.1
30	1800	*9.3*	*RAF(deg)*	89.3	58.7	39.4	18.2	9.3
			AofA(deg)	80.0	49.4	30.1	8.9	0.0
			Vtot	7.8	9.1	12.2	24.8	47.8
			Vrot(m/s)	0.1	3.1	6.3	15.7	31.4
20	1200	*13.8*	*RAF(deg)*	89.5	67.9	51.0	26.3	13.9
			AofA(deg)	75.7	54.1	37.2	12.5	0.1
			Vtot	7.8	8.4	10.0	17.5	32.4
			Vrot(m/s)	0.0	1.6	3.1	7.9	15.7
10	600	*26.2*	*RAF(deg)*	89.8	78.5	67.9	44.6	26.3
			AofA(deg)	63.6	52.4	41.8	18.5	0.1
			Vtot	7.8	7.9	8.4	11.0	17.5

Figure 4.4 RAF angles at various radii and rotational speeds for a HAWT

Wind speed	15	kts	7.716	m/s
Ideal rotational speed	500	rev/min		
Required pitch	*0.93*	m		
Diameter	6	m	Deviations from ideal conditions	

			wind (m/s)	1	2	4	6	7.8
			wind(kts)	1.944	3.888	7.776	11.664	15.066
			RPM	250	250	250	250	250
% rad	dia(mm)	blade angle	Vrot(m/s)	78.5	78.5	78.5	78.5	78.5
100	6000	*2.8*	*RAF(deg)*	0.7	1.5	2.9	4.4	5.6
			AofA(deg)	-2.1	-1.4	0.1	1.6	2.8
			Vtot(m/s)	78.5	78.6	78.6	78.8	78.9
			Vrot(m/s)	70.7	70.7	70.7	70.7	70.7
90	5400	*3.1*	*RAF(deg)*	0.8	1.6	3.2	4.9	6.3
			AofA(deg)	-2.3	-1.5	0.1	1.7	3.1
			Vtot(m/s)	70.7	70.7	70.8	70.9	71.1
			Vrot(m/s)	62.8	62.8	62.8	62.8	62.8
80	4800	*3.5*	*RAF(deg)*	0.9	1.8	3.6	5.5	7.0
			AofA(deg)	-2.6	-1.7	0.1	1.9	3.5
			Vtot(m/s)	62.8	62.9	63.0	63.1	63.3
			Vrot(m/s)	55.0	55.0	55.0	55.0	55.0
70	4200	*4.0*	*RAF(deg)*	1.0	2.1	4.2	6.2	8.0
			AofA(deg)	-3.0	-1.9	0.1	2.2	4.0
			Vtot(m/s)	55.0	55.0	55.1	55.3	55.5
			Vrot(m/s)	47.1	47.1	47.1	47.1	47.1
60	3600	*4.7*	*RAF(deg)*	1.2	2.4	4.9	7.3	9.3
			AofA(deg)	-3.5	-2.3	0.2	2.6	4.7
			Vtot(m/s)	47.1	47.2	47.3	47.5	47.8
			Vrot(m/s)	39.3	39.3	39.3	39.3	39.3
50	3000	*5.6*	*RAF(deg)*	1.5	2.9	5.8	8.7	11.2
			AofA(deg)	-4.2	-2.7	0.2	3.1	5.6
			Vtot(m/s)	39.3	39.3	39.5	39.7	40.0
			Vrot(m/s)	31.4	31.4	31.4	31.4	31.4
40	2400	*7.0*	*RAF(deg)*	1.8	3.6	7.3	10.8	13.9
			AofA(deg)	-5.2	-3.4	0.3	3.8	6.9
			Vtot(m/s)	31.4	31.5	31.7	32.0	32.4
			Vrot(m/s)	23.6	23.6	23.6	23.6	23.6
30	1800	*9.3*	*RAF(deg)*	2.4	4.9	9.6	14.3	18.2
			AofA(deg)	-6.9	-4.4	0.3	5.0	8.9
			Vtot(m/s)	23.6	23.6	23.9	24.3	24.8
			Vrot(m/s)	15.7	15.7	15.7	15.7	15.7
20	1200	*13.8*	*RAF(deg)*	3.6	7.3	14.3	20.9	26.3
			AofA(deg)	-10.2	-6.5	0.5	7.1	12.5
			Vtot(m/s)	15.7	15.8	16.2	16.8	17.5
			Vrot(m/s)	7.9	7.9	7.9	7.9	7.9
10	600	*26.2*	*RAF(deg)*	7.3	14.3	27.0	37.4	44.6
			AofA(deg)	-18.9	-11.9	0.8	11.2	18.5
			Vtot(m/s)	7.9	8.1	8.8	9.9	11.0

Figure 4.5 RAF angles at various radii and wind speeds for a HAWT

Operation at wind speeds other than the design speed produced angles of attack that were not optimal. The direction of the lift vector is perpendicular to the relative airflow (RAF). If the RAF angle is analysed in figures 4.4 and 4.5 it can be seen that if 90^0 is added to the direction of the RAF the resultant direction of the lift force is not in the ideal direction for producing torque about the turbine's shaft. This is particularly evident near the tips. The direction of the lift force tends to bend the blade tips away from the wind more than it tends to rotate them about the shaft. This force results in "coning" of the blades and is a structural design consideration with HAWT's.

4.6 DIRECTION OF THE LIFT VECTOR – DARRIEUS ROTOR

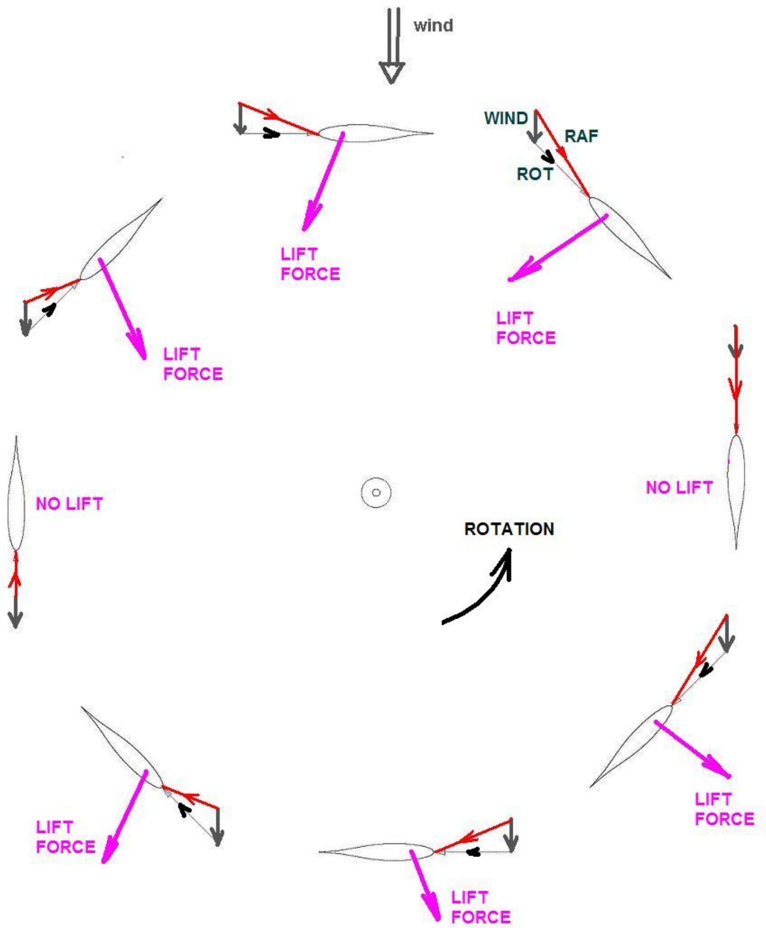

Figure 4.6 RAF and lift force directions Darrieus rotor

The direction of the RAF and the lift vector are shown at various positions during one revolution of a Darrieus rotor. The RAF is calculated by summing the wind vector and the rotational speed vector. The lift force is perpendicular to the RAF. If the line of action of the RAF is extended it can be seen that it has a small effective radius about the axis of rotation of the machine. This is the primary reason for the low torque capability of the machine and its poor starting torque.

4.7 DISCUSSION

It is evident that both the HAWT and the Darrieus both have fundamental drawbacks, yet these are the only 2 types of wind turbine in large scale use. It is the opinion of the author that a device can be developed that does not suffer the drawbacks listed above and yet can produce a viable amount of energy at low tip speed ratios. The high tip speed ratios that are required to make the HAWT and Darrieus effective result in unnecessary noise, blade fatigue, requirement for very accurate balancing and catastrophic results in the case of blade failure. The device upon which this project is based is intended to operate at low tip speed ratios, yet still produce viable amounts of energy in a safe, quiet manner.

4.8 DIRECTION OF THE RAF – PROPOSED DEVICE

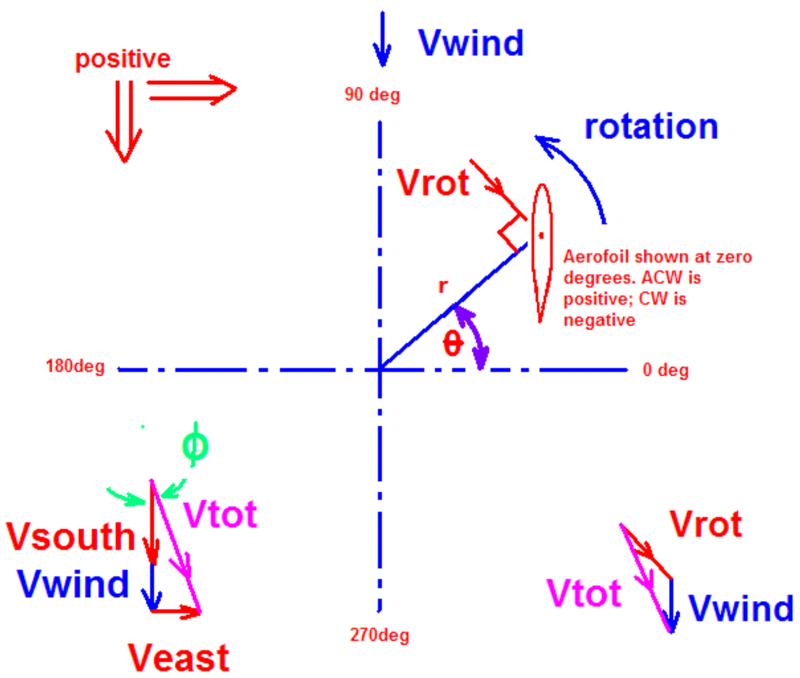

Figure 4.7 RAF direction and magnitude

Figure 4.7 shows the method used to sum the wind and rotational velocity vectors to obtain the resultant relative airflow (RAF) velocity. The rotational velocity vector was resolved into vertical and horizontal components referred to as V_{south} and $V_{east.}$ V_{south} was summed with $V_{wind.}$ The total was then vector summed with V_{east} using Pythagoras to obtain V_{tot} which is the magnitude of the relative airflow (RAF). The direction of the RAF was obtained by considering the right angled vector triangle and solving for the appropriate angle. Lift force and torque were also calculated and are explained by example considering the values in the column for the 60^{o} turbine position in Figure 4.8.

	Units		FRONT HALF												
	deg	ϴ	0	15	30	45	60.0	75	90	105	120	135	150	165	180
Angular speed	RPM	86.9	87	87	87	87	86.9	87	87	87	87	87	87	87	87
r	m	0.84	1	1	1	1	0.8	1	1	1	1	1	1	1	1
Vrot	m/s		8	8	8	8	7.6	8	8	8	8	8	8	8	8
Vwind	m/s	16	16	16	16	16	16.0	16	16	16	16	16	16	16	16
Vrot(south comp)	m/s		8	7	7	5	3.8	2	0	-2	-4	-5	-7	-7	-8
Vrot(east comp)	m/s		0	2	4	5	6.6	7	8	7	7	5	4	2	0
Vsouth(total)	m/s		24	23	23	21	19.8	18	16	14	12	11	9	9	8
Vtot	m/s		24	23	23	22	20.9	19	18	16	14	12	10	9	8
RAF direction	deg		0	5	10	14	18.5	22	26	28	29	27	22	13	0
desired a of a	deg		10	10	10	10	10.0	10	10	10	10	10	10	10	10
reqd angle	deg		10	15	20	24	28.5	32	36	38	39	37	32	23	10
F (lift force)	N		193	190	182	168	150.9	131	109	87	66	49	35	27	24
Φ (lift force dir)	deg		90	95	100	104	108.5	112	116	118	119	117	112	103	90
H (hor comp of F)	N		193	190	179	163	143.1	121	98	76.8	58.3	43.5	32.8	26.3	24.1
M (mom arm)	m		0.00	0.22	0.42	0.59	0.7	0.81	0.84	0.81	0.73	0.59	0.42	0.22	0.00
T (Torque)	Nm		0	41.2	75.3	97	104.1	98	82.3	62.3	42.4	25.9	13.8	5.72	0

	Units	BACK HALF											
	deg	195	210	225	240	255	270	285	300	315	330	345	360
Angular speed	RPM	87	87	87	87	87	87	87	87	87	87	87	87
r	m	1	1	1	1	1	1	1	1	1	1	1	1
Vrot	m/s	8	8	8	8	8	8	8	8	8	8	8	8
Vwind	m/s	16	16	16	16	16	16	16	16	16	16	16	16
Vrot(south comp)	m/s	-7	-7	-5	-4	-2	0	2	4	5	7	7	8
Vrot(east comp)	m/s	-2	-4	-5	-7	-7	-8	-7	-7	-5	-4	-2	0
Vsouth(total)	m/s	9	9	11	12	14	16	18	20	21	23	23	24
Vtot	m/s	9	10	12	14	16	18	19	21	22	23	23	24
RAF direction	deg	-13	-22	-27	-29	-28	-26	-22	-18	-14	-10	-5	0
desired a of a	deg	10	10	10	10	10	10	10	10	10	10	10	10
reqd angle	deg	-23	-32	-37	-39	-38	-36	-32	-28	-24	-20	-15	-10
F (lift force)	N	27	35	49	66	87	109	131	151	168	182	190	193
Φ (lift force dir)	deg	-103	-112	-117	-119	-118	-116	-112	-108	-104	-100	-95	-90
H (hor comp of F)	N	26.3	32.8	43.5	58.31	76.8	98	121	143	163	179	190	193
M (mom arm)	m	0.22	0.42	0.59	0.73	0.81	0.84	0.81	0.73	0.59	0.42	0.22	0.00
T (Torque)	Nm	5.72	13.8	25.9	42.42	62.3	82.3	98	104	97	75.3	41.2	0

↑ **example used**

Figure 4.8 Magnitude of RAF,lift force and torque

The experimental platform had the following specifications which were used for the calculation example: Aerofoil span=1300mm; Aerofoil chord=400mm; Turbine radius=840mm. It was found in later testing that a TSR=0.478 yielded the best power coefficient for this particular device and this value was used in the calculation example. At an assumed wind speed of 16m/s and with a TSR=0.478 the rotational speed would be:

$$N = \frac{60V}{\pi D} \tag{4.8}$$

$$N = \frac{60(16)(0.478)}{\pi(0.84)2}$$

$$N = 86.94 rev/\min$$

$$V_{rot} = \frac{\pi DN}{60} \tag{4.9}$$

$$V_{rot} = \frac{\pi(0.84)2(86.94)}{60}$$

$V_{rot} = 7.65m/s$

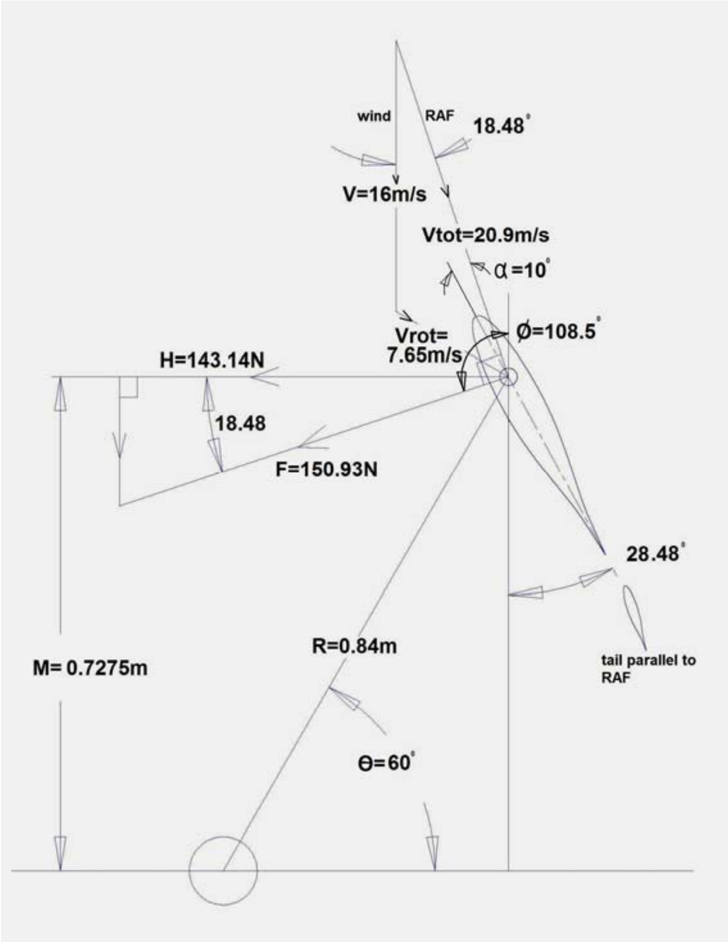

Figure 4.9 Direction of RAF and forces at 60° turbine position

Equation (4.1) was used to calculate the lift force.

$$F = C_L \frac{1}{2} \rho V^2 A$$

$$F = (1.1)\ \frac{1}{2}(1.208)(20.9)^2(1.3)(0.4)$$

$$F = 150.93N$$

Variables used: ρ = 1.208 kg/m^3 ; A = 1.3×0.4 = 0.52 m^2 ; C_L = 1.1 (read off graph)[12]

The lift force was resolved into vertical and horizontal components. Torque was calculated using the product of the horizontal component of the lift force and the dimension M.

The horizontal component of the lift force H:

$H = F\cos(90-\Phi)$ for the front half (4.10)

$H = 150.93\cos(90-108.5)$

$H = 143.14N$

$H = F\cos(90+\Phi)$ for the back half (4.11)

The effective moment arm of this component:

$M = r(\sin\theta)$ (4.12)

$M = 0.84(\sin 60)$

$M = 0.728m$

The Torque produced would be the horizontal component of the lift force multiplied by the effective moment arm

$T = H.M$ (4.13)

$T = 143.14(0.728)$

$T = 104.12Nm$

Based on the values in Figure 4.8 the orientation of the aerofoils at various positions in the rotation circle for 87 rev/min and 16m/s wind speed would be as shown in Figure 4.10

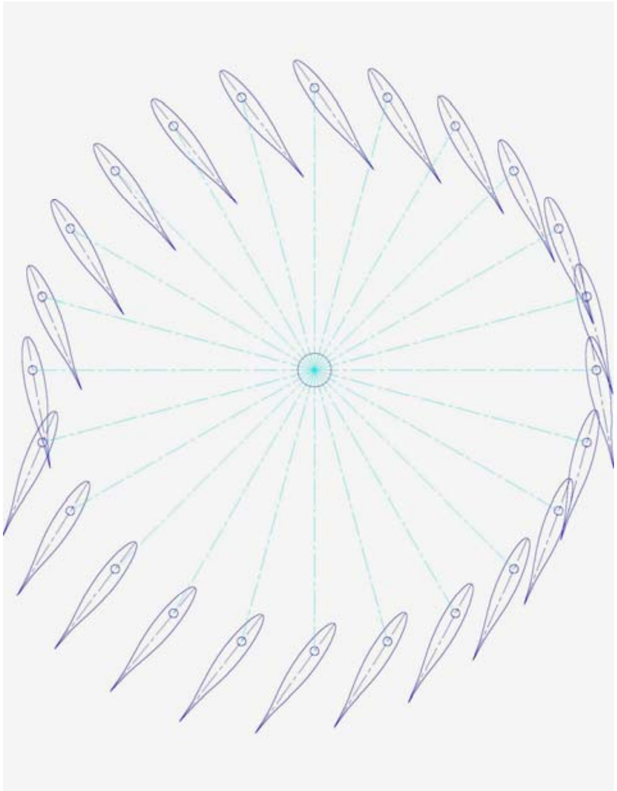

Figure 4.10 Aerofoil orientation

Figure 4.11 shows Torque plotted against Rotation angle

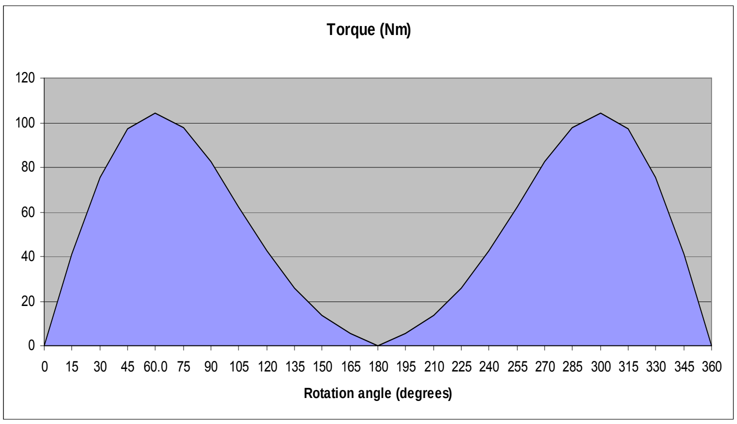

Figure 4.11 Torque output from main shaft

The work done per revolution was calculated by determining the area of the graph. The graph was symmetrical.

$$W = T\theta \qquad (4.14)$$

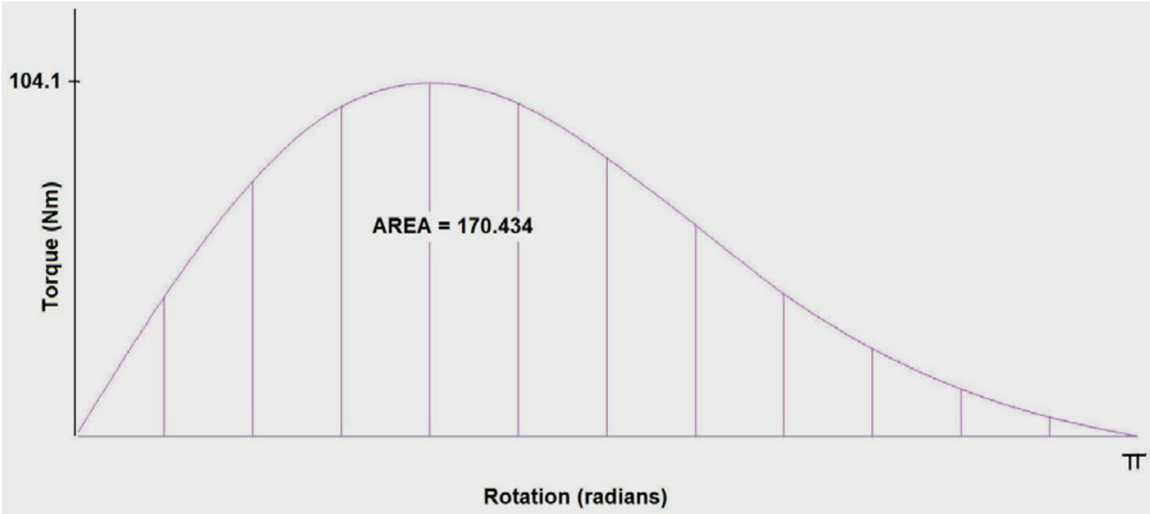

Figure 4.12 Torque graph area (half revolution)

$W = (170.434)2$

$W = 340.86 J / rev$

At 86.94 rev/min (1.449 rev/s):

$P = 340.86(1.449)$

$P = 493.9W$

This would be the theoretical power produced by one blade, neglecting blade drag losses as well as wake effects between blades. Due to the low solidity of the device and the low TSR the method used above should provide a reasonable approximation of power output. The calculations assume that sufficient resisting torque was applied to the output shaft to maintain the chosen speed.

4.9 DIRECTION OF THE LIFT VECTOR – PROPOSED DEVICE

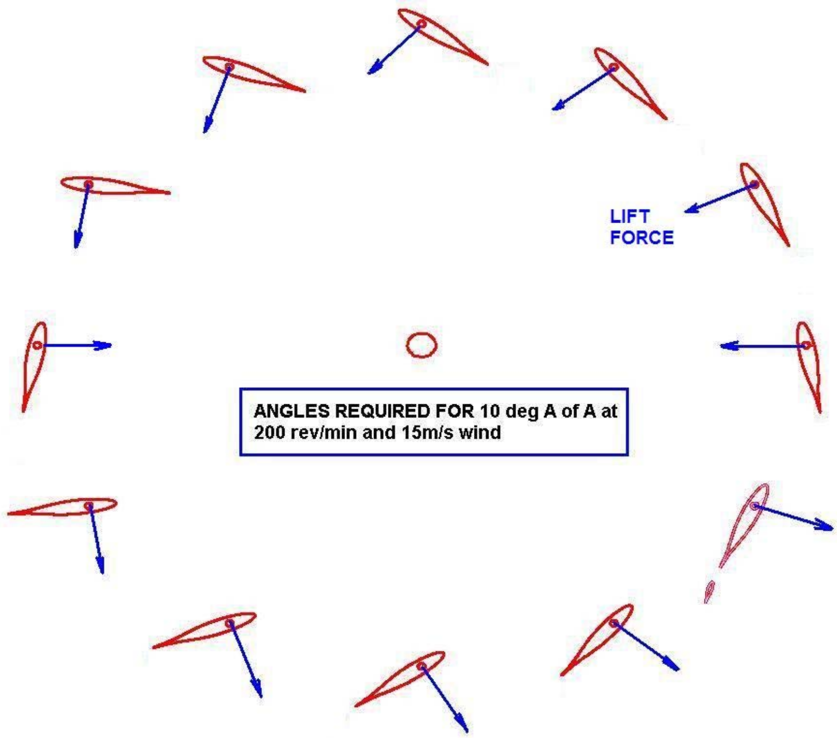

Figure 4.13 Required angles – proposed device

Figure 4.13 shows the orientation of the aerofoils and their lift forces at 200 rev/min with a 15 m/s wind. If reviewed in comparison to Figure 4.6 and if the lines of action of the lift vectors are extended, it is apparent that a larger effective crank radius exists about the main shaft at most positions in comparison to the Darrieus rotor. This gives the device a larger torque output than the Darrieus rotor.

4.10 EFFICIENCY PREDICTIONS - PROPOSED DEVICE

According to Gipe[24] the total power in the wind is:

$$P_{wind} = \frac{1}{2}\rho \cdot A \cdot V^3 \qquad (4.15)$$

Where ρ is air density; A is the vertical cross section of wind considered and V is the wind velocity. Considering the vertical cross section of wind to which the device is exposed as being 1.68 m by 1.3 m; the total wind power available at 16 m/s is:

$$P_{wind} = \frac{1}{2}(1.208)\cdot(1.68)\cdot(1.3)\cdot(16^3)$$

$$P_{wind} = 5403.18W$$

The power coefficient (efficiency) of the device

$$C_p = \frac{P_{output}}{P_{wind}} \quad (4.16)$$

$$C_p = \frac{493.9}{5403.18}$$

$$C_p = 0.0914$$

$C_p = 9.14\%$ (*this is for one blade, neglecting induced drag, blade aspect ratio considerations and mechanical losses)*

4.11 DISCUSSION

Figures 4.10 and 4.13 show the blade orientations at two different rotational speeds. It is evident that as the rotational speed increases the solidity of the device increases. It would seem logical that a high solidity (such as the farm windmill) would yield high output (C_p) however this is not the case. The reason for this was determined by Albert Betz in 1926[24] and is well explained by quoting Gipe[24]."We must strike a balance between a rotor that completely stops the wind and one that allows the wind to pass through unimpeded". Betz demonstrated mathematically that the optimum was reached when the rotor reduced the wind speed by one third. By conserving two thirds of the wind's momentum after passing through the rotor an optimal quantity of the wind passed through the blades rather than being deflected around them. A rotor disc of high solidity would cause most of the wind to pass around it and little energy would be extracted from the wind by the blades. Betz concluded by using a linear momentum theory[24] that the maximum power that could be extracted by a propeller type turbine was 16/27 of the total wind power (59%).

4.12 SUMMARY

For the proposed device to have an advantage over HAWT or Darrieus machines its unique features should be exploited. The low solidity at low rotational speeds is a unique phenomenon not found in other machines. At low speeds it is possible to have a large blade area, yet still have a low solidity. According to the Betz principle explained in 4.11 this holds advantages. Performance tests in the following chapters are all based on a device with the same blade area. Future tests on blades of increased area are worth pursuing.

CHAPTER 5

CALIBRATION OF DATA MEASUREMENT SYSTEM

5.1 INTRODUCTION

Determining the actual torque output from the main shaft was necessary to obtain meaningful power coefficient values. Two different methods were used to obtain actual torque values, namely:

- Measuring the holding torque required on the casing of the generator by means of a load cell
- Measuring the actual electrical power output from the generator and factoring this for mechanical and electrical efficiency

The first method was used during early experiments and the recorded data was used to calculate the actual torque input to the generator. This system did not allow for the mechanical losses in the drive system. It also required AC power for the loadcell which was available during static testing but not when using the mobile test platform. A simpler and more effective means of determining the output power was to measure the actual electrical output and determine a single efficiency correction factor for the mechanical drive system and electrical generator. Applying this factor to the value of the electrical output power would enable the actual power in the main shaft to be determined. The tests conducted to obtain the efficiency compared actual input torque to the main shaft, against actual electrical power output. Various methods were investigated and attempted to accurately input the required amount of torque. The simplest and most effective was to remove the wind turbine and replace it with a drum. A cord was wound around the drum and a steady pull manually applied via a spring balance.

5.2 TEST METHOD FOR DETERMINING THE EFFICIENCY

To ensure that an accurate result was obtained the drive system was tested in the same configuration as it was used in actual wind performance tests. The top shaft and aerofoils were removed. The chain lubrication as well as chain and belt tensions were not altered in anyway from that used in actual wind performance tests.

- A drum of 295mm diameter was attached to the main shaft in the place of the top shaft.
- 30m of cord was wound around the drum.
- The drum was rotated by applying a tensile force to the cord by means of a calibrated spring balance.
- Electrical output and rotational speed was logged at various cord tensions.

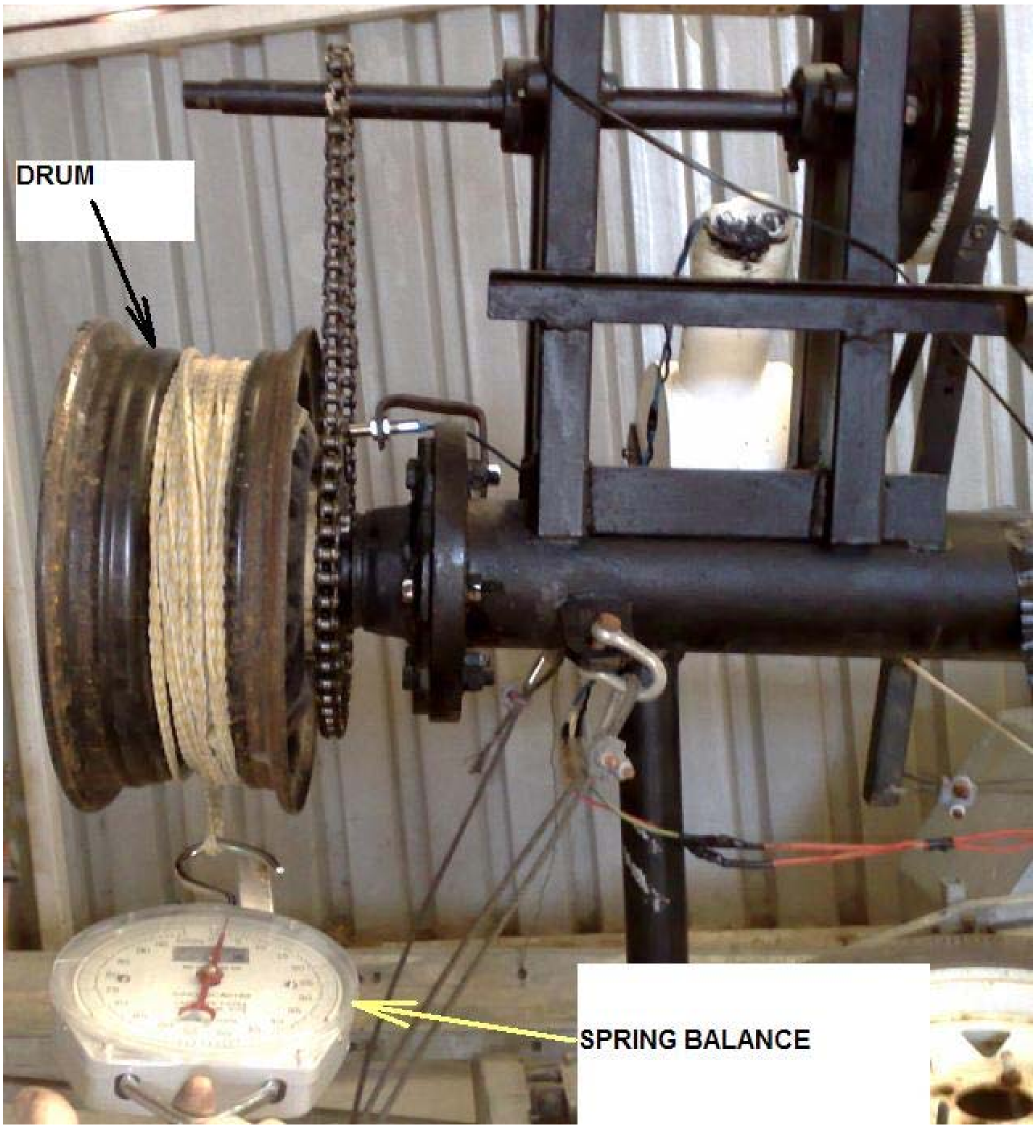

Figure 5.1 Experimental setup for efficiency measurements

5.3 TEST RESULTS

An extract from the full set of test results as appearing in Appendix C is shown in Table 5.2. The headings are defined as follows:

Heading	Units	Comment
Time	Actual time of day (local)	
Input Torque	Nm	Calculated as product of drum radius and cord tension
Input Power	W	Calculated using input torque and rotational speed
Voltage	V	Recorded by logger
Amps	A	Recorded by logger
Output Power	W	Calculated using product of voltage and amperage
Rot spd	rev/m	Recorded by logger
Eff	factor	Quotient of output power and input power
Eff %	%	Efficiency factor expressed as percentage

Table 5.1 Definition of headings

TIME	Input Torque (Nm)	Input Power (W)	Voltage	Amps	Output Power W	Rot spd RPM	Eff	Eff %
low electrical load		10kg pull						
12:31:04	14.5	53.0	24.615	0.82	20.28	35.00	0.38	38.2
12:31:06	14.5	92.4	22.623	0.7	15.88	61.00	0.17	17.2
12:31:08	14.5	78.8	20.22	1.07	21.59	52.00	0.27	27.4
12:31:10	14.5	72.7	20.733	0.64	13.29	48.00	0.18	18.3
12:31:12	14.5	77.3	22.256	0.7	15.62	51.00	0.20	20.2
12:31:14	14.5	86.4	20.132	0.7	14.13	57.00	0.16	16.4
12:31:16	14.5	86.4	19.311	0.64	12.38	57.00	0.14	14.3
12:31:18	14.5	77.3	26.637	0.76	20.32	51.00	0.26	26.3
12:31:20	14.5	62.1	18.608	0.58	10.79	41.00	0.17	17.4
12:31:23	14.5	74.2	22.696	0.82	18.7	49.00	0.25	25.2
12:31:25	14.5	89.4	18.974	0.82	15.63	59.00	0.17	17.5
12:31:27	14.5	81.8	20.103	0.7	14.11	54.00	0.17	17.2
12:31:29	14.5	77.3	25.538	1.01	25.72	51.00	0.33	33.3
12:31:31	14.5	68.2	21.201	0.64	13.59	45.00	0.20	19.9
12:31:33	14.5	74.2	19.385	0.64	12.43	49.00	0.17	16.7
12:31:35	14.5	74.2	19.722	0.64	12.64	49.00	0.17	17.0
12:31:37	14.5	66.7	17.788	0.7	12.49	44.00	0.19	18.7
12:31:39	14.5	62.1	24.601	0.95	23.27	41.00	0.37	37.5

12:31:41	14.5	81.8	18.168	0.58	10.54	54.00	0.13	12.9
12:31:43	14.5	77.3	16.982	0.7	11.92	51.00	0.15	15.4
12:31:45	14.5	63.6	24.513	0.76	18.7	42.00	0.29	29.4
12:31:47	14.5	65.2	21.143	0.64	13.55	43	0.21	20.8
12:31:49	14.5	80.3	17.978	0.58	10.43	53	0.13	13.0
12:31:51	14.5	72.7	18.081	0.7	12.69	48	0.17	17.5
12:31:53	14.5	57.6	16.821	0.7	11.81	38	0.21	20.5
12:31:55	14.5	75.8	19.487	0.58	11.3	50.00	0.15	14.9
12:31:57	14.5	83.3	18.242	0.64	11.69	55.00	0.14	14.0
12:31:59	14.5	66.7	19.531	0.64	12.52	44.00	0.19	18.8
12:32:01	14.5	65.2	18.799	0.64	12.05	43.00	0.18	18.5
12:32:03	14.5	78.8	25.114	0.7	17.63	52.00	0.22	22.4
12:32:05	14.5	72.7	20.762	0.7	14.57	48.00	0.20	20.0
12:32:07	14.5	56.1	17.084	0.7	11.99	37.00	0.21	21.4
12:32:09	14.5	66.7	16.322	0.58	9.467	44.00	0.14	14.2
12:32:11	14.5	66.7	17.465	0.52	9.064	44.00	0.14	13.6
12:32:13	14.5	54.5	17.172	0.58	9.96	36.00	0.18	18.3
12:32:15	14.5	71.2	17.07	0.64	10.94	47.00	0.15	15.4
12:32:17	14.5	74.2	17.026	0.52	8.836	49.00	0.12	11.9
12:32:19	14.5	62.1	18.711	0.82	15.42	41.00	0.25	24.8
12:32:21	14.5	6.1	0.015	-0.09	-0	4.00	0.00	0.0
							ave	**19.4**
low electrical load 15kg pull								
12:34:09	21.7	9.1	15.326	0.46	7.019	4.00	0.77	77.2
12:34:11	21.7	175.0	39.238	1.13	44.3	77.00	0.25	25.3
12:34:13	21.7	195.5	40.41	1.25	50.59	86.00	0.26	25.9
12:34:15	21.7	186.4	32.747	1.25	41	82.00	0.22	22.0
12:34:17	21.7	193.2	31.429	1.44	45.1	85.00	0.23	23.3
12:34:19	21.7	209.1	42.403	1.31	55.68	92.00	0.27	26.6
12:34:21	21.7	179.6	33.744	1.19	40.16	79.00	0.22	22.4
12:34:23	21.7	211.4	39.546	1.31	51.92	93.00	0.25	24.6
12:34:25	21.7	193.2	32.264	1.62	52.2	85.00	0.27	27.0
12:34:27	21.7	197.7	41.377	1.5	61.9	87.00	0.31	31.3
12:34:29	21.7	220.5	43.165	1.25	54.04	97.00	0.25	24.5
12:34:31	21.7	181.8	32.982	1.37	45.32	80.00	0.25	24.9
12:34:33	21.7	197.7	33.744	1.37	46.36	87.00	0.23	23.4
12:34:35	21.7	206.8	37.993	1.25	47.57	91.00	0.23	23.0
12:34:37	21.7	193.2	39.355	1.31	51.67	85.00	0.27	26.7
12:34:39	21.7	220.5	41.04	1.92	78.92	97.00	0.36	35.8
12:34:41	21.7	200.0	34.154	1.37	46.93	88.00	0.23	23.5
12:34:43	21.7	190.9	30.872	1.25	38.65	84.00	0.20	20.2
12:34:45	21.7	215.9	43.326	1.62	70.1	95.00	0.32	32.5
12:34:47	21.7	188.7	34.359	1.25	43.02	83.00	0.23	22.8
12:34:49	21.7	202.3	31.399	1.44	45.06	89.00	0.22	22.3

See appendix c for full set of results

Table 5.2 Test results

The test was repeated for 10kg, 15kg and 20kg loads at low, ½ and ¾ electrical loads. For tabulated results of all the measurements see Appendix C. The raw data obtained from the logger is displayed in Figure 5.2.

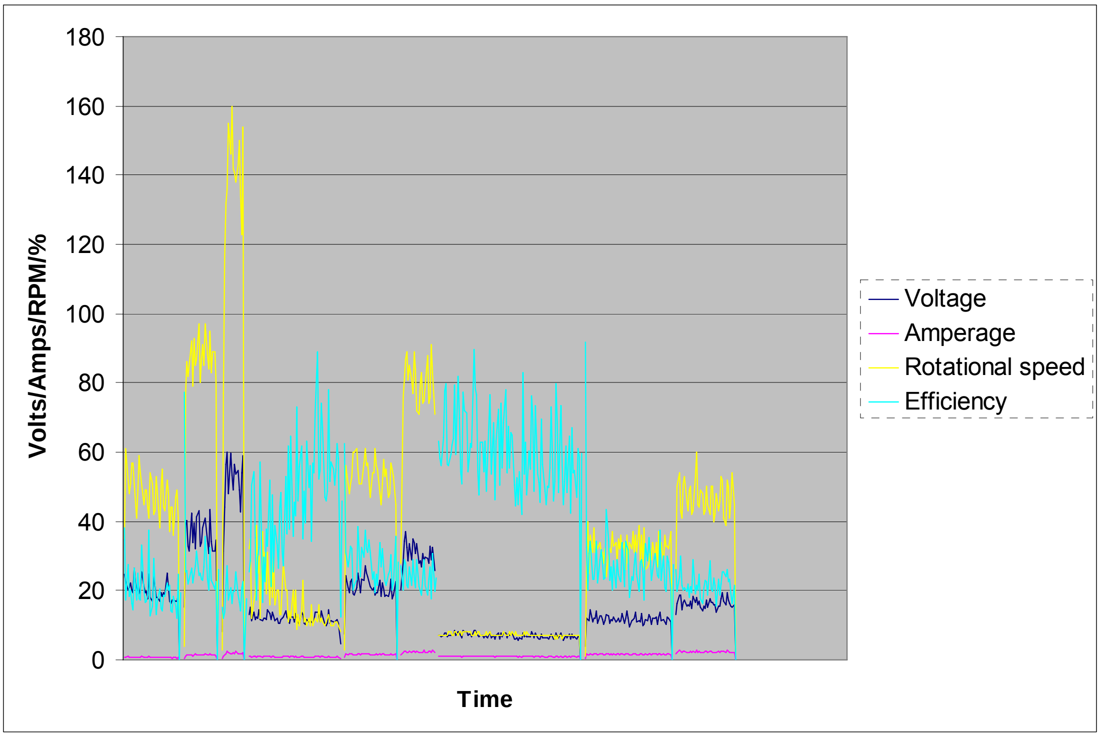

Figure 5.2 Test data graph

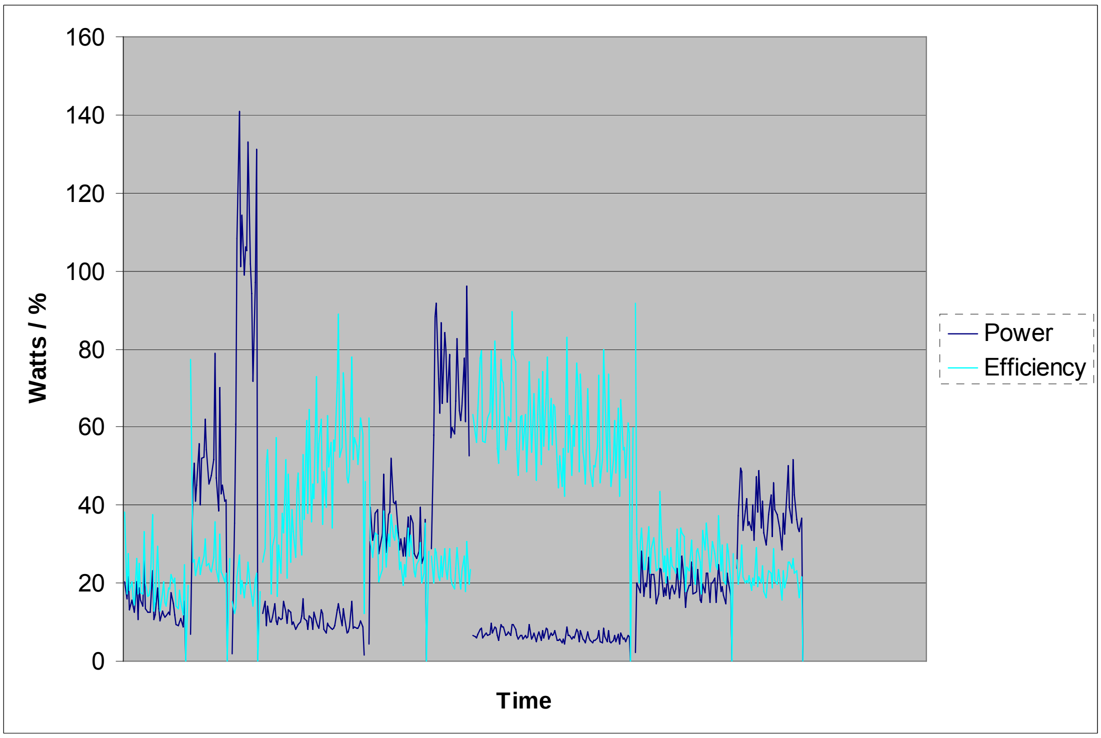

Figure 5.3 Efficiency / Output Power relationship

5.4 DISCUSSION

In Figure 5.3 it was evident that when the power output was below approximately 20W, the efficiency increased to as high as 90%. Any increase over approximately 20W however, resulted in the efficiency reducing to, and stabilising at approximately 20%. The expected performance measurements were all likely to be well over 20W, hence it was decided to use the 20% efficiency figure throughout in future performance measurements and analysis (Chapter 8).

CHAPTER 6

FUNCTIONALITY TESTING OF EXPERIMENTAL PLATFORM

6.1 INTRODUCTION

In this chapter a number of different tests were conducted to evaluate the functionality and performance of the experimental platform. Due to the lack of literature on a device such as this, many aspects of its design required testing and refinement before its functionality was at an adequate level to perform the actual performance testing covered in Chapter 8. The sequence of the tests was conducted in the chronological order in which they are presented. Subsequent tests were normally based on a deficiency or possible improvement identified in the preceding test.

6.2 STABILITY AND GEAR RATIO TESTING

The aim was to determine the functionality of the device at wind speeds of 7-10 m/s with emphasis on determining the suitability of initial gear ratio (136 teeth to 28 teeth =4.86:1) as well as the stability. The vertical axis reciprocating aerofoil wind energy harvester was setup as shown in Figure 6.1 with 3 aerofoils of chord 400mm and span 1300mm running at a radius of 840mm. The generator fitted was a Kestrel 300 generator type 0501 (serial number NMMU) coupled to main shaft via 5M HTD belt running on pulleys of 136 teeth and 28 teeth.

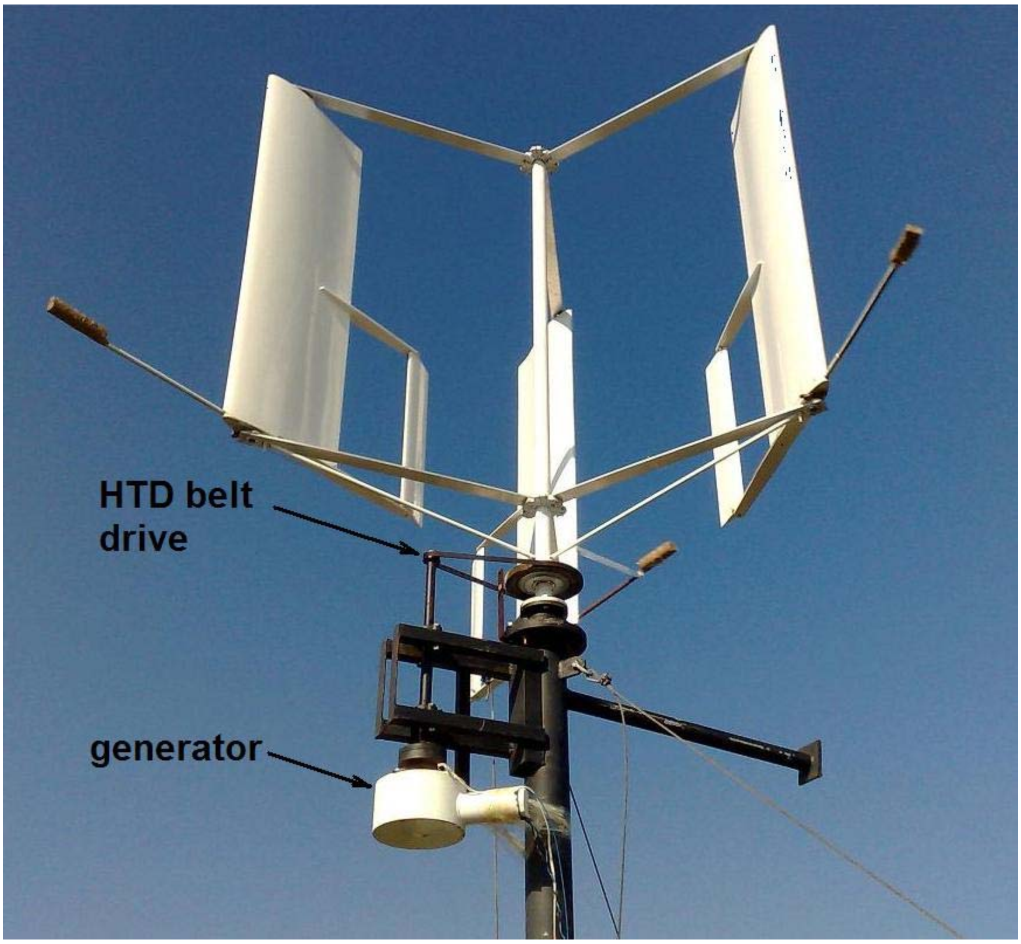

Figure 6.1:Setup of reciprocating aerofoil wind energy harvester

An Eagle Tree “e-Logger V3” with live computer display and data logging of amperage, voltage, power, ampere-hrs and rotational speed was utilised. A Pace Scientific WSD-100 wind speed and direction sensor was utilised to capture wind data which was logged on the XR5 data logger. The wind logger was set to record at 1s intervals and started after which the brake was applied and the mast raised by means of the hand winch. Once the mast was secured in the vertical position the brake was released and the device started to rotate automatically. The e-Logger was started precisely at the turn of a minute (using the computer clock) and the date and time used as a file name for the logged data. This allowed synchronisation between logged wind data and electrical output data. Photographs and video footage was taken for analysis. The device was allowed to run for 10 minutes after which the brake was applied and the loggers stopped.

Data was saved and imported into “Excel” for analysis. File names used were based on date and time to avoid confusion between experiments.

6.2.1 Results

Average wind speed, voltage, rotational speed, amperage and power output values are tabulated in Table 6.1 for the 10 minute test period. Analysis of the video footage and photographs showed that at times the aerofoils moving downwind in the rear half of the rotation circle became unstable. Figure 6.2 illustrated the orientation of aerofoil C which when compared to the expected orientation in Figure 4.13 showed the instability. The rotational speed was also visibly seen to reduce following periods of instability.

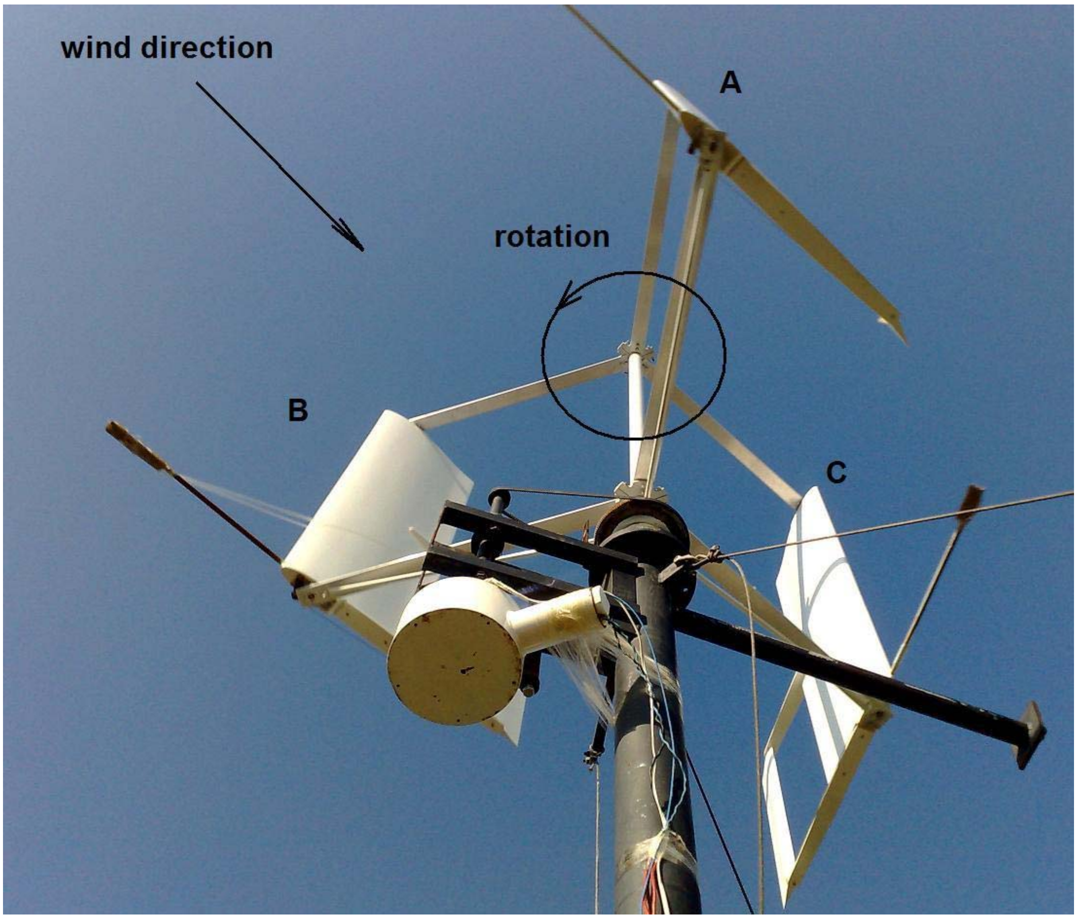

Figure 6.2: Observed instability of downwind aerofoil

Wind Speed (m/s)	Voltage (V)	Rotational speed of generator (rev/min)	Rotational speed of main shaft (rev/min)	Amperage (Amps)	Power (W)
7.66	3.83	253	52	2.38	9.11

Table 6.1 Results of Experiment 6.2

6.2.2 Analysis

The radius of the rotation circle of the aerofoils was measured to be 840mm. With a rotational speed of 52 rev/min the instantaneous linear velocity of the downwind aerofoil was calculated as follows:

$$V = \frac{\pi \cdot D \cdot N}{60} \qquad (6.1)$$

Where D = 1.68m and N = 52 rev/min

$V = 4.57 m/s$

In 4.8 it was noted that if the instantaneous linear velocity of the aerofoil exceeded the wind speed the tail would attempt to align the aerofoil with the relative airflow and the aerofoil would reverse direction. If the rotational speed were steadily increased it would be likely to see instability as the peripheral speed approached wind speed. The calculated value for V based on average rotational speed was less than the average wind speed, however analysis of the data revealed peak values of V in excess of the wind speed for brief periods which were likely to have caused brief periods of instability. The device occupied a vertical rectangular shaped cross sectional area of 1.3m vertically by 1.68m horizontally. The theoretical total wind power available from this cross sectional area based on the kinetic energy of the moving wind mass can be calculated as:

$$P_{wind} = \frac{1}{2}\rho \cdot A \cdot V^3$$ (using equation 4.10)

Using the average value of wind speed recorded of 7.66 m/s (from Table 6.1); air density of 1.208 kg/m^3;

$$P_{wind} = \frac{1}{2}(1.208)(1.3)(1.68)7.66^3$$

$$P_{wind} = 593W$$

The absolute efficiency of the device during this experiment was therefore:

$$\eta = \frac{P_{output}}{P_{wind}}$$ (using equation 4.11)

$$\eta = \frac{9.11}{593}$$

$$\eta = 1.54\%$$

6.2.3 Conclusions

The extremely low calculated efficiency is likely to have been caused by the aerodynamic braking effect caused whenever the device became unstable. The generator was unable to adequately resist the torque produced by the device and prevent instability speed being reached (even when the output wires were short circuited). The aerodynamic braking effect caused at speeds above instability speed appear to render the device safe from overspeed failures in high wind conditions. The rated power of the generator was 300 W at 500 rev/min, hence it should have had the capacity to provide adequate restraining torque to prevent instability, provided its rotational speed was high enough. To achieve this the speed increasing ratio between the main shaft and generator required increasing.

6.3 MOVING PLATFORM FEASIBILITY TESTING

The aim of this experiment was to determine the feasibility of mounting the device on a moving vehicle to simulate higher wind speeds and to test the altered gear ratio of 17.93:1. A further aspect to check was whether the turbulence normally experienced in close proximity to the ground would be lessened by moving the device through relatively still air rather than placing it in wind of the equivalent strength. The only change to the machine from experiment 6.2 was the addition of the secondary shaft and chain drive to increase the gear ratio. The chain drive had sprockets of 48 and 13 teeth in the total gear ratio of:

$$G = \frac{T_1}{T_2} \cdot \frac{T_3}{T_4} \tag{6.2}$$

$$G = \frac{136}{28} \cdot \frac{48}{13}$$

$$G = 17.93$$

Light bulbs were used as the electrical load. These were arranged in banks of five wired in parallel. A total of sixty 12V bulbs of 21W each were used.

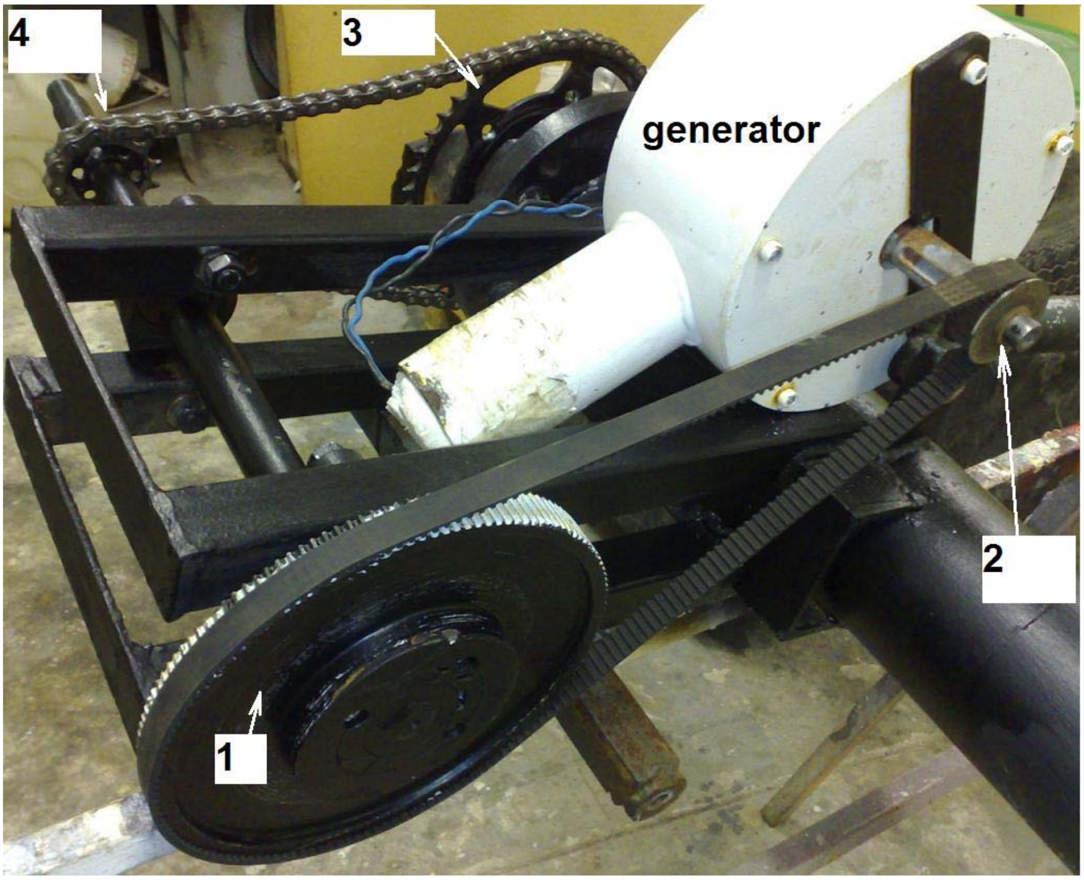

Figure 6.3: Belt and chain drives

Figure 6.4: Moving test platform

The vehicle and trailer were positioned at the downwind end of a 1000m long aircraft runway as depicted in Figure 6.4. The electrical load was disconnected and the mast raised by means of the hand winch with the brake applied. Once the mast was secured in the vertical position the brake was released and the device started to rotate automatically in the ambient wind which was estimated to be 5 m/s. The vehicle was then accelerated to a speed of 40km/h and this speed maintained. The observer regulated the electrical load whilst observing the rotation of the device.

6.3.1 Observations

It was possible to regulate the speed of rotation of the device by altering the number of banks of light bulbs connected. The device could also be completely stopped by connecting all the lights. When all electrical load was disconnected the device would overspeed (as described in 6.2). It was noted that 3 banks of lights resulted in a steady rotation (approximately 315W).

6.3.2 Conclusions

The generator was able to adequately resist the torque produced by the device and hence the gear ratio was deemed to be suitable for further testing. The mobile experimental platform was considered to be feasible for use in future testing when adequate wind was not available. The smoothness of operation observed, suggested that turbulence was less than when the unit was static and experiencing similar wind speeds. It was concluded that the mobile platform would be an inexpensive way of simulating the lesser turbulence that would be experienced at the top of a high mast and a feasible alternative to wind tunnel testing.

6.4 AEROFOIL MASS BALANCE TESTING

To minimise rotation of the aerofoils about their pivots due to centrifugal effects it was decided to add mass balances (see Chapter 3) to each aerofoil to position the centre of gravity of the aerofoil close to its pivot. The aim of this experiment was to determine the effect of increased mass balance weights on stability and to make a comparison with previous experiments where the unit was run with partial balance of approximately 50% (as in 6.2). The experimental platform used was identical to that used in 6.3 except that additional mass was added to the mass balance arms on each aerofoil. The aerofoils were initially intentionally over balanced to an extent of 30%. This was achieved by placing the aerofoils in a horizontal position and adding mass until the aerofoils were hanging level. The total mass applied was noted and a further 30% added. Wind speed and direction sensors were mounted directly below the rotating components as shown in Figure

6.5 and connected to the XR5 data logger. Light bulbs were used for electrical load.

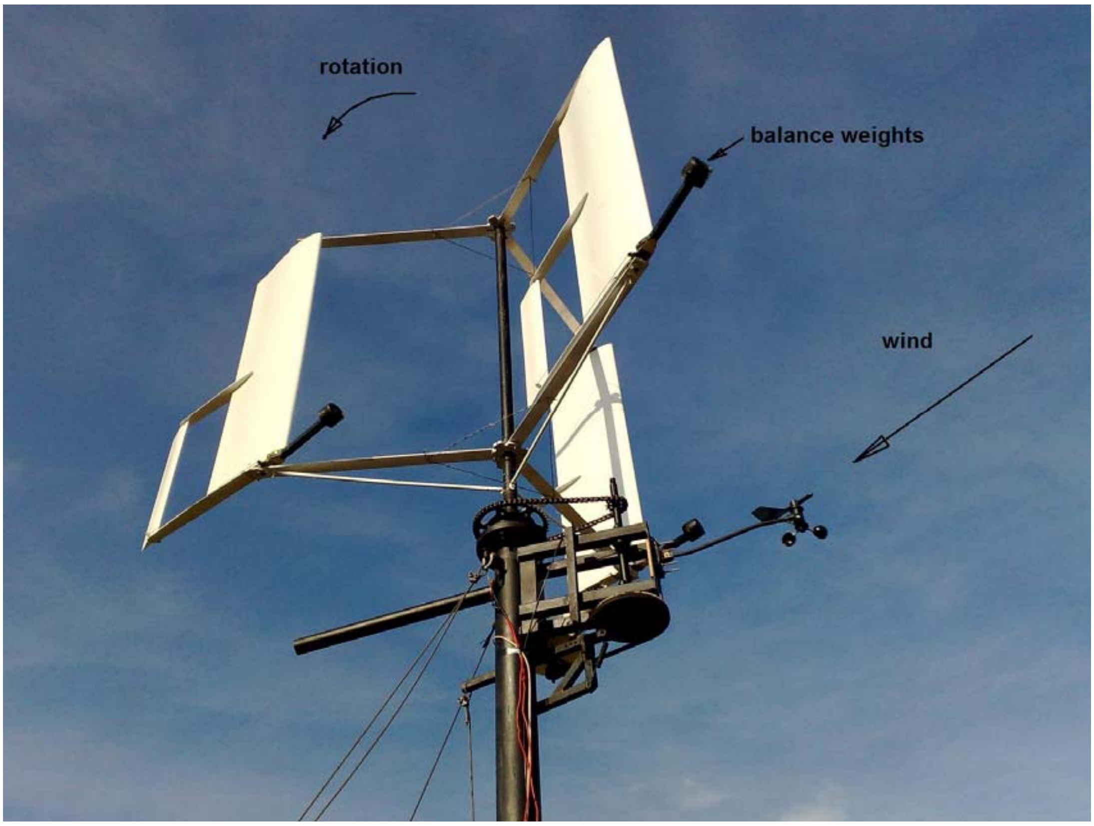

Figure 6.5: Rotation with balance weights of mass (130%)

The wind speed logger was set to display real time data and started. The electrical load was disconnected and the mast raised by means of the hand winch with the brake applied. Once the mast was secured in the vertical position an initial electrical load of three bulbs was connected, the brake was released and the device started to rotate. The motion of the aerofoils was recorded with video footage and still images. The test was repeated with the balance mass reduced to 100%.

6.4.1 Observations

Comparison of Figure 6.5 and 6.2 indicated improved alignment of the aerofoils to that predicted in Figures 4.10 and 4.13. This was observed even when all electrical load was removed and the device was allowed to approach a tip speed ratio of 1. No change in aerofoil alignment was observed on images taken with 100% balance and 130% balance.

6.4.2 Conclusion

Based on review of video footage and still images it was concluded that the device displayed more stable operation with fully balanced aerofoils than with partially balanced aerofoils.

6.5 LIFT FORCE TESTING - Vertical

The aim of this experiment was to determine the actual force generated by each aerofoil and to compare this with the calculated values. Two aerofoils were removed from the machine. A Berkley R0996 load cell with digital read out was attached between one of the radial arms and a temporary structure secured to the mast as shown in Figure 6.6. The load cell was positioned perpendicular to the radial arm.

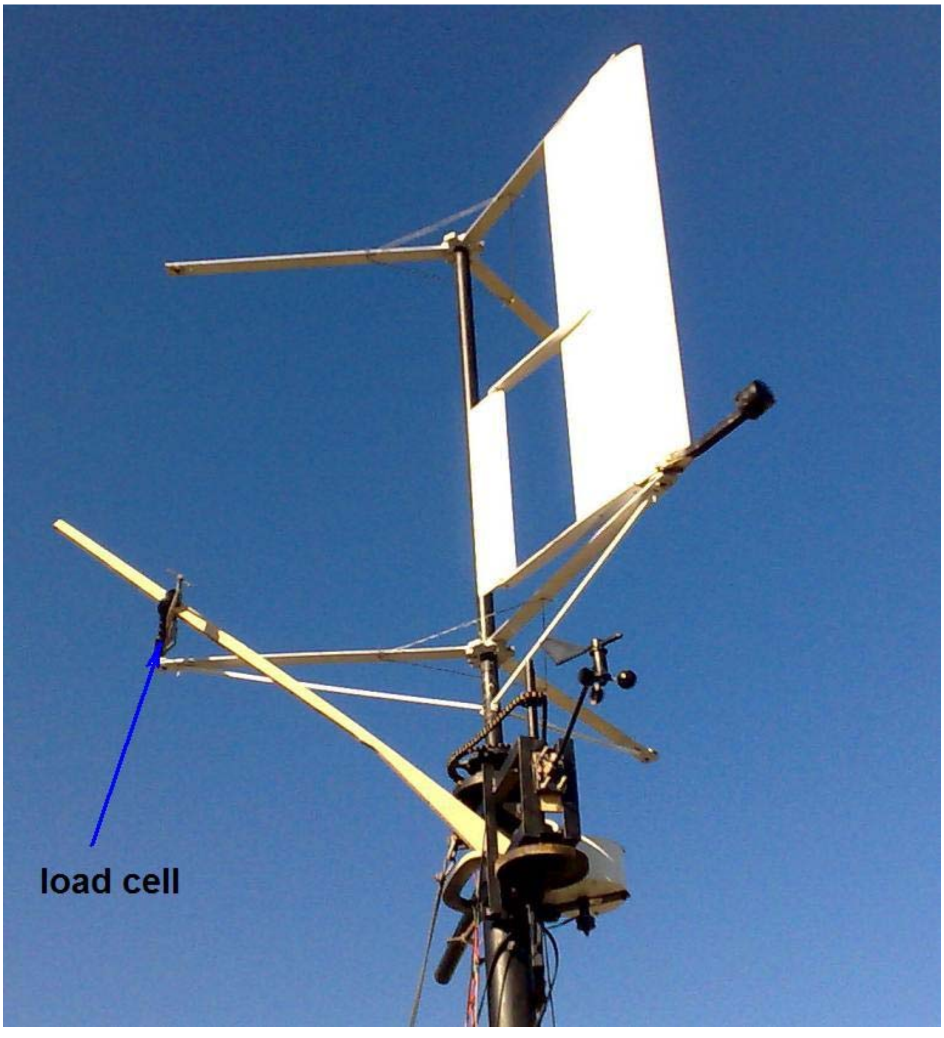

Figure 6.6: Load cell to measure aerodynamic force

The wind speed logger was set to display real time data and started. The mast was raised by means of the hand winch with the brake applied. Once the mast was secured in the vertical position the load cell was reset and the brake released.

6.5.1 Observations

The aerofoil was seen to oscillate by approximately 10^{o} in an erratic manner.

6.5.2 Conclusion

The freely pivoting aerofoil had its tail set at 10^{0} to the main aerofoil. The oscillating motion of the aerofoil was likely to have occurred due to the main aerofoil reaching its critical angle of attack and stalling. Whilst 10^{0} is less than the critical angle for this aerofoil, the turbulence in the wind may have caused it to exceed 10^{0} and reach its critical angle for short periods. Once reaching the stall angle a pitching moment would have occurred which is a likely explanation for the oscillating motion. The force results obtained from this experiment displayed unacceptably high scatter and were not considered satisfactory. A follow up experiment was planned (6.6) with the aerofoil fixed at the correct angle and not allowed to pivot freely.

6.6 LIFT FORCE TESTING - Horizontal

The purpose of this test was to determine the actual aerodynamic force on an aerofoil and to make comparison with the theoretical values. One aerofoil was removed from the machine (as used in previous experiments 6.2 – 6.5) and was mounted horizontally on a vehicle test rig as depicted in Figure 6.7.

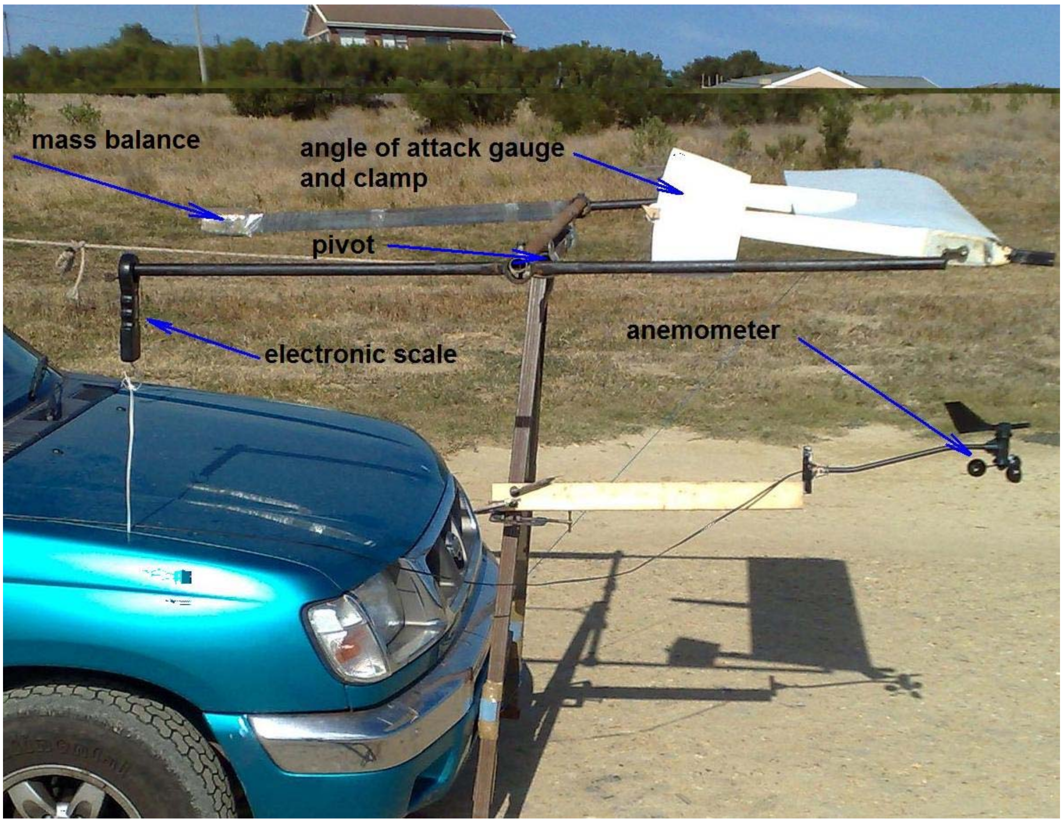

Figure 6.7: Vehicle test rig – lift force

The Pace Scientific WSD-100 anemometer was attached to the vehicle in a position likely to have undisturbed airflow and coupled to the XR5 data logger. A Berkley R0996 electronic scale with digital read out was used for force measurements as well as a spring balance. The wind logger was set to "real time" display and started. The vehicle was positioned at the downwind end of 1000m long aircraft runway. The alignment of the angle of attack gauge was checked by means of a spirit level. The vehicle was then driven at various speeds and readings of force and wind speed were recorded with the assistance of an observer.

6.6.1 Results

Scale readings obtained were as follows.

	kg	N	kg	N	kg	N	kg	N	kg	N
Wind Speed (m/s)	6 deg	6 deg corrected	8 deg	8 deg corrected	10 deg	10 deg corrected	12 deg	12 deg corrected	14 deg	14 deg corrected
10									2	31.392
11									3	41.202
12										
13									4	51.012
14			2	31.392			3	41.202	5	60.822
15									5	60.822
16			3	41.202	3	41.202				
17			4	51.012					5.5	65.727
18	3	41.202			3	41.202	5	60.822		
19	4	51.012					6	70.632		
20					5	60.822			8	90.252
21			6	70.632			10	109.872	10	109.872
22			8	90.252						
23					8	90.252	12	129.492	12	129.492
24	6	70.632	9	100.062						
25	11	119.682	10	109.872						
26			11	119.682						
27	10	109.872								

Table 6.2 Results of Aerofoil / Vehicle test

The mass of the spring balance was 1.2 kg more than that of the electronic scale. Due to the fact that the test rig was balanced for the mass of the electronic scale the readings in table 6.2 needed to all be increased by 1.2kg hence the corrected columns.

6.6.2 Observations

Readings from the electronic scale were found to be erratic. This was likely to be due to the slow sampling rate of the scale and the vibration and movement of the vehicle test rig. The test was stopped and the electronic scale replaced with a spring balance. The readings from the analogue read out of the spring balance were much easier to record and even though the needle fluctuated somewhat it was possible to obtain consistent readings. During the test runs a number of woollen tufts were taped to the underside of the aerofoil. The tufts remained aligned with the airflow at angles of attack of less than 10^{o}. Beyond this angle the rear most tufts were seen to start moving away from the surface of the aerofoil and oscillating from side to side. This was indicative of the aerofoil starting to stall[25]. By 14^{o} all but the front most tufts behaved in the same way. Angles in excess of 14^{o} were not tested as the aerofoil was deemed to be fully stalled.

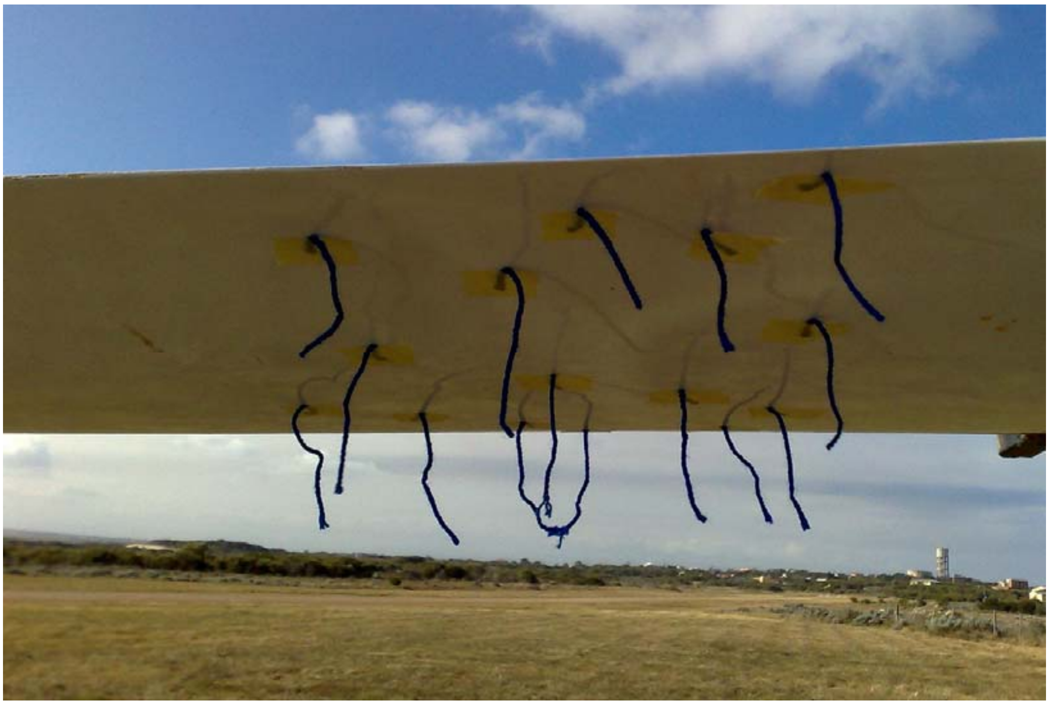

Figure 6.8: Tufts taped to lower surface of aerofoil

6.6.3 Analysis

By manipulating equation 2.4, the actual lift coefficient values achieved were calculated and tabulated in Table 6.3.

$$F = C_L \frac{1}{2} \rho V^2 A \qquad \text{(using equation 2.4)}$$

$$C_{L(actual)} = \frac{2(F)}{(\rho)V^2(A)}$$

Using:

$$A = 1.3(0.4)$$
$$A = 0.52m^2$$

Wind Speed (m/s)	N CL	N 8 deg corrected	N CL	N 10 deg corrected	N CL	N 12 deg corrected	N CL	N 14 deg corrected	N CL
10								31.392	1.21
11								41.202	1.31
12									
13								51.012	1.16
14		31.392	0.62			41.202	0.81	60.822	1.19
15								60.822	1.04
16		41.202	0.62	41.202	0.62				
17		51.012	0.68					65.727	0.87
18	0.49			41.202	0.49	60.822	0.72		
19						70.632	0.75		
20				60.822	0.58			90.252	0.87
21		70.632	0.62			109.872	0.96	109.872	0.96
22		90.252	0.72						
23				90.252	0.66	129.492	0.94	129.492	0.94
24	0.47	100.062	0.67						
25	0.74	109.872	0.68						
26		119.682	0.68						
27	0.58								
averages	0.57		0.66		0.59		0.84		1.06

Table 6.3 Actual coefficients of lift achieved

6.6.4 Conclusions

According to Abbott [11] the lift coefficient should increase with angle of attack until the critical angle is reached (stall) after which the lift coefficient will reduce. Results from Table 6.3 indicate the same trend. The lift coefficient is independent of velocity[11], meaning that C_L values in each column of table 6.3 should have been identical. If the highest and lowest values in each column are excluded the variance remains within 20%. The highest actual coefficient of lift achieved was 1.1 at 14^{o}.

The aspect ratio of the aerofoil used was 1300/400 = 3.25. According to Abbott[11], slightly greater lift coefficients should be possible to achieve by increasing the aspect ratio.

6.7 THROTTLING DEVICE TESTING

The aim of this test was to test the feasibility of the feathering and throttling device. The vertical axis reciprocating aerofoil wind energy harvester as tested in 6.2 to 6.4 was fitted with mechanical control of tail deflection. Light bulbs were used for electrical load. The experimental setup was positioned in the wind.

The electrical load was disconnected and all the tail control arms were manually placed in the feather position (zero tail movement). The mast was raised by means of the hand winch with the brake applied. Once the mast was secured in the vertical position the brake was released. Tests with the control arms at various other positions followed. Setting of the control arms required the brake to be applied each time to allow manual movement of the control arms.

6.7.1 Observations

The average wind speed logged for the duration of the test was calculated to be 6.93m/s. The wind was easterly and noted as “steady”. In the full feather position the unit was totally stationary even with the electrical load disconnected. Figure 6.9 shows the unit stationary in the feathered position with all the blades orientated straight into the wind.

Figure 6.9 Feathered position – unit at rest

Placing the control levers in the maximum power position resulted in the unit starting to turn immediately upon the brake being released.

Figure 6.10 Control arms at max power setting – unit rotating under load

Placing the levers in intermediate positions resulted in reduced power output, however this was not quantified in this experiment.

6.7.2 Conclusion

The control system was considered to be feasible and installation of the radio control receivers, battery packs and wiring was implemented in preparation for a follow up experiment where intermediate power settings would be tested and quantified.

6.8 SUMMARY

The series of tests documented in this chapter outline some of the research and development required to bring the vertical axis reciprocating aerofoil wind energy harvester from concept stage to a functional, robust, reasonably efficient device. Due to the uniqueness of the concept and the many variables not yet experimented with at this stage of the project it would be reasonable to assume that further performance enhancements would be possible with optimisation of the overall geometry of the device. This could include blade aerofoil selection, aspect ratio, tail deflection angle and other variables. Some of these variables are explored in future chapters and others require future research.

CHAPTER 7

CONTROL

7.1 OVERVIEW

The quantity of energy available in a given cross section of wind is proportional to the cube of the wind velocity[1]. If a cross section of 1.3m height and 1.68m width is considered, the power available from the wind can be calculated as follows:

$$P_{wind} = \frac{1}{2}\rho \cdot A \cdot V^3 \qquad \text{(using equation 4.10)}$$

$$P_{wind} = \frac{1}{2}\rho(1.3)(1.68)V^3$$

Using air density of 1.208 kg/m^3 the following theoretical wind power characteristics were compiled:

Wind speed knots	Wind speed m/s	Power W
5	2.6	22.4
10	5.1	179.6
15	7.7	606.1
20	10.3	1436.8
25	12.9	2806.2
30	15.4	4849.1
35	18.0	7700.1
40	20.6	11494.1
45	23.1	16365.6
50	25.7	22449.4
55	28.3	29880.1

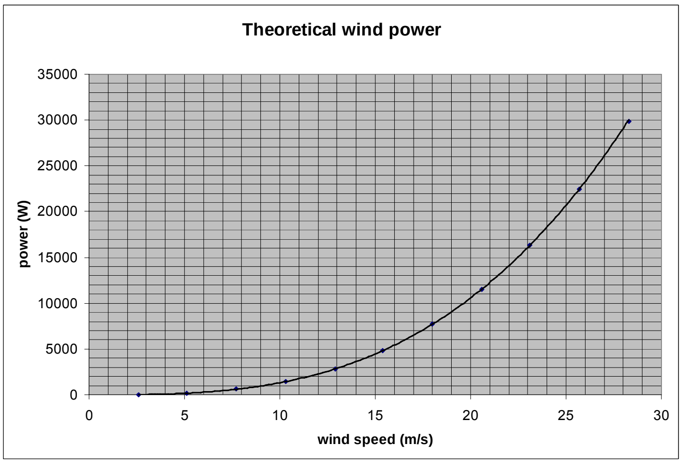

Table 7.1 / Figure 7.1 Theoretical wind power

The challenge that faces the wind turbine designer is to design a device that produces a viable amount of energy at low wind speeds, yet is able to withstand high wind speeds. According to Manwell [1] the wind speed in Port Elizabeth (South Africa) exceeds 10m/s for only 750 hrs per annum (8.6% of the time). Assuming a total efficiency of 40% a turbine occupying the cross section detailed above would produce less than 500W for 91.4% of the time. If less than 500 W is considered unviable then the only alternative would be for the turbine to be made larger in an attempt to extract energy from a larger cross section of wind. This larger turbine would however have to withstand the much greater power of the wind during storm conditions which may prevail for less than 1% of the time. For the turbine to operate under the vastly different range of conditions described above, some form of control is desirable.

7.2 CONTROL METHODOLOGY FOR HORIZONTAL AXIS WIND TURBINES

7.2.1 Braking

Certain small turbines use mechanical or electrical braking to prevent overspeed in high wind conditions. The heat from the braking needs to be dissipated and the blades need to be able to withstand the high lift forces to which they are still subjected during braking.

7.2.2 Generator output control

Provided the generator used has adequate capacity and its output is controllable it may be possible to restrain a turbine exposed to very high winds in this way. With reference to table 7.1 it is unlikely that a generator of approximately 20 kW capacity would be financially viable to fit to a turbine that produces less than 500W for 92% of the time.

7.2.3 Aerodynamic control

A few methods exist which limit the input of energy into the turbine. On conventional horizontal axis wind turbines the entire blade angle can be changed[1] or aerodynamic drag can be created on the blades by means of spoilers, tip brakes or pitchable tips[26]. Changing the pitch of the entire blade is the method most commonly used on large modern horizontal axis wind turbines. The blade is either moved towards feather or towards stall, both of which reduce wind power input to the turbine. The former resulting in the smoothest and quietest means of limiting power input to the turbine. As described in section 4.4 the blade of a HAWT is twisted to optimize the lift produced at various radii along the blade. It is therefore impossible to rotate such a blade into a truly feathered position where all points along the blade are producing zero lift. A conventional HAWT therefore still experiences lift forces at some points on its blades when "feathered" in storm or high wind conditions. Even though an angle may be achieved where no torque is produced, significant force is still experienced by the blades under such conditions.

7.3 CONTROL OF THE PROPOSED DEVICE

The proposed device had untwisted blades of symmetrical section hinged at their ¼ chord. Symmetrical aerofoils produce no lift when presented to the airflow at zero angle of attack. According to Riblett[23] symmetrical aerofoils hinged at ¼ chord have no pitching moment, meaning that little or no force will be required to keep the blades at a zero angle of attack / zero lift condition. Each aerofoil (blade) was freely pivoted and aligned by a tail. The potential therefore existed to have zero lift produced by the blades by merely aligning each tail with its aerofoil. Under these conditions the device would immediately come to a complete stop with no lift being produced from any part of the blade. The only force experienced by the blades under these conditions would be a small drag force. According to Abbott[11] a typical symmetrical section such as the one used in this study would at zero angle of attack have a coefficient of drag of 0.006. In a 55 kt (28.3 m/s) gale the drag force experienced by each of the blades as described in 7.1 could be calculated using equation 4.2 as:

$$D = C_D \frac{1}{2} \rho V^2 A$$

Using air density of 1.208 kg/m^3; Aerofoil area of 1.3m by 1.68m and C_d=0.006

$$D = 0.006(\frac{1}{2})(1.208)(28.3)^2(1.3)(1.68)$$

$D = 6.34N$ (negligible)

Apart from total feathering, control of the tails of each blade would offer the potential for throttling of the device from full power to zero power in a smooth seamless fashion.

7.4 CONTROLLING THE TAILS – POSSIBLE METHODS

7.4.1 Mechanical

The device as tested in experiment 6.4 relied on a single tension linkage between the roller cam follower and the tail. The tension linkage pulled the tail in one direction during cam lift and was resisted by a spring on the tail. When the cam follower returned to its base position the spring pulled the tail in the opposite direction.

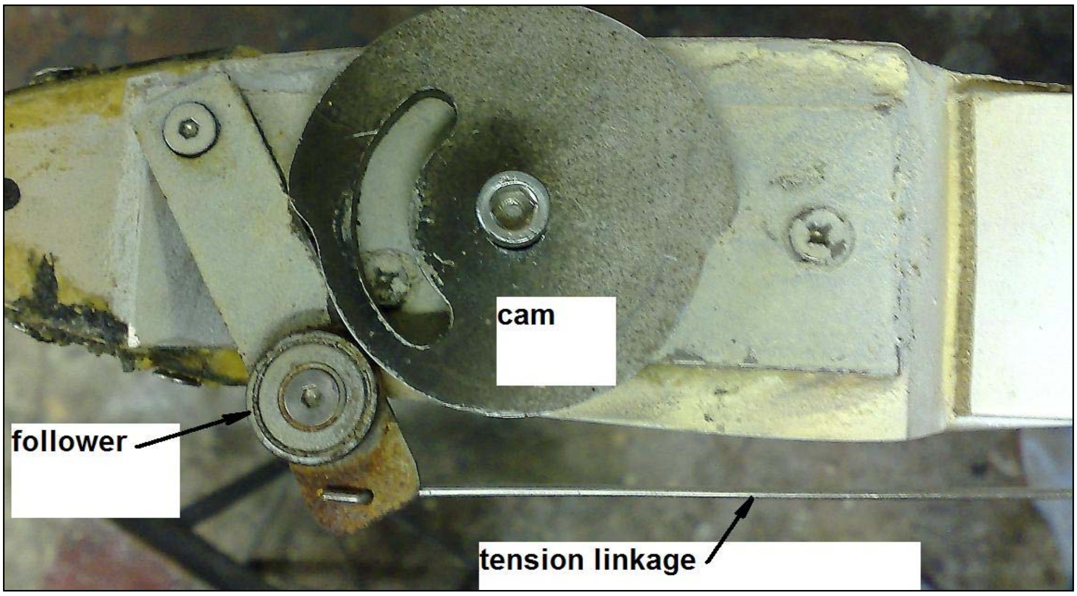

Figure 7.2 Cam and follower

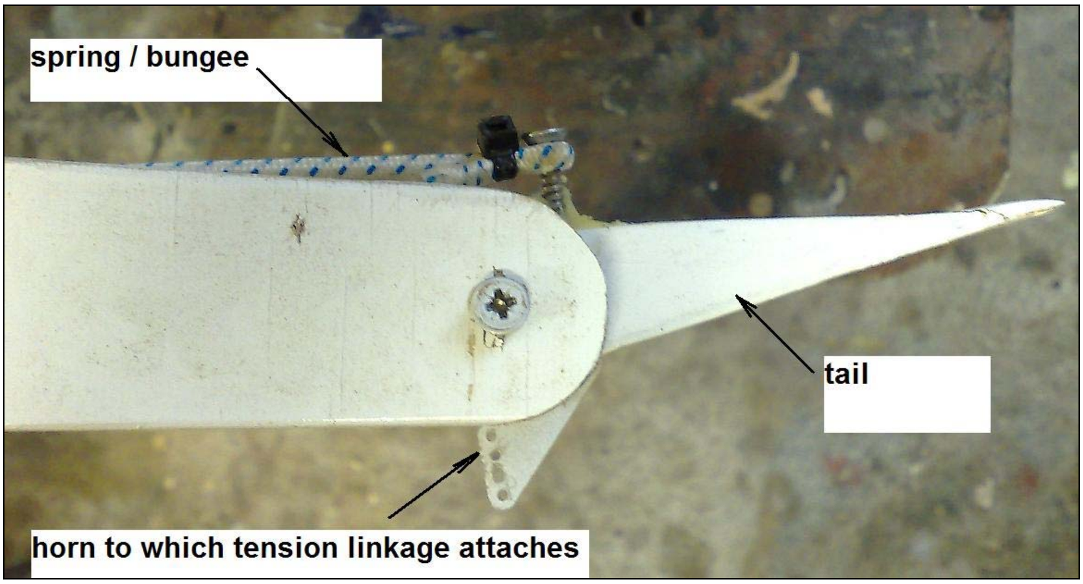

Figure 7.3 Tail

The system as described in Figure 7.2 and 7.3 worked adequately when full deflection of the tail was required in both directions (for maximum power output). No simple means could be devised to obtain partial deflection of the tails or for locking of the tails at the zero angle of attack position. The system was modified to use two tension linkages and a centering spring on the tails as shown in Figure 7.3 and 7.4. The tension linkages were adjusted to a length that caused no tail movement with full cam movement when the tensioning/control arm was set to the loose position. When the tensioning/control arm was set to the tight position the tail deflected to the maximum angle (approximately 10^0). Setting of the control arm to an intermediate position would provide partial tail deflection and hence partial power output from the device. Movement of the control arm remotely by mechanical means would be possible by means of two sets of swash plates similar to those used in the control of helicopter blades.

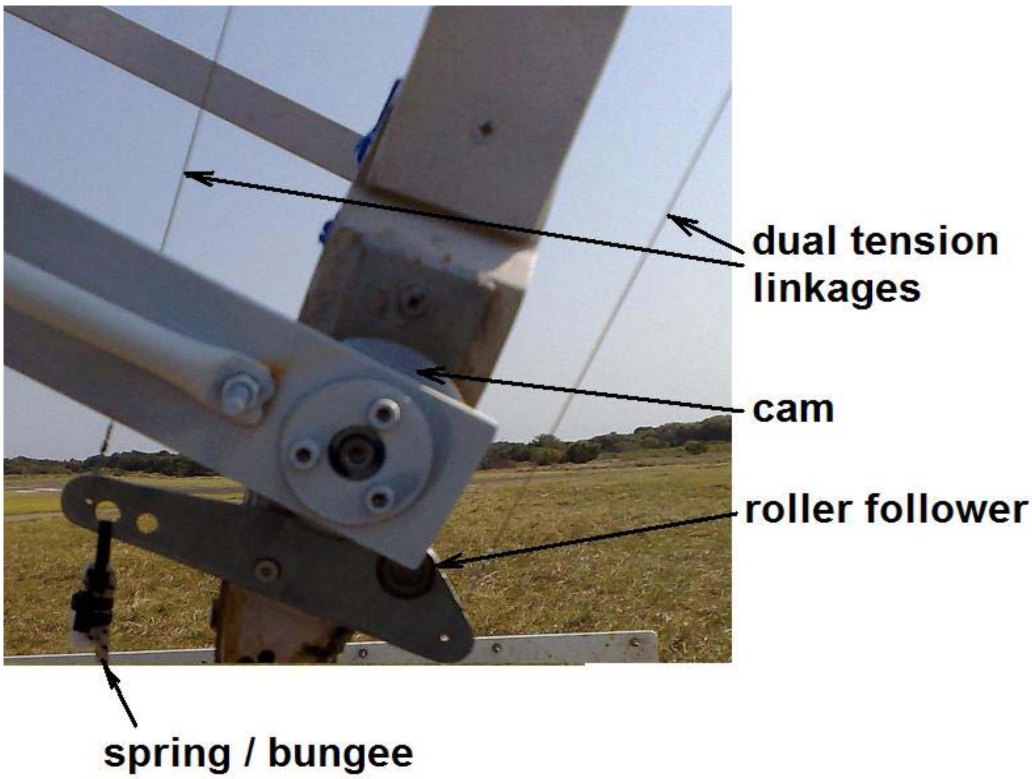

Figure 7.4 Modified cam follower bellcrank

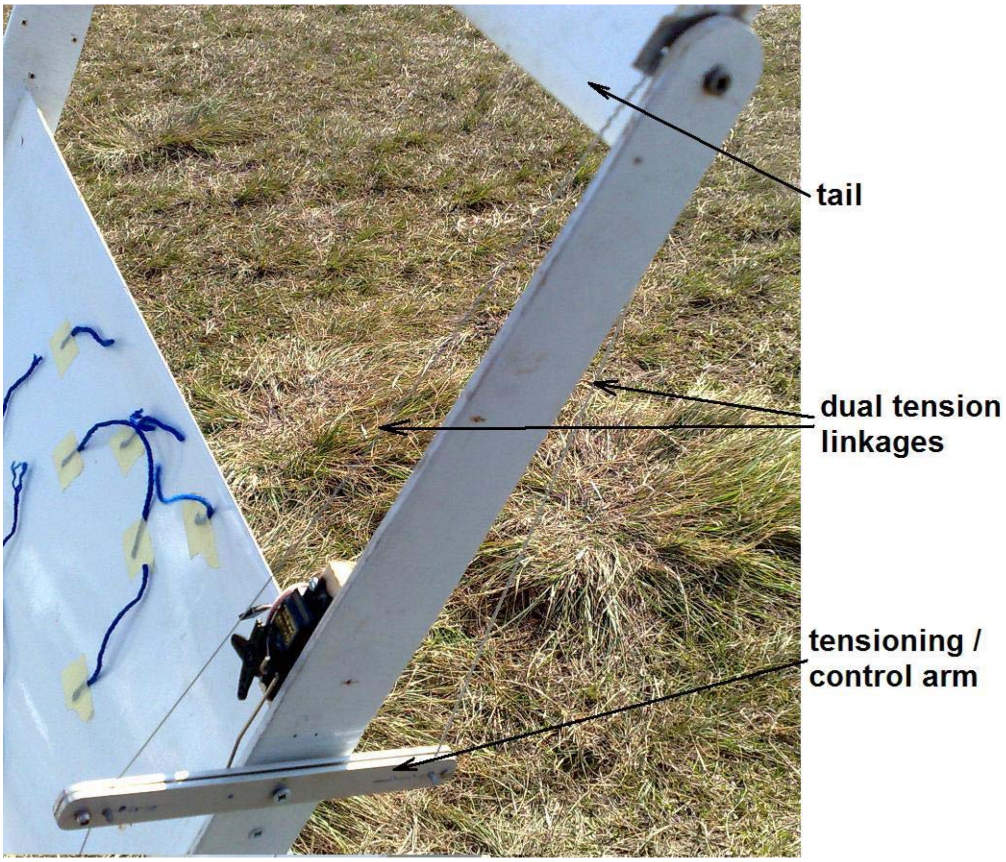

Figure 7.5 Modified tail control system

7.4.2 Electro/Mechanical

An alternative means of controlling the tensioning arms without the need for swash plates was by using radio controlled servo motors mounted on each blade. The 3 servo motors each have a battery pack and receiver and are controlled simultaneously by a single transmitter. Experiment 6.7 details the experiment conducted to determine the feasibility of the control system.

7.5 SUMMARY

It was decided to utilise the system described in 7.4.2 for the performance testing during the remainder of this study as it involved minimal mechanical changes to the experimental platform. If an entirely new machine were constructed it is likely that swash plates would offer a more practical and robust design solution.

CHAPTER 8

PERFORMANCE TESTING AND EVALUATION

8.1 INTRODUCTION

Preceding Chapters 3,6 and 7 dealt with the optimization of the experimental platform to the point where its functionality was adequate for conducting research aimed at performance evaluation.

The results obtained in Section 6.2 showed that the mounting of the experimental platform on a moving vehicle held two main advantages;

- A number of different wind speeds could be simulated in a short space of time.
- The airflow over the experimental platform was less turbulent and more representative of that which would be expected at the top of a high mast.

For these reasons most of the performance data in this chapter was obtained using the mobile experimental platform.

8.2 DATA RECORDED

8.2.1 Wind direction (*channel 1: 0-2.5V*)

Due to the fact that the wind direction sensor was mounted to the moving platform, the values for wind direction had no correlation to actual compass direction. It was determined that a reading of 282^o was obtained when the vehicle traveled in a straight line in zero ambient wind. Any readings greater than 282^o thus indicated a cross wind component from the right and readings less than 282^o indicated a crosswind component from the left.

8.2.2 Voltage (*channel 2: 0-5V*)

DC output voltage from the generator of up to 60V was recorded using an INP/12 voltage scaling cable.

8.2.3 Amperage (*channel 3: 0-5V*)

DC output amperage from the generator of +/-100A was recorded using a DC100A current sensor.

8.2.4 Wind speed (*channel X: pulse*)

Wind speed in m/s.

8.2.5 Rotational speed of main shaft (*channel Y: pulse*)

Rotational speed was recorded using a proximity switch sensing off the 47 tooth chain sprocket. The relatively low rotational speed required a high resolution switching rate for the proximity switch for stable results. This was achieved by sensing off the 47 teeth on the sprocket. The logger was scaled accordingly to cater for the 47 teeth and to record data in rev/min.

8.3 DATA INTERPRETATION

8.3.1 Power output

According to Hughes[27] the product of amperage and voltage is power, measured in Watts (W). Recorded values of amperage and voltage were thus multiplied to give the actual electrical power output of the machine (W). The mechanical power output of the main shaft would be higher than the electrical power output due to mechanical and electrical losses. This was quantified and discussed in Chapter 5.

8.3.2 Tip speed to wind speed ratio (TSR)

Gipe[24] defines tip speed ratio as the ratio of blade tip speed to wind speed. The experimental platform used had blades running at a radius of 0.84m. The entire blade therefore runs at one speed which is also the tip speed. This was calculated as follows:

$$V_{tip} = \frac{\pi \cdot D \cdot N}{60} \qquad (8.1)$$

where $D = 0.84(2) = 1.68m$; N = angular velocity of main shaft in rev/min.

Tip speed ratio is thus:

$$TSR = \frac{V_{tip}}{V_{wind}} \qquad (8.2)$$

8.4 SIGNIFICANT DATA RELATIONSHIPS

8.4.1 Power / Wind speed

The power in the wind is proportional to the cube of the wind speed[24]. A power output / wind speed graph for any wind machine would be expected to follow this trend as described in Section 7.1.

8.4.2 Voltage / Rotational speed

A graphical display of voltage against rotational speed was considered significant as any deviation from an approximately linear increase would be an indication of a fault with the generator or an indication that its capacity had been exceeded.

8.4.2 Tip speed ratio / Power output

Reference to Figure 2.21 indicates the emphasis placed on tip speed ratio when considering the effectiveness of various wind machines. Tip speed ratio was compared to power output as well as to power coefficient. The latter being a ratio between power produced and power in the wind.

8.5 SIGNIFICANT PARAMETERS AFFECTING PERFORMANCE

8.5.1 Blade angle of attack

The basic principle of operation of the experimental platform is that the aerofoils are optimally angled to the relative airflow at all times thus producing a maximum lift force. Exceeding the optimal angle would result in the aerofoil stalling. A stalled aerofoil generates more drag which would slow the rotation of the machine and hence reduce power output. The influence of this angle on the power output was seen as a significant parameter to optimise by experimentation.

8.5.2 Rotational speed

The rotational speed of the machine at a particular wind speed could be varied by changing the electrical load. The change in rotational speed for a particular wind speed resulted in a change of the TSR.

8.6 PERFORMANCE MEASUREMENT DATA SET

Table 8.2 is an example of the data obtained during a typical test session. Data was obtained using the experimental platform as described in Chapter 6 and 7 mounted on the moving platform. The methodology used in all such tests was to obtain a spread of results with wind speeds between zero and approximately 16m/s during the duration of each vehicle run. Vehicle run durations averaged approximately two minutes each. Vehicle speed was gradually increased in increments to ensure that the 2 minute time interval available was equally spread across different wind speeds. The headings used in the tables of results are defined in Table 8.1. Performance tests were conducted when ambient wind was less than 5m/s to minimise the effects of turbulence. Tests were conducted "into wind" to minimise the vehicle's ground speed required. Tests were only conducted when minimal crosswind component existed (<2m/s). The preferred wind direction at the test site for minimal turbulence was westerly and hence all tests were conducted with a light ambient westerly wind.

Heading	Units	Comment
Date	Test date	
Time	Time of day	Local time
Direction	Degrees	282^o = zero crosswind component (see Section 8.2.1)
Voltage	V	Recorded by logger
Amps	A	Recorded by logger
Output Power	W	Calculated using product of voltage and amperage
Wind speed	m/s	Recorded by logger
Rot spd	rev/m	Recorded by logger
TSR	Ratio	Calculated using equation 8.2

Table 8.1 Definition of headings

					W	m/s	rev/m	
date	time	direction	volts	amps	power	wind spd	rot spd	TSR
2008/10/07	15:59:41	337.055	5.832	2.35	13.7052	9	7	0.068
2008/10/07	15:59:43	352.44	5.465	1.923	10.5092	9	11	0.108
2008/10/07	15:59:45	349.451	2.227	1.129	2.51428	9	3	0.029
2008/10/07	15:59:47	340.659	5.04	1.801	9.07704	10	6	0.053
2008/10/07	15:59:49	341.802	5.084	1.862	9.46641	8	5	0.055
2008/10/07	15:59:51	314.901	3.399	1.557	5.29224	10	9	0.079
2008/10/07	15:59:53	284.396	8.601	2.961	25.4676	12	9	0.066

2008/10/07	15:59:55	284.044	6.945	3.266	22.6824	13	14	0.095
2008/10/07	15:59:57	282.725	9.158	4.243	38.8574	15	16	0.094
2008/10/07	15:59:59	282.286	11.385	4.121	46.9176	15	21	0.123
2008/10/07	16:00:01	282.11	9.582	3.388	32.4638	15	18	0.106
2008/10/07	16:00:03	287.033	17.861	6.258	111.774	17	28	0.145
2008/10/07	16:00:05	286.066	15.722	5.83	91.6593	17	29	0.150
2008/10/07	16:00:07	279.209	7.81	3.877	30.2794	15	20	0.117
2008/10/07	16:00:09	290.725	11.56	4.548	52.5749	15	21	0.123
2008/10/07	16:00:11	277.714	15.634	5.525	86.3779	16	32	0.176
2008/10/07	16:00:13	279.385	16.63	6.136	102.042	20	33	0.145
2008/10/07	16:00:15	278.505	16.396	7.906	129.627	18	32	0.156
2008/10/07	16:00:17	277.187	13.641	6.685	91.1901	20	41	0.180
2008/10/07	16:00:19	276.747	16.85	7.357	123.965	18	35	0.171
2008/10/07	16:00:21	284.308	12.029	6.319	76.0113	20	37	0.163
2008/10/07	16:00:23	279.473	10.33	4.182	43.2001	17	27	0.140
2008/10/07	16:00:25	278.945	11.209	5.342	59.8785	17	23	0.119
2008/10/07	16:00:27	284.484	17.158	7.357	126.231	18	25	0.122
2008/10/07	16:00:29	274.022	16.967	6.685	113.424	17	25	0.129
2008/10/07	16:00:31	284.308	19.795	7.662	151.669	18	30	0.147
2008/10/07	16:00:33	284.835	16.674	7.54	125.722	18	36	0.176
2008/10/07	16:00:35	278.769	11.414	5.098	58.1886	17	26	0.135
2008/10/07	16:00:37	285.626	16.44	6.197	101.879	18	25	0.122
2008/10/07	16:00:39	281.055	14.945	6.807	101.731	19	29	0.134
2008/10/07	16:00:41	278.945	13.714	5.647	77.443	18	28	0.137
2008/10/07	16:00:43	277.275	12.733	6.074	77.3402	17	21	0.109
2008/10/07	16:00:45	282.11	18.3	6.807	124.568	19	31	0.144
2008/10/07	16:00:47	282.286	13.758	6.502	89.4545	18	31	0.151
2008/10/07	16:00:49	283.956	12.337	4.487	55.3561	18	30	0.147
2008/10/07	16:00:51	280.176	16.088	7.723	124.248	18	29	0.142
2008/10/07	16:00:53	291.956	12.22	6.258	76.4728	18	31	0.151
2008/10/07	16:00:56	281.846	12.982	5.586	72.5175	18	32	0.156
2008/10/07	16:00:58	285.978	9.084	4.243	38.5434	18	29	0.142
2008/10/07	16:01:00	289.143	10.799	5.525	59.6645	17	32	0.166
2008/10/07	16:01:02	305.846	4.454	1.679	7.47827	13	20	0.135
2008/10/07	16:01:04	329.758	3.429	1.679	5.75729	11	9	0.072
2008/10/07	16:01:06	344	7.165	3.388	24.275	10	14	0.123

Table 8.2 Typical data set

Typical graphs indicating the data relationships deemed significant are displayed in Figures 8.1 to 8.3. Data for the example graphs was obtained from the data set tabulated in Table 8.2

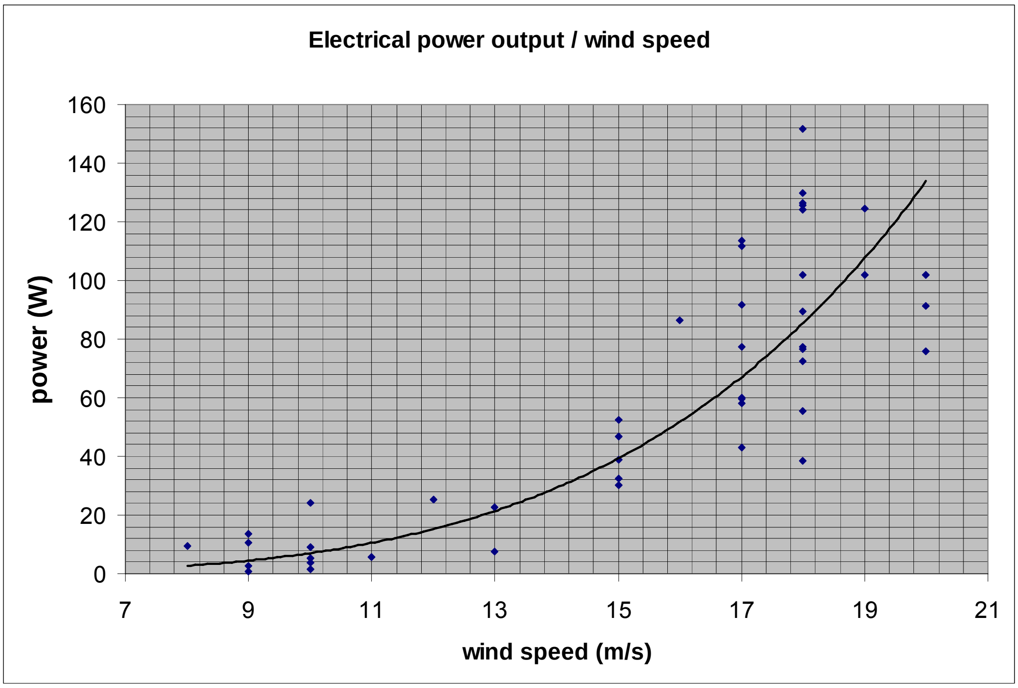

Figure 8.1 Power / wind speed graph for data set 8.2

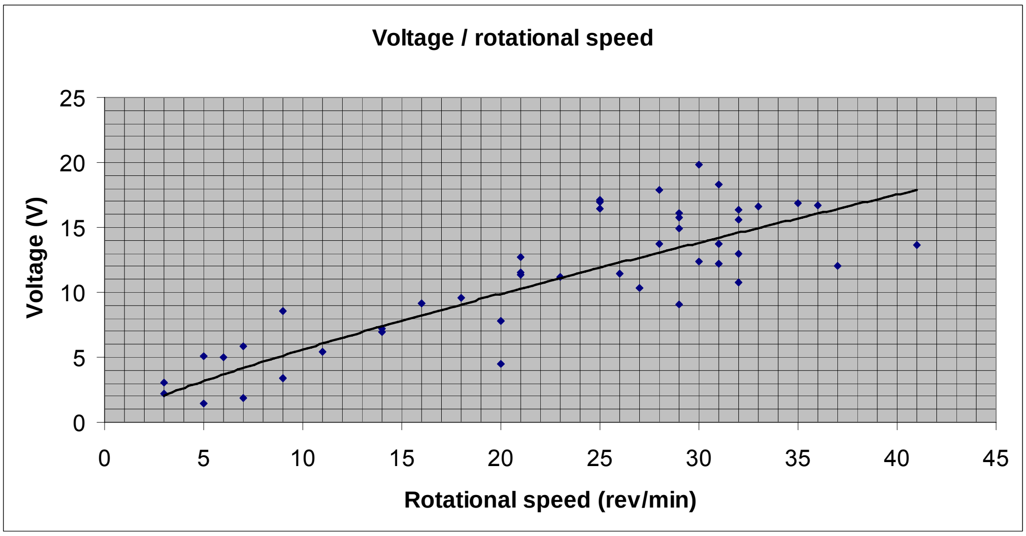

Figure 8.2 Voltage / rotational speed graph for data set 8.2

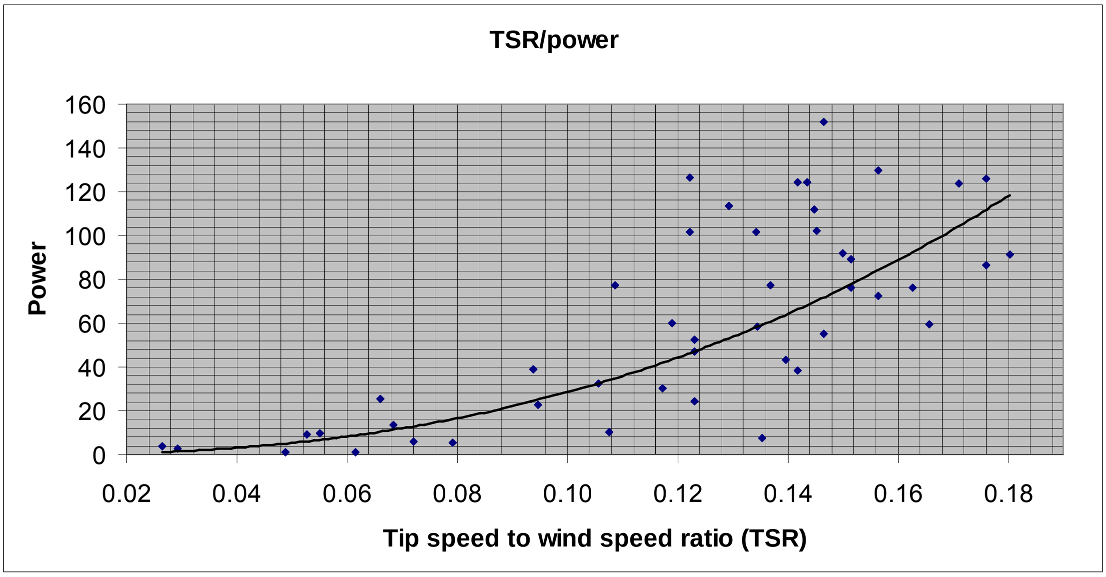

Figure 8.3 TSR / Power graph for data set 8.2

8.7 PERFORMANCE CHARACTERISTICS FOR EXPERIMENTAL PLATFORM

The full data set relating to the graphs in section 8.8 is tabulated in Appendix A. The headings as detailed in Table 8.1 were applicable. All results referred to operation at 10^0 angle of attack unless specified otherwise. Figure 8.4 shows the electrical power output plotted against wind speed whilst the electrical load was set to “low” (25.4Ω). Rotational speed and hence TSR during this test was the highest of the four tests due to the low electrical load. The trend of the graph followed the expected trend as described in Section 7.1, namely that of exponential wind power increase with increase in wind speed.

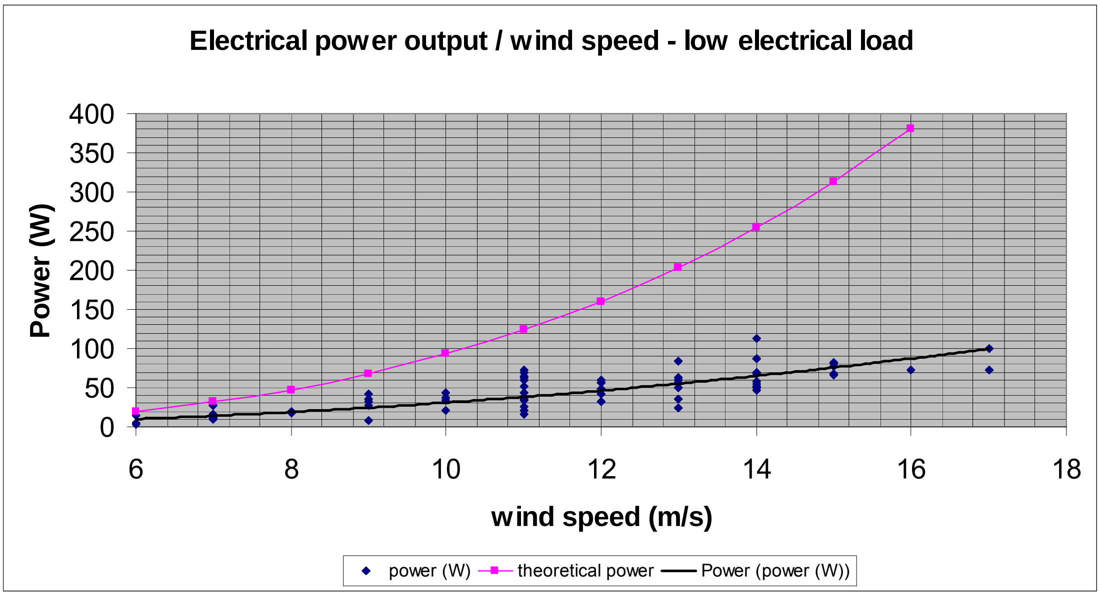

Figure 8.4 Performance with minimum electrical load

Performance when loaded to ½ and ¾ electrical load (12.7Ω and 6.35Ω respectively) are displayed in Figures 8.5 and 8.6. The highest power output was obtained during the test at ¾ electrical load. Trendlines for these graphs followed the predicted pattern as discussed in Section 7.1.

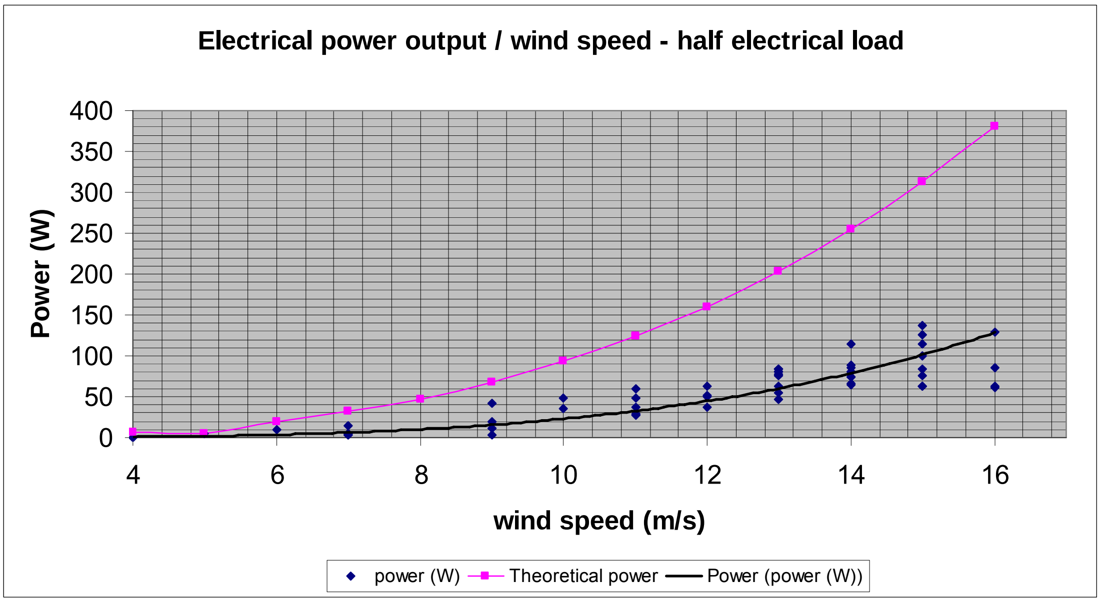

Figure 8.5 Performance with half electrical load

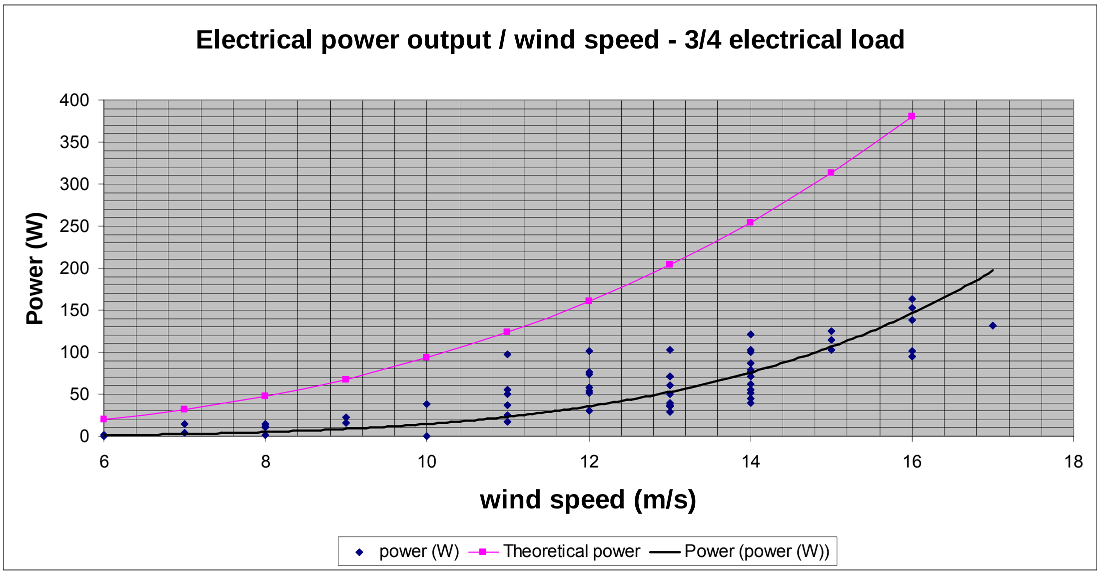

Figure 8.6 Performance with 3/4 electrical load

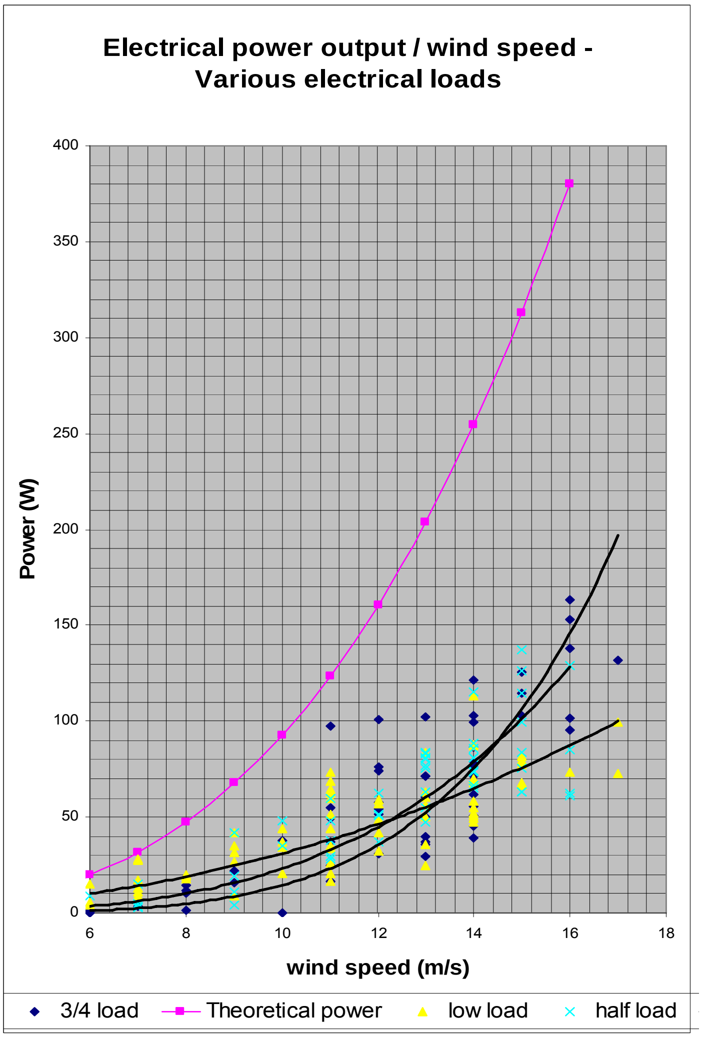

Figure 8.7 Performance with various electrical loads

The final of the four tests was conducted with full electrical load (generator short circuited). The rotational speed and power output was the lowest of the four tests. This final test indicated that the generator capacity was adequate to absorb the wind energy harvested by the device at wind speeds of up to 19.5m/s. This further indicated that the gearing utilised between the main shaft and generator was appropriate. This test indicated that overspeed of the device could be prevented by electrical loading up to a wind speed of 19.5m/s.

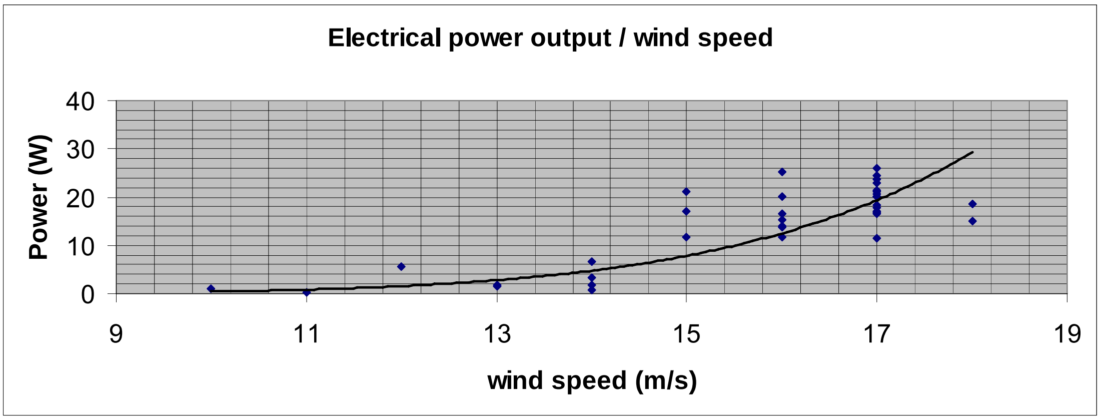

Figure 8.8 Performance with maximum electrical load

Figure 8.8 shows the relationship between tip speed ratio and electrical power output. The highest power was obtained when the tip speed ratio was 0.478 and the rotational speed 87 rev/min. Tip speed ratios higher than 0.478 yielded reducing power outputs.

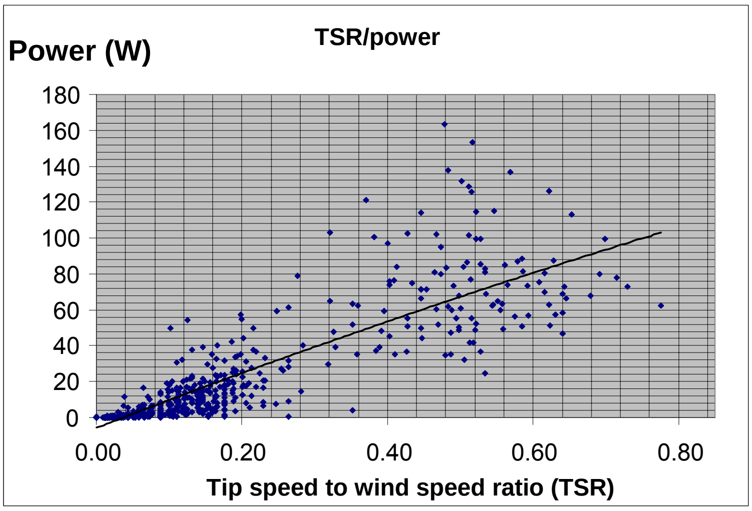

Figure 8.9 Tip speed ratio – power relationship

Plots of power coefficient against wind speed and TSR are shown in Figures 8.10 and 8.11. Figure 8.10 indicated that the most efficient TSR to run this particular machine at was 0.36. When compared to other wind power devices (see Figure 2.21) it is evident that the maximum power point for this device occurs at a relatively low TSR.

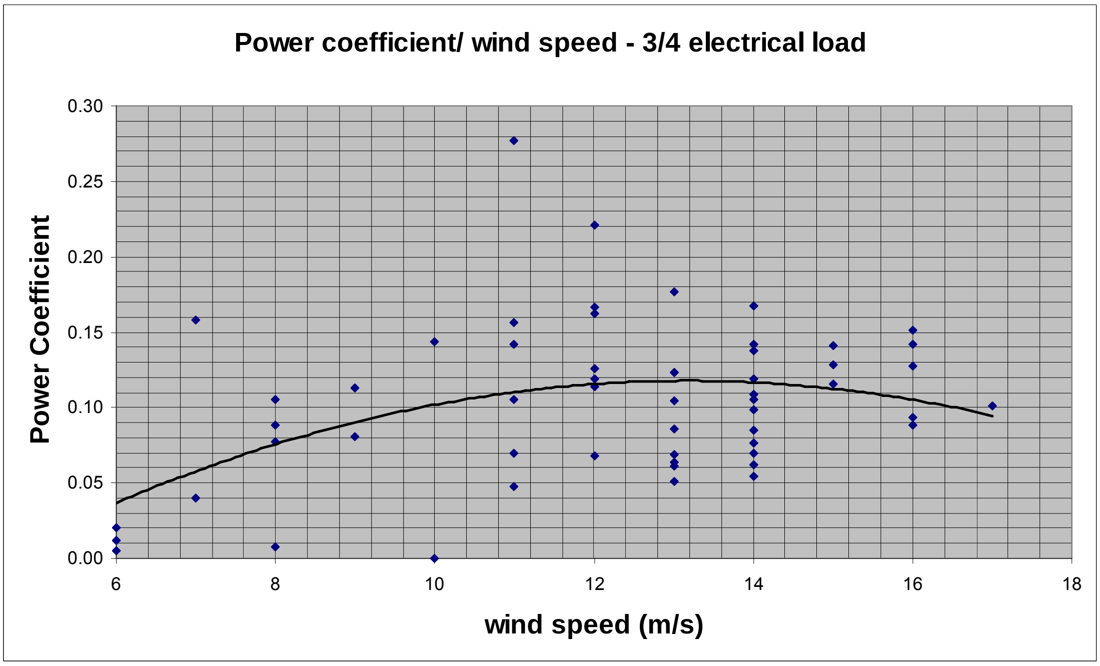

Figure 8.10 Power coefficient / wind speed relationship

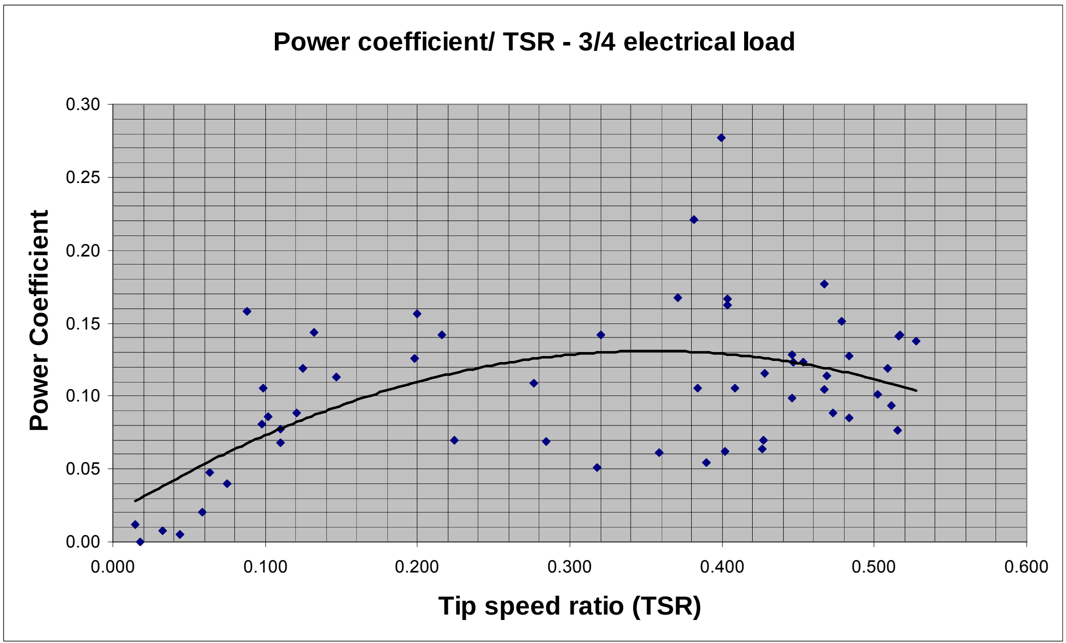

Figure 8.11 Power coefficient / Tip speed ratio relationship

An extract from the data set for the maximum power condition is displayed in Table 8.3 and corresponds to the peak power point in Figure 8.8.

Date	Time	Wind direction	Voltage	Amperage	Power	Wind speed	Rot speed	TSR
2008/10/28	14:57:38	297.67	30.916	5.281	163.27	16	87	0.478

Table 8.3 Data extract

The maximum electrical power output of 164W was achieved at a TSR of 0.478. The combined efficiency of the mechanical gearing and the electrical generator was determined in Chapter 5 to be 21% under similar conditions. The electrical output power was corrected to obtain the actual power in the main shaft as follows:

$$P_{shaft} = \frac{164}{0.2}$$

$$P_{shaft} = 820W$$

Using the value of wind speed recorded of 16 m/s; air density of 1.208 kg/m^3; blade span of 1.3m and radius of rotation of 0.84m, the maximum power coefficient was calculated as follows[24]

$$C_P = \frac{P_{shaft}}{P_{wind}} \qquad (8.1)$$

$$C_P = \frac{P_{shaft}}{\frac{1}{2}\rho.v^3.A.}$$

$$C_P = \frac{820}{\frac{1}{2}(1.208)16^3(0.84)2(1.3)}$$

$$C_P = 0.15$$

8.7.1 Performance with reduced angle of attack

One of the original assumptions made was that the aerofoils should be operated at an angle of attack close to their stalling angle. At this angle the maximum lift coefficient would be achieved and hence the maximum amount of aerodynamic lift (force) would be developed. During performance testing the experimental platform was operated with reduced angle of attack (approximately 6^o). This was achieved by reducing the maximum tail deflection angles by using the "throttling device” described in Chapter 7. The results are displayed in Figure 8.9. When Figure 8.9 is compared with Figure 8.6 it is evident that power output was approximately half of that obtained at the same wind speeds at 10^o angle of attack. This verified the original assumption. Reduction of the tail deflection angles would therefore only be used to safeguard the device in the event of an impending overspeed situation in high wind conditions or to stop it from turning for maintenance or other reasons. Under normal operating conditions when maximum efficiency was required the tail deflection angles would be allowed to reach their maximum limits of approximately 10^o.

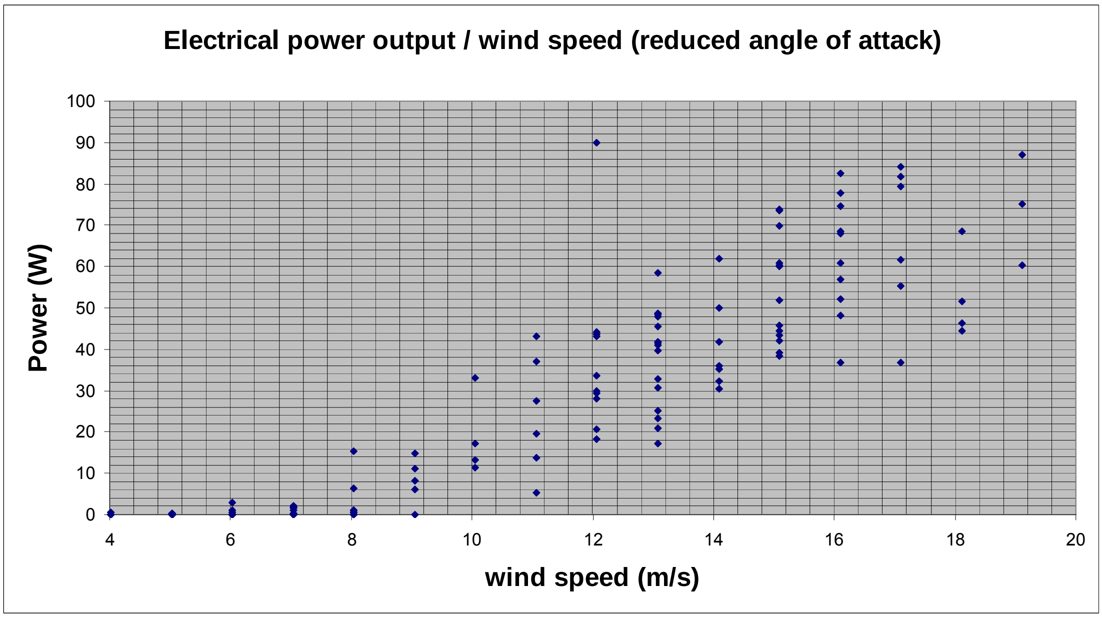

Figure 8.12 Power output at reduced angle of attack

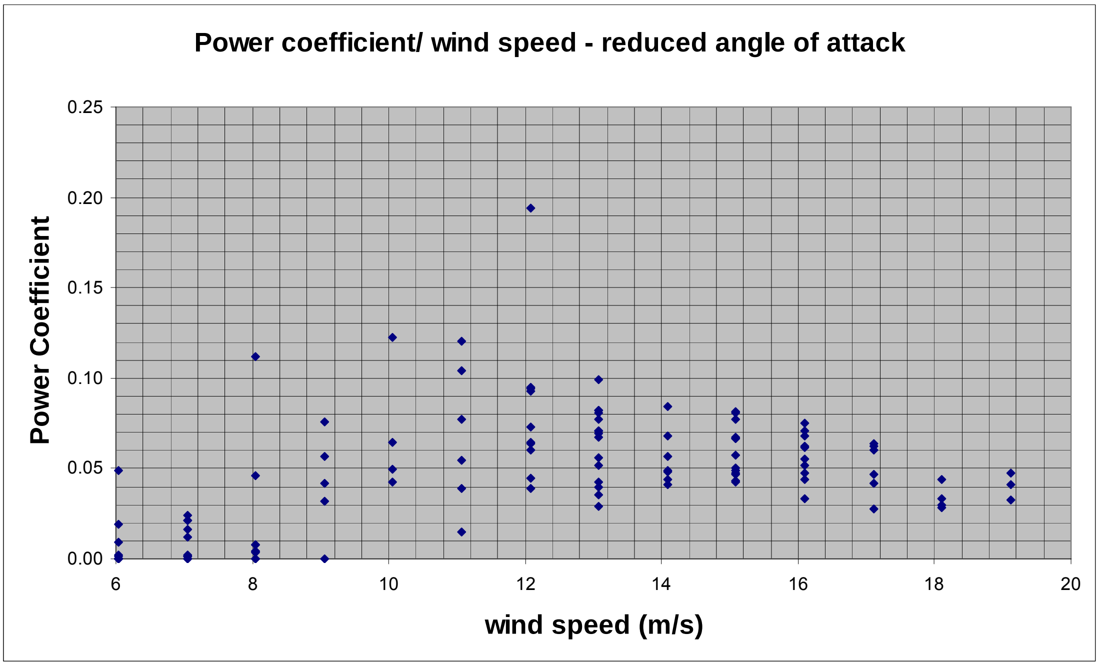

Figure 8.13 Power coefficient / wind speed at reduced angle of attack

8.8 SUMMARY

The performance tests conducted on the experimental platform indicated that the device produced its maximum power at very low rotational speeds in comparison to other wind turbines. The tip speed ratio at which maximum power was achieved was lower than anticipated and this together with the ability to fully throttle the device were seen as the two main advantages that this research has highlighted.

CHAPTER 9

RECOMMENDATIONS

9.1 OVERVIEW

The experimental platform used in this research achieved a maximum power coefficient of 0.15 at tip speed ratios between 0.36 and 0.48. Figure 9.1 indicates how the research platform compared with other devices in terms of power coefficient.

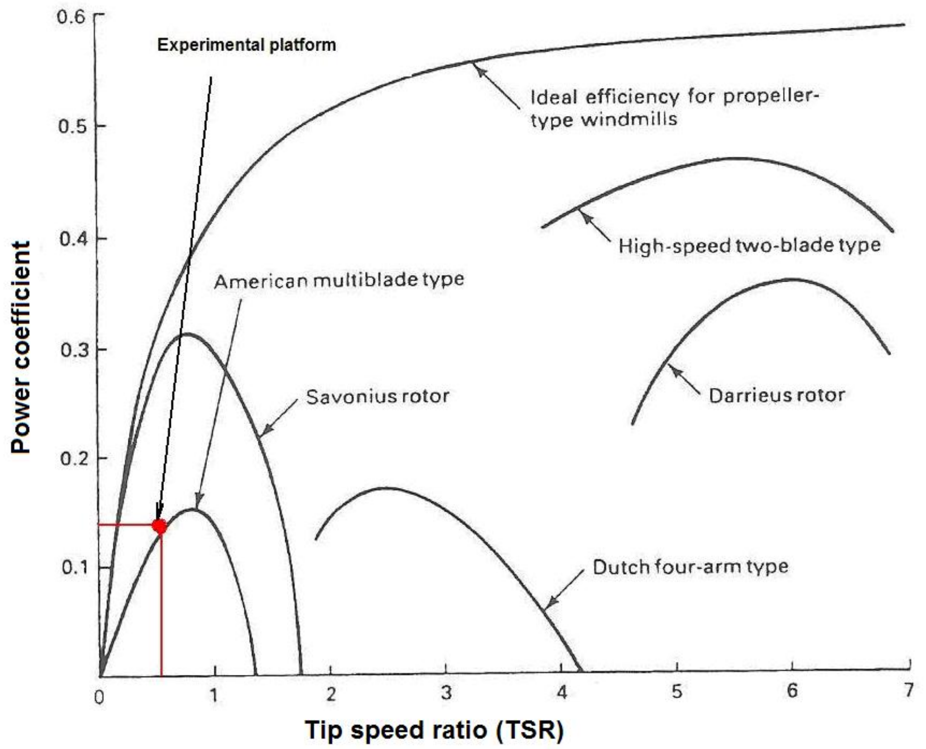

Figure 9.1 Performance of experimental platform in relation to other devices[17]

It was evident from Figure 9.1 that the measured power coefficient was less than that claimed for Darrieus and HAWT's. It did however achieve its maximum power output at extremely low tip speed ratios. The device used as the experimental platform for this project would therefore not be suitable for applications where power coefficient were the main criteria. It would however be well suited to applications where quiet operation with low rotational speed and high torque were required. It has become evident that the main criteria used to rate wind turbines is their power coefficient. Whilst this criteria is obviously of importance it needs to be assessed together with acquisition cost; cost per kW.h and environmental impact.

If a turbine based on the experimental platform can be installed for a lower cost per watt of rated power output than other types then it could be deemed preferable. Figure 2.21 and 9.1 suggested that it is impossible for a propeller type windmill to exceed the power coefficients of the “ideal curve” (Betz). As described previously the experimental platform used in this project in its current form is limited to a tip speed ratio of 1. According to Figure 2.21 a propeller type windmill running at a tip speed ratio of 1 is limited to an absolute maximum of 0.4 power coefficient. Research and development of the experimental platform on which this thesis is based resulted in a viable low altitude mast mounted solution that provides a possible alternative to the HAWT.

9.2 FINAL CONCLUSIONS

The research conducted in this project resulted in the development of a unique type of wind turbine. Positive features that made it different to other vertical axis machines in existence were:

- Aerofoils that remain aligned with the relative airflow automatically by means of the tails. Aerofoils are freely pivoted.
- Extremely high starting torque (higher than that of a Savonius rotor).
- Peak power output at an extremely low tip speed ratio (0.48) resulting in totally quiet operation and less danger in the event of blade failure.

Negative features with reference to other VAWT’s

- Lower power coefficient in comparison to high TSR machines.
- More mechanically complex than fixed blade devices such as Darrieus, Savonius or Giromill
- Low rotational speed not ideal for direct drive electricity generators.

9.2.1 Overcoming the negative aspects

With further development and experimentation with different overall diameters and aerofoil aspect ratios it is reasonable to assume that the power coefficient could be increased somewhat over that obtained to date. If used for electricity generation the use of direct drive generators may be feasible following further research in large diameter slow rotation generators. According to a paper by Eriksson[21] this may be feasible. Operation at TSR >1 may also be a possible method to increase the power coefficient. This would have required limiting the travel of the freely pivoting blades in quadrants 2 and 3 as shown in Figure 9.11 and effectively altering the device to run as a Darrieus rotor in these two quadrants. If power coefficient increase were considered vital this may have been feasible, however the very advantages that make the device unique would have been lost, namely quiet operation and low speed. Hence this was not pursued but could form the basis for further research.

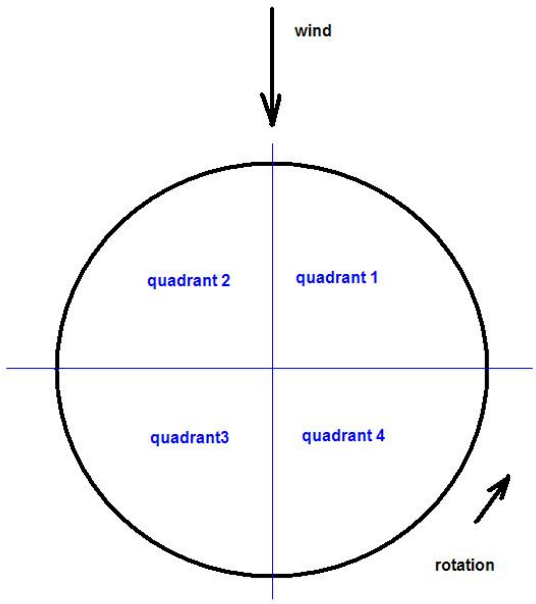

Figure 9.2 Plan view showing quadrants

9.2.2 Utilising the positive aspects

The device was slow turning, totally quiet and had high starting and running torque. The first two aspects permit the device to be used in close proximity to people and property without undue danger or disruption. The slow speed and high torque are ideally suited to water pumping or compressing air. In countries where no “feed in” policy exists to the national electricity grid (eg South Africa) the issue of energy storage is vital for the viability of medium scale wind systems. Users are then able to generate and store energy for later use. Pumping water to high ground for later use with hydro turbines would be one possibility in areas in close proximity to high ground. The compression and storage of air holds possibilities warranting further investigation for medium scale wind systems. Large scale storage[28,29,30] by means of compressed air has been investigated and utilised on a very limited scale. The use of a positive, variable displacement piston type air compressor and similar air motor driving an electrical generator would likely be the most efficient way of maximising the use of wind energy from the proposed device. If a variable displacement compressor were driven by the wind turbine its displacement could be controlled to regulate the power it absorbed thereby governing the rotational speed of the wind turbine. Apart from preventing overspeed, this would be a means of ensuring operation at the optimum TSR.

A possible arrangement is shown in Figure 9.12 for medium sized wind energy harvesting, storage and later use. The system shown below should be ideally suited to the VAWT developed in this project and work in this regard is planned for the future.

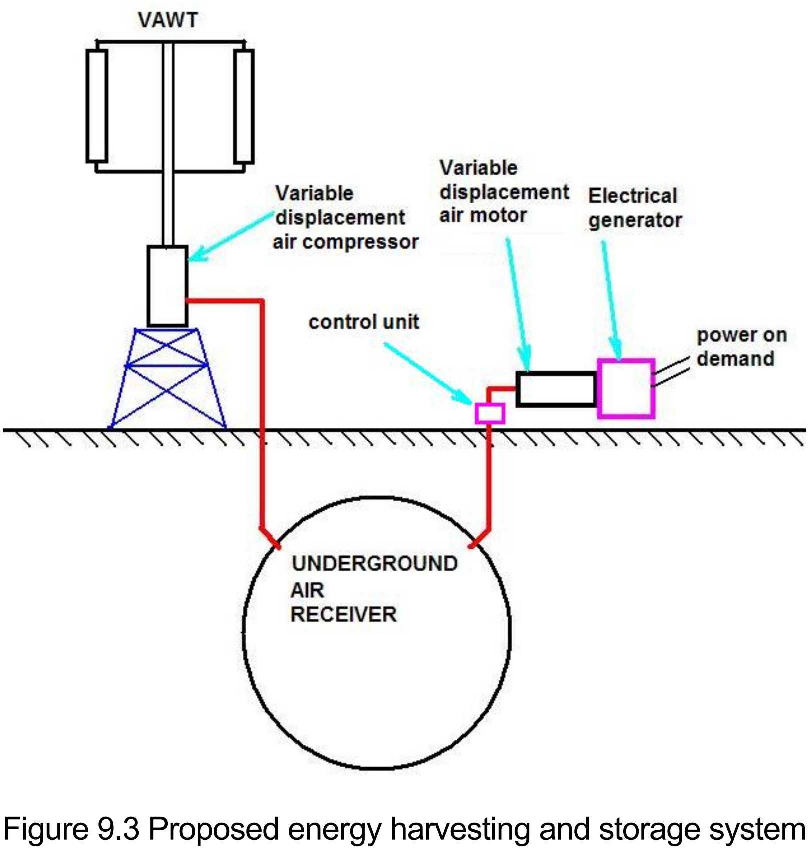

Figure 9.3 Proposed energy harvesting and storage system

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APPENDIX A

Final performance data 28 October 2008-10-29

<u>Notes:</u>

Data obtained during four runs (see notes in table)

Electrical loading adjusted via resistance bank as follows:

- Minimum electrical load 14:48-14:50 (first run)
- ½ electrical load 14:53-14:54 (second run)
- ¾ electrical load 14:57-14:58 (third run)
- Full electrical load 15:01-15:02 (fourth run)

TSR = tip speed ratio (calculated)

Date	Time	Direction	Voltage	Amperage	Power output	Wind speed	Rotational speed	Tip speed ratio
		degrees	Volts	Amps	W	m/s	RPM	TSR
2008/10/28	14:44:23	71.648	3.751	0.519	1.9468	6	3	0.044
2008/10/28	14:44:26	49.055	7.341	0.946	6.9446	7	5	0.063
2008/10/28	14:44:28	43.956	2.037	0.214	0.4359	5	3	0.053
2008/10/28	14:44:30	55.912	9.744	1.313	12.794	5	8	0.141
2008/10/28	14:44:32	7.033	3.56	0.397	1.4133	4	8	0.176
2008/10/28	14:44:34	35.692	0.879	0.031	0.0272	5	3	0.053
2008/10/28	14:44:36	59.165	6.022	0.824	4.9621	5	7	0.123
2008/10/28	14:44:38	57.846	2.549	0.275	0.701	5	2	0.035
2008/10/28	14:44:40	40.879	5.612	0.763	4.282	6	6	0.088
2008/10/28	14:44:42	68.484	12.571	1.74	21.874	8	12	0.132
2008/10/28	14:44:44	57.758	14.784	2.167	32.037	9	12	0.117
2008/10/28	14:44:46	65.319	12.689	1.801	22.853	7	16	0.201
2008/10/28	14:44:48	69.099	8.674	1.252	10.86	7	10	0.126
2008/10/28	14:44:50	48.352	14.696	2.106	30.95	6	14	0.205
2008/10/28	14:44:52	58.11	16.645	2.411	40.131	9	17	0.166
2008/10/28	14:44:54	68.835	6.842	0.946	6.4725	7	9	0.113
2008/10/28	14:44:56	42.989	11.033	1.618	17.851	7	8	0.101
2008/10/28	14:44:58	56.264	9.245	1.313	12.139	7	11	0.138
2008/10/28	14:45:00	54.154	11.516	1.679	19.335	10	11	0.097
2008/10/28	14:45:02	51.692	7.121	1.007	7.1708	7	12	0.151
2008/10/28	14:45:04	60.132	14.549	2.167	31.528	7	14	0.176
2008/10/28	14:45:06	43.253	15.062	2.167	32.639	8	15	0.165
2008/10/28	14:45:08	44.659	15.56	2.167	33.719	6	13	0.191
2008/10/28	14:45:10	62.418	10.256	1.435	14.717	7	11	0.138
2008/10/28	14:45:12	41.846	5.524	0.763	4.2148	6	10	0.147
2008/10/28	14:45:14	56.44	4.44	0.641	2.846	5	8	0.141
2008/10/28	14:45:16	55.121	5.158	0.702	3.6209	6	7	0.103
2008/10/28	14:45:18	91.429	6.842	0.946	6.4725	7	9	0.113
2008/10/28	14:45:20	58.637	3.692	0.519	1.9161	5	6	0.106

2008/10/28	14:45:22	60.22	1.89	0.214	0.4045	5	2	0.035
2008/10/28	14:45:24	65.846	3.297	0.458	1.51	7	3	0.038
2008/10/28	14:45:27	62.505	8.777	1.129	9.9092	6	5	0.073
2008/10/28	14:45:29	48.967	6.872	0.946	6.5009	6	6	0.088
2008/10/28	14:45:31	37.538	5.48	0.763	4.1812	7	8	0.101
2008/10/28	14:45:33	50.901	4.733	0.641	3.0339	6	6	0.088
2008/10/28	14:45:35	62.242	2.081	0.641	1.3339	7	5	0.063
2008/10/28	14:45:37	59.692	5.495	0.092	0.5055	6	5	0.073
2008/10/28	14:45:47	104.615	3.443	0.031	0.1067	3	3	0.088
2008/10/28	14:45:51	142.066	0.015	0.031	0.0005	3	0	0.000
2008/10/28	14:45:55	80.967	21.89	0.763	16.702	5	13	0.229
2008/10/28	14:45:57	70.769	16.703	0.519	8.6689	5	13	0.229
2008/10/28	14:45:59	44.923	6.403	0.153	0.9797	4	8	0.176
2008/10/28	14:46:01	7.385	5.626	0.092	0.5176	4	7	0.154
2008/10/28	14:46:03	71.736	11.604	0.336	3.8989	3	12	0.352
2008/10/28	14:46:05	57.319	17.714	0.519	9.1936	3	9	0.264
2008/10/28	14:46:07	56.352	16.425	0.519	8.5246	7	14	0.176
2008/10/28	14:46:09	51.253	16.938	0.702	11.89	7	17	0.214
2008/10/28	14:46:11	62.33	20.322	0.641	13.026	8	13	0.143
2008/10/28	14:46:13	70.593	20.674	0.702	14.513	5	16	0.281
2008/10/28	14:46:15	66.286	10.637	0.336	3.574	6	13	0.191
2008/10/28	14:46:17	78.505	6.769	0.153	1.0357	4	8	0.176
2008/10/28	14:46:19	57.231	6.901	0.214	1.4768	4	7	0.154
2008/10/28	14:46:21	7.297	16.19	0.458	7.415	5	14	0.246
2008/10/28	14:46:23	62.154	14.872	0.519	7.7186	6	12	0.176
2008/10/28	14:46:25	39.385	14.447	0.458	6.6167	5	13	0.229
2008/10/28	14:46:27	354.725	2.388	0.214	0.511	4	4	0.088
2008/10/28	14:46:29	41.055	5.114	0.092	0.4705	2	4	0.176
2008/10/28	14:46:31	57.495	12.147	0.336	4.0814	6	11	0.161
2008/10/28	14:46:33	33.67	4.718	0.031	0.1463	7	4	0.050
2008/10/28	14:46:42	343.121	6.418	0.336	2.1564	3	5	0.147
2008/10/28	14:46:44	355.868	2.637	0.214	0.5643	1	3	0.264
2008/10/28	14:46:48	0.088	4.821	0.153	0.7376	4	7	0.154
2008/10/28	14:46:50	58.549	2.549	0.031	0.079	4	2	0.044
2008/10/28	14:46:54	34.637	4.425	0.092	0.4071	4	4	0.088
2008/10/28	14:46:56	55.824	5.07	0.092	0.4664	5	4	0.070
2008/10/28	14:47:00	110.505	6.476	0.153	0.9908	5	5	0.088
2008/10/28	14:47:02	129.231	9.846	0.336	3.3083	5	7	0.123
2008/10/28	14:47:04	116.571	4.777	0.153	0.7309	4	5	0.110
2008/10/28	14:47:06	107.692	2.315	0.031	0.0718	3	3	0.088
2008/10/28	14:47:08	144.703	5.055	0.153	0.7734	4	3	0.066
2008/10/28	14:47:10	119.033	4.703	0.153	0.7196	6	4	0.059
2008/10/28	14:47:12	176.791	5.582	0.275	1.5351	5	5	0.088
2008/10/28	14:47:14	176	3.912	0.153	0.5985	4	4	0.088
2008/10/28	14:47:16	134.681	5.714	0.214	1.2228	6	6	0.088
2008/10/28	14:47:18	175.824	2.183	0.092	0.2008	4	3	0.066
2008/10/28	14:47:24	178.374	2.608	0.214	0.5581	5	1	0.018
2008/10/28	14:47:28	154.198	7.722	0.275	2.1236	7	6	0.075
2008/10/28	14:47:30	128.088	3.546	0.092	0.3262	6	4	0.059
2008/10/28	14:47:32	144.176	0.015	0.031	0.0005	6	2	0.029
2008/10/28	14:47:34	138.813	8.117	0.275	2.2322	5	5	0.088
2008/10/28	14:47:36	122.901	10.227	0.336	3.4363	5	7	0.123
2008/10/28	14:47:38	152.088	3.634	0.092	0.3343	4	4	0.088
2008/10/28	14:47:40	164.308	1.89	0.092	0.1739	4	2	0.044
2008/10/28	14:47:42	171.077	8.396	0.336	2.8211	5	5	0.088

2008/10/28	14:47:44	163.253	5.685	0.214	1.2166	5	5	0.088
2008/10/28	14:47:47	167.912	5.201	0.214	1.113	5	5	0.088
2008/10/28	14:47:49	157.451	4.396	0.153	0.6726	5	6	0.106
2008/10/28	14:47:51	164.308	5.436	0.275	1.4949	5	6	0.106
2008/10/28	14:47:53	159.209	8.22	0.336	2.7619	5	7	0.123
2008/10/28	14:47:55	176.088	6.462	0.397	2.5654	5	6	0.106
2008/10/28	14:47:57	165.89	7.297	0.275	2.0067	5	7	0.123
2008/10/28	14:47:59	165.011	9.026	0.397	3.5833	5	6	0.106
2008/10/28	14:48:01	167.209	9.538	0.336	3.2048	6	9	0.132
2008/10/28	14:48:03	149.978	5.128	0.214	1.0974	5	6	0.106
2008/10/28	14:48:05	145.758	2.271	0.092	0.2089	4	3	0.066
2008/10/28	14:48:07	120.264	2.784	0.153	0.426	4	3	0.066
2008/10/28	14:48:09	85.451	4.777	0.153	0.7309	4	5	0.110
2008/10/28	14:48:11	82.374	10.051	0.275	2.764	5	9	0.158
2008/10/28	14:48:13	50.198	3.795	0.092	0.3491	4	4	0.088
2008/10/28	14:48:15	25.407	7.033	0.153	1.076	7	8	0.101
START FIRST RUN								
2008/10/28	14:48:17	360	10.007	0.519	5.1936	6	6	0.088
2008/10/28	14:48:19	341.978	17.993	0.824	14.826	6	9	0.132
2008/10/28	14:48:21	339.604	8.396	0.458	3.8454	6	12	0.176
2008/10/28	14:48:23	323.165	25.656	1.068	27.401	7	15	0.188
2008/10/28	14:48:25	334.593	20.308	0.946	19.211	8	19	0.209
2008/10/28	14:48:27	325.538	20.527	0.824	16.914	7	16	0.201
2008/10/28	14:48:29	335.297	17.304	0.763	13.203	7	14	0.176
2008/10/28	14:48:31	326.242	14.095	0.641	9.0349	7	15	0.188
2008/10/28	14:48:33	316.923	15.575	0.702	10.934	7	13	0.163
2008/10/28	14:48:35	293.011	20.22	0.885	17.895	8	16	0.176
2008/10/28	14:48:37	304.791	21.084	0.946	19.945	8	15	0.165
2008/10/28	14:48:39	312.176	29.495	1.19	35.099	9	42	0.411
2008/10/28	14:48:41	315.604	27.883	1.007	28.078	7	21	0.264
2008/10/28	14:48:43	300.22	25.714	1.618	41.605	9	53	0.518
2008/10/28	14:48:45	281.758	25.187	1.068	26.9	9	26	0.254
2008/10/28	14:48:47	298.813	29.582	1.068	31.594	9	27	0.264
2008/10/28	14:48:49	289.319	23.15	1.129	26.136	11	32	0.256
2008/10/28	14:48:51	299.868	36.586	1.618	59.196	12	54	0.396
2008/10/28	14:48:54	301.714	34.652	1.801	62.408	11	97	0.776
2008/10/28	14:48:56	297.934	43.575	1.679	73.162	11	74	0.592
2008/10/28	14:48:58	298.989	38.3	1.557	59.633	11	61	0.488
2008/10/28	14:49:00	301.187	29.773	1.19	35.43	13	72	0.487
2008/10/28	14:49:02	300.747	39.458	1.74	68.657	11	67	0.536
2008/10/28	14:49:04	300.571	36.044	1.435	51.723	11	44	0.352
2008/10/28	14:49:06	293.187	29.231	1.19	34.785	11	60	0.480
2008/10/28	14:49:08	283.868	30.93	1.19	36.807	10	60	0.528
2008/10/28	14:49:10	291.253	29.67	1.923	57.055	12	81	0.594
2008/10/28	14:49:12	282.813	53.846	1.618	87.123	14	92	0.578
2008/10/28	14:49:14	294.945	38.33	1.801	69.032	14	102	0.641
2008/10/28	14:49:16	290.374	38.93	1.618	62.989	13	92	0.623
2008/10/28	14:49:18	298.462	53.7	2.106	113.09	14	104	0.653
2008/10/28	14:49:20	302.33	41.582	2.106	87.572	14	100	0.628
2008/10/28	14:49:22	295.209	43.473	1.557	67.687	14	108	0.679
2008/10/28	14:49:24	285.626	33.495	1.252	41.936	12	70	0.513
2008/10/28	14:49:26	303.209	43.56	1.679	73.137	16	117	0.643
2008/10/28	14:49:28	299.429	43.824	1.862	81.6	15	100	0.586
2008/10/28	14:49:30	307.253	33.465	1.74	58.229	14	102	0.641

2008/10/28	14:49:32	299.78	35.385	1.618	57.253	12	86	0.630
2008/10/28	14:49:34	294.066	41.568	1.557	64.721	11	69	0.552
2008/10/28	14:49:36	302.33	38.579	1.557	60.068	13	82	0.555
2008/10/28	14:49:38	285.626	28.527	1.129	32.207	12	69	0.506
2008/10/28	14:49:40	288.615	36.425	2.289	83.377	13	71	0.480
2008/10/28	14:49:42	289.495	33.875	1.435	48.611	12	68	0.498
2008/10/28	14:49:44	291.692	55.311	1.801	99.615	17	135	0.699
2008/10/28	14:49:46	282.462	40.41	1.923	77.708	15	122	0.715
2008/10/28	14:49:48	298.11	43.297	1.679	72.696	17	141	0.730
2008/10/28	14:49:50	299.253	40.967	1.618	66.285	15	110	0.645
2008/10/28	14:49:52	303.033	33.685	1.679	56.557	13	85	0.575
2008/10/28	14:49:54	287.121	33.919	1.496	50.743	14	93	0.584
2008/10/28	14:49:56	293.802	24.44	1.007	24.611	13	79	0.535
2008/10/28	14:49:58	287.473	34.784	1.435	49.915	13	66	0.447
2008/10/28	14:50:00	287.736	40.542	1.679	68.07	15	85	0.498
2008/10/28	14:50:03	299.868	45.934	1.74	79.925	15	118	0.692
2008/10/28	14:50:05	289.758	41.641	1.679	69.915	14	98	0.616
2008/10/28	14:50:07	296	36.879	1.496	55.171	14	68	0.427
2008/10/28	14:50:09	284.659	37.993	1.374	52.202	14	83	0.522
2008/10/28	14:50:11	297.143	34.212	1.374	47.007	14	102	0.641
2008/10/28	14:50:13	292.923	37.597	1.313	49.365	14	89	0.559
2008/10/28	14:50:15	303.385	35.326	1.374	48.538	12	71	0.520
2008/10/28	14:50:17	309.714	33.597	1.313	44.113	11	56	0.448
2008/10/28	14:50:19	292.484	21.729	0.946	20.556	10	26	0.229
2008/10/28	14:50:21	298.725	28.029	1.19	33.355	11	29	0.232
2008/10/28	14:50:23	316.659	35.209	1.252	44.082	10	23	0.202
2008/10/28	14:50:25	314.462	21.773	0.946	20.597	11	29	0.232
2008/10/28	14:50:27	284.484	19.956	0.824	16.444	11	18	0.144
2008/10/28	14:50:29	252.132	28.542	1.19	33.965	10	22	0.194
2008/10/28	14:50:31	215.297	13.451	0.641	8.6221	9	18	0.176
END FIRST RUN								
2008/10/28	14:50:33	191.736	7.282	0.275	2.0026	7	10	0.126
2008/10/28	14:50:35	163.956	2.095	0.031	0.0649	5	3	0.053
2008/10/28	14:50:37	123.868	2.3	0.031	0.0713	5	3	0.053
2008/10/28	14:50:41	155.604	4.542	0.092	0.4179	4	4	0.088
2008/10/28	14:50:43	179.077	5.949	0.275	1.636	5	6	0.106
2008/10/28	14:50:45	194.11	2.081	0.092	0.1915	4	4	0.088
2008/10/28	14:50:47	221.626	0.015	0.031	0.0005	4	2	0.044
2008/10/28	14:50:49	219.516	0.469	0.031	0.0145	3	2	0.059
2008/10/28	14:50:51	214.242	0.264	0.031	0.0082	4	0	0.000
2008/10/28	14:50:53	225.67	8.278	0.336	2.7814	6	2	0.029
2008/10/28	14:50:55	223.824	4.85	0.214	1.0379	7	4	0.050
2008/10/28	14:50:57	216.879	5.392	0.275	1.4828	6	4	0.059
2008/10/28	14:50:59	212.396	2.007	0.153	0.3071	4	3	0.066
2008/10/28	14:51:01	205.802	10.93	0.458	5.0059	7	6	0.075
2008/10/28	14:51:04	203.868	8.308	0.336	2.7915	6	10	0.147
2008/10/28	14:51:06	209.67	9.919	0.397	3.9378	5	9	0.158
2008/10/28	14:51:08	219.604	9.963	0.458	4.5631	5	10	0.176
2008/10/28	14:51:10	251.692	5.524	0.275	1.5191	6	6	0.088
2008/10/28	14:51:12	225.407	8.85	0.397	3.5135	7	7	0.088
2008/10/28	14:51:14	242.725	16.22	0.58	9.4076	7	9	0.113
2008/10/28	14:51:16	224	13.216	0.58	7.6653	8	11	0.121
2008/10/28	14:51:18	228.747	16.542	0.824	13.631	7	14	0.176
2008/10/28	14:51:20	215.56	17.773	0.763	13.561	9	16	0.156

2008/10/28	14:51:22	202.725	12.425	0.458	5.6907	9	16	0.156
2008/10/28	14:51:24	214.066	15.575	0.641	9.9836	8	10	0.110
2008/10/28	14:51:26	208.44	9.07	0.397	3.6008	7	13	0.163
2008/10/28	14:51:28	198.945	5.582	0.214	1.1945	5	5	0.088
2008/10/28	14:51:30	194.725	7.634	0.336	2.565	7	5	0.063
2008/10/28	14:51:32	202.374	3.985	0.214	0.8528	6	7	0.103
2008/10/28	14:51:34	231.297	11.136	0.458	5.1003	7	7	0.088
2008/10/28	14:51:36	225.231	8.22	0.336	2.7619	6	7	0.103
2008/10/28	14:51:38	237.011	9.187	0.336	3.0868	6	8	0.117
2008/10/28	14:51:40	222.769	7.971	0.336	2.6783	8	6	0.066
2008/10/28	14:51:42	206.418	18.491	0.763	14.109	9	16	0.156
2008/10/28	14:51:44	193.67	14.051	0.58	8.1496	8	13	0.143
2008/10/28	14:51:46	233.582	9.304	0.397	3.6937	8	9	0.099
2008/10/28	14:51:48	187.077	15.604	0.641	10.002	9	11	0.108
2008/10/28	14:51:50	183.736	22.608	0.885	20.008	8	17	0.187
2008/10/28	14:51:52	170.022	8.542	0.336	2.8701	6	10	0.147
2008/10/28	14:51:54	158.857	9.07	0.397	3.6008	5	8	0.141
2008/10/28	14:51:56	146.901	2.066	0.031	0.064	5	2	0.035
2008/10/28	14:52:02	360	6.784	0.397	2.6932	6	3	0.044
2008/10/28	14:52:04	356.835	5.846	0.397	2.3209	8	9	0.099
2008/10/28	14:52:06	352.352	6.139	0.397	2.4372	6	5	0.073
2008/10/28	14:52:08	349.802	12.19	0.58	7.0702	8	9	0.099
2008/10/28	14:52:10	356.835	12.674	0.58	7.3509	8	14	0.154
2008/10/28	14:52:12	358.945	17.626	1.557	27.444	7	17	0.214
2008/10/28	14:52:14	351.912	9.187	0.763	7.0097	6	7	0.103
2008/10/28	14:52:16	349.363	17.055	1.374	23.434	8	16	0.176
2008/10/28	14:52:19	360	9.495	0.885	8.4031	8	9	0.099
2008/10/28	14:52:21	349.363	16.835	1.374	23.131	8	12	0.132
2008/10/28	14:52:23	340.835	9.597	0.824	7.9079	7	8	0.101
2008/10/28	14:52:25	334.505	18.842	1.374	25.889	7	16	0.201
2008/10/28	14:52:27	347.956	9.333	0.824	7.6904	7	7	0.088
2008/10/28	14:52:29	342.242	10.549	0.946	9.9794	6	10	0.147
2008/10/28	14:52:31	335.209	13.612	1.19	16.198	8	12	0.132
2008/10/28	14:52:33	332.747	13.055	1.007	13.146	9	9	0.088
2008/10/28	14:52:35	315.516	28.205	2.167	61.12	11	33	0.264
2008/10/28	14:52:37	293.538	22.491	1.74	39.134	11	41	0.328
2008/10/28	14:52:39	296.352	13.758	1.129	15.533	10	16	0.141
2008/10/28	14:52:41	300.571	22.667	1.74	39.441	9	15	0.147
2008/10/28	14:52:43	289.495	15.136	1.252	18.95	8	13	0.143
2008/10/28	14:52:45	285.451	14.315	1.129	16.162	7	15	0.188
2008/10/28	14:52:47	290.198	4.249	0.397	1.6869	7	6	0.075
2008/10/28	14:52:49	293.363	9.729	0.885	8.6102	7	9	0.113
2008/10/28	14:52:51	312.352	8.41	0.702	5.9038	7	9	0.113
2008/10/28	14:52:53	306.901	2.608	0.275	0.7172	6	2	0.029
2008/10/28	14:52:55	303.209	0.015	0.092	0.0014	8	1	0.011
2008/10/28	14:52:57	312.879	0.015	0.092	0.0014	8	1	0.011
START SECOND RUN								
2008/10/28	14:52:59	306.286	5.231	0.519	2.7149	7	4	0.050
2008/10/28	14:53:01	313.67	13.832	1.068	14.773	7	9	0.113
2008/10/28	14:53:03	317.538	7.341	0.641	4.7056	7	10	0.126
2008/10/28	14:53:05	326.154	5.773	0.58	3.3483	7	5	0.063
2008/10/28	14:53:07	305.846	24.205	1.74	42.117	9	19	0.186
2008/10/28	14:53:09	307.868	29.084	2.045	59.477	11	31	0.248
2008/10/28	14:53:11	294.418	25.714	1.862	47.879	10	37	0.325

2008/10/28	14:53:13	298.725	20.967	1.679	35.204	10	18	0.158
2008/10/28	14:53:15	281.495	17.861	1.557	27.81	11	20	0.160
2008/10/28	14:53:17	294.33	29.949	2.167	64.899	14	51	0.320
2008/10/28	14:53:19	292.747	33.451	2.411	80.65	13	91	0.616
2008/10/28	14:53:21	299.429	28.864	2.167	62.548	12	49	0.359
2008/10/28	14:53:23	287.385	26.256	1.923	50.49	12	68	0.498
2008/10/28	14:53:25	306.813	40.161	3.205	128.72	16	93	0.511
2008/10/28	14:53:27	286.154	33.07	2.534	83.799	13	61	0.413
2008/10/28	14:53:29	300.044	25.89	1.984	51.366	12	85	0.623
2008/10/28	14:53:31	293.099	31.985	2.35	75.165	15	74	0.434
2008/10/28	14:53:33	300.835	28.938	2.106	60.943	16	91	0.500
2008/10/28	14:53:35	300.044	33.128	2.534	83.946	15	86	0.504
2008/10/28	14:53:37	302.681	32.747	2.473	80.983	14	85	0.534
2008/10/28	14:53:39	288.264	26.96	2.045	55.133	13	73	0.494
2008/10/28	14:53:41	300.747	23.751	1.984	47.122	13	72	0.487
2008/10/28	14:53:44	286.418	32.366	2.289	74.086	14	90	0.565
2008/10/28	14:53:46	283.341	30.593	2.717	83.121	13	79	0.535
2008/10/28	14:53:48	279.385	37.568	2.656	99.781	15	89	0.522
2008/10/28	14:53:50	290.11	33.729	2.534	85.469	14	84	0.528
2008/10/28	14:53:52	285.714	34.095	2.595	88.477	14	93	0.584
2008/10/28	14:53:54	289.143	29.7	2.473	73.448	14	78	0.490
2008/10/28	14:53:56	285.626	34.066	2.35	80.055	13	70	0.474
2008/10/28	14:53:58	285.714	28.396	2.228	63.266	13	52	0.352
2008/10/28	14:54:00	282.374	29.802	2.717	80.972	14	74	0.465
2008/10/28	14:54:02	296.176	33.524	2.534	84.95	16	102	0.561
2008/10/28	14:54:04	293.187	29.128	2.167	63.12	15	95	0.557
2008/10/28	14:54:06	298.374	26.769	2.35	62.907	15	93	0.545
2008/10/28	14:54:08	286.681	32.923	2.289	75.361	13	90	0.609
2008/10/28	14:54:10	297.758	28.996	2.289	66.372	14	71	0.446
2008/10/28	14:54:12	292.484	36.674	3.144	115.3	14	87	0.547
2008/10/28	14:54:14	281.846	41.158	3.327	136.93	15	97	0.569
2008/10/28	14:54:16	286.154	37.201	3.083	114.69	15	89	0.522
2008/10/28	14:54:18	288.967	28.879	2.167	62.581	16	99	0.544
2008/10/28	14:54:20	287.56	42.608	2.961	126.16	15	106	0.622
2008/10/28	14:54:22	295.56	31.062	2.473	76.816	13	76	0.514
2008/10/28	14:54:24	288.176	22.212	2.167	48.133	11	49	0.392
2008/10/28	14:54:26	287.385	22.315	1.679	37.467	11	27	0.216
2008/10/28	14:54:28	314.813	21.875	1.679	36.728	12	30	0.220
2008/10/28	14:54:30	300.396	15.575	1.252	19.5	9	16	0.156
2008/10/28	14:54:32	291.341	6.52	0.58	3.7816	9	11	0.108
2008/10/28	14:54:34	259.341	19.663	1.496	29.416	11	19	0.152
2008/10/28	14:54:36	233.231	11.092	1.007	11.17	9	13	0.127
2008/10/28	14:54:38	186.725	7.766	0.58	4.5043	7	12	0.151
2008/10/28	14:54:40	182.593	11.018	0.824	9.0788	6	10	0.147
2008/10/28	14:54:42	170.286	7.297	0.58	4.2323	5	6	0.106
2008/10/28	14:54:44	158.505	1.377	0.153	0.2107	4	2	0.044
END SECOND RUN								
2008/10/28	14:54:48	157.802	0.015	0.031	0.0005	4	0	0.000
2008/10/28	14:54:56	177.846	0.015	0.031	0.0005	7	0	0.000
2008/10/28	14:55:00	201.407	0	0.031	0	5	0	0.000
2008/10/28	14:55:02	221.275	0.015	0.031	0.0005	4	1	0.022
2008/10/28	14:55:04	228.484	0.864	0.092	0.0795	4	0	0.000
2008/10/28	14:55:06	223.209	0.015	0.031	0.0005	5	0	0.000
2008/10/28	14:55:13	202.198	1.758	0.153	0.269	6	0	0.000

2008/10/28	14:55:15	220.923	0.205	0.031	0.0064	5	1	0.018
2008/10/28	14:55:17	219.692	0	0.092	0	5	0	0.000
2008/10/28	14:55:21	232.527	0.015	0.092	0.0014	5	0	0.000
2008/10/28	14:55:23	210.813	0.015	0.031	0.0005	5	0	0.000
2008/10/28	14:55:29	226.374	0.015	0.092	0.0014	6	1	0.015
2008/10/28	14:55:31	205.451	0	0.092	0	8	0	0.000
2008/10/28	14:55:33	191.648	0.015	0.092	0.0014	8	1	0.011
2008/10/28	14:55:35	195.429	7.385	0.58	4.2833	7	5	0.063
2008/10/28	14:55:37	216.352	15.37	1.129	17.353	6	14	0.205
2008/10/28	14:55:39	234.901	4.425	0.336	1.4868	6	6	0.088
2008/10/28	14:55:41	199.648	3.238	0.214	0.6929	8	2	0.022
2008/10/28	14:55:43	202.11	14.842	1.007	14.946	8	10	0.110
2008/10/28	14:55:45	191.736	7.033	0.519	3.6501	7	9	0.113
2008/10/28	14:55:47	220.22	5.597	0.458	2.5634	6	6	0.088
2008/10/28	14:55:49	229.538	7.531	0.519	3.9086	5	7	0.123
2008/10/28	14:55:51	205.011	6.051	0.458	2.7714	7	7	0.088
2008/10/28	14:55:53	248.352	1.099	0.153	0.1681	6	2	0.029
2008/10/28	14:55:55	214.505	0.791	0.092	0.0728	6	1	0.015
2008/10/28	14:55:57	236.835	0.41	0.031	0.0127	6	1	0.015
2008/10/28	14:55:59	231.736	0.015	0.031	0.0005	5	1	0.018
2008/10/28	14:56:01	237.099	0.733	0.092	0.0674	5	1	0.018
2008/10/28	14:56:03	204.923	0	0.031	0	6	1	0.015
2008/10/28	14:56:05	210.198	2.022	0.214	0.4327	8	4	0.044
2008/10/28	14:56:07	179.868	15.355	1.068	16.399	8	10	0.110
2008/10/28	14:56:09	166.945	5.934	0.397	2.3558	8	7	0.077
2008/10/28	14:56:11	141.011	11.004	0.763	8.3961	7	8	0.101
2008/10/28	14:56:13	114.901	9.568	0.641	6.1331	8	10	0.110
2008/10/28	14:56:15	78.593	8.864	0.58	5.1411	7	7	0.088
2008/10/28	14:56:17	34.637	5.89	0.275	1.6198	5	7	0.123
2008/10/28	14:56:19	0.527	8.498	0.519	4.4105	9	6	0.059
2008/10/28	14:56:21	346.637	21.026	1.679	35.303	8	18	0.198
2008/10/28	14:56:23	341.89	12.161	1.007	12.246	7	9	0.113
2008/10/28	14:56:25	358.593	9.582	0.824	7.8956	6	9	0.132
2008/10/28	14:56:27	349.451	3.736	0.397	1.4832	6	6	0.088
2008/10/28	14:56:29	317.714	4.484	0.458	2.0537	6	3	0.044
2008/10/28	14:56:31	328	11.766	0.946	11.131	6	10	0.147
2008/10/28	14:56:33	341.363	5.348	1.007	5.3854	7	11	0.138
2008/10/28	14:56:35	356.835	2.081	0.458	0.9531	8	4	0.044
2008/10/28	14:56:37	340.308	8.513	1.557	13.255	8	8	0.088
2008/10/28	14:56:39	335.209	6.725	1.19	8.0028	7	7	0.088
2008/10/28	14:56:41	352.352	0.278	0.153	0.0425	8	1	0.011
2008/10/28	14:56:43	360	0.689	0.214	0.1474	8	1	0.011
2008/10/28	14:56:46	329.67	0.015	0.153	0.0023	7	1	0.013
2008/10/28	14:56:48	352.527	0.044	0.153	0.0067	7	0	0.000
2008/10/28	14:56:50	332.659	0.015	0.092	0.0014	7	1	0.013
2008/10/28	14:56:52	322.022	0.015	0.092	0.0014	5	1	0.018
2008/10/28	14:56:54	326.505	0.015	0.092	0.0014	6	0	0.000
START THIRD RUN								
2008/10/28	14:56:56	323.868	2.3	0.458	1.0534	8	3	0.033
2008/10/28	14:56:58	328.088	9.172	1.557	14.281	7	7	0.088
2008/10/28	14:57:00	331.78	8.337	1.435	11.964	8	11	0.121
2008/10/28	14:57:02	318.945	0.015	0.153	0.0023	10	2	0.018
2008/10/28	14:57:04	302.242	9.875	1.679	16.58	11	8	0.064
2008/10/28	14:57:06	295.648	15.106	2.656	40.122	13	42	0.284

2008/10/28	14:57:08	304.088	24.952	4.121	102.83	14	51	0.320
2008/10/28	14:57:10	302.857	20.689	3.449	71.356	13	67	0.453
2008/10/28	14:57:12	290.11	18.901	3.205	60.578	13	69	0.467
2008/10/28	14:57:14	293.89	18.168	3.022	54.904	11	25	0.200
2008/10/28	14:57:16	304.352	13.114	2.35	30.818	12	15	0.110
2008/10/28	14:57:18	296	17.172	2.9	49.799	13	15	0.101
2008/10/28	14:57:20	292.923	12.029	2.045	24.599	11	28	0.224
2008/10/28	14:57:22	286.593	24.689	3.938	97.225	11	50	0.400
2008/10/28	14:57:24	279.648	16.454	3.022	49.724	11	27	0.216
2008/10/28	14:57:26	297.055	21.114	3.51	74.11	12	55	0.403
2008/10/28	14:57:28	292.22	20.337	3.51	71.383	13	66	0.447
2008/10/28	14:57:30	287.385	25.201	3.999	100.78	12	52	0.381
2008/10/28	14:57:32	298.637	21.67	3.51	76.062	12	55	0.403
2008/10/28	14:57:34	293.187	18.623	3.083	57.415	12	27	0.198
2008/10/28	14:57:36	290.022	20.982	3.755	78.787	14	44	0.276
2008/10/28	14:57:38	297.67	30.916	5.281	163.27	16	87	0.478
2008/10/28	14:57:40	294.769	28.557	4.609	131.62	17	97	0.502
2008/10/28	14:57:42	294.242	24.601	4.121	101.38	16	93	0.511
2008/10/28	14:57:44	297.407	25.289	4.06	102.67	15	73	0.428
2008/10/28	14:57:46	286.505	21.011	3.388	71.185	14	71	0.446
2008/10/28	14:57:48	289.67	21.377	3.571	76.337	14	65	0.408
2008/10/28	14:57:50	285.538	25.187	4.06	102.26	13	69	0.467
2008/10/28	14:57:52	286.154	22.271	3.877	86.345	14	81	0.509
2008/10/28	14:57:54	282.11	13.231	2.228	29.479	13	47	0.318
2008/10/28	14:57:56	286.242	30.066	5.098	153.28	16	94	0.517
2008/10/28	14:57:58	285.978	29.509	4.67	137.81	16	88	0.484
2008/10/28	14:58:00	285.626	23.414	4.06	95.061	16	86	0.473
2008/10/28	14:58:02	293.451	17.67	3.144	55.554	14	82	0.515
2008/10/28	14:58:04	295.385	27.81	4.365	121.39	14	59	0.371
2008/10/28	14:58:06	297.758	27.971	4.487	125.51	15	88	0.516
2008/10/28	14:58:08	294.945	15.927	2.839	45.217	14	64	0.402
2008/10/28	14:58:10	280.527	14.696	2.411	35.432	13	53	0.359
2008/10/28	14:58:12	281.407	17.114	2.961	50.675	14	68	0.427
2008/10/28	14:58:14	302.242	15.136	2.595	39.278	14	62	0.390
2008/10/28	14:58:16	287.912	14.256	2.595	36.994	11	48	0.384
2008/10/28	14:58:18	276.484	14.227	2.595	36.919	13	63	0.426
2008/10/28	14:58:20	293.89	19.282	3.205	61.799	14	77	0.484
2008/10/28	14:58:23	284.22	24.952	3.999	99.783	14	84	0.528
2008/10/28	14:58:25	293.451	24.791	4.609	114.26	15	76	0.446
2008/10/28	14:58:27	294.242	17.48	2.961	51.758	12	64	0.469
2008/10/28	14:58:29	291.78	18.374	2.961	54.405	12	17	0.125
2008/10/28	14:58:31	292.571	15.282	2.473	37.792	10	15	0.132
2008/10/28	14:58:33	298.637	11.341	1.923	21.809	9	15	0.147
2008/10/28	14:58:35	314.198	4.425	0.824	3.6462	7	6	0.075
2008/10/28	14:58:37	314.286	1.714	0.397	0.6805	6	1	0.015
2008/10/28	14:58:39	304.352	2.549	0.458	1.1674	6	4	0.059
2008/10/28	14:58:41	306.549	9.172	1.557	14.281	8	9	0.099
2008/10/28	14:58:43	280.703	9.597	1.618	15.528	9	10	0.098
2008/10/28	14:58:45	234.11	7.575	1.374	10.408	8	10	0.110
2008/10/28	14:58:47	202.901	1.26	0.214	0.2696	6	3	0.044
END THIRD RUN								
2008/10/28	14:58:49	212.484	0.015	0.031	0.0005	4	0	0.000
2008/10/28	14:58:51	184.527	0.015	0.031	0.0005	3	0	0.000
2008/10/28	14:58:59	185.231	0.088	0.031	0.0027	3	0	0.000

2008/10/28	14:59:01	208.352	0	0.031	0	3	0	0.000
2008/10/28	14:59:03	208.176	0.015	0.092	0.0014	3	1	0.029
2008/10/28	14:59:05	188.22	0.015	0.031	0.0005	5	0	0.000
2008/10/28	14:59:07	202.286	0.703	0.092	0.0647	5	2	0.035
2008/10/28	14:59:09	186.022	0.689	0.031	0.0214	6	0	0.000
2008/10/28	14:59:11	179.253	1.275	0.214	0.2729	5	3	0.053
2008/10/28	14:59:13	180.132	2.256	0.336	0.758	5	3	0.053
2008/10/28	14:59:15	184.176	3.692	0.58	2.1414	5	4	0.070
2008/10/28	14:59:17	190.945	2.945	0.458	1.3488	5	4	0.070
2008/10/28	14:59:19	231.033	0.015	0.031	0.0005	5	1	0.018
2008/10/28	14:59:23	193.319	1.451	0.275	0.399	7	4	0.050
2008/10/28	14:59:25	245.011	0.015	0.092	0.0014	6	0	0.000
2008/10/28	14:59:27	202.901	1.245	0.214	0.2664	6	2	0.029
2008/10/28	14:59:29	189.978	0.059	0.031	0.0018	5	0	0.000
2008/10/28	14:59:31	216.088	1.875	0.397	0.7444	5	2	0.035
2008/10/28	14:59:35	199.121	0.615	0.092	0.0566	7	1	0.013
2008/10/28	14:59:37	224	0.132	0.031	0.0041	6	1	0.015
2008/10/28	14:59:39	215.385	0.161	0.031	0.005	6	2	0.029
2008/10/28	14:59:42	222.593	0.015	0.092	0.0014	7	1	0.013
2008/10/28	14:59:44	219.253	0.015	0.031	0.0005	6	0	0.000
2008/10/28	14:59:46	196.132	2.447	0.458	1.1207	9	2	0.020
2008/10/28	14:59:48	194.725	6.886	1.129	7.7743	7	7	0.088
2008/10/28	14:59:50	220.923	6.945	1.129	7.8409	8	8	0.088
2008/10/28	14:59:52	188.396	7.253	1.19	8.6311	8	8	0.088
2008/10/28	14:59:54	190.242	3.048	0.519	1.5819	6	5	0.073
2008/10/28	14:59:56	222.154	2.593	0.458	1.1876	6	4	0.059
2008/10/28	14:59:58	210.637	6.667	1.068	7.1204	8	6	0.066
2008/10/28	15:00:00	228.835	1.07	0.214	0.229	6	3	0.044
2008/10/28	15:00:02	210.022	0.879	0.153	0.1345	5	0	0.000
2008/10/28	15:00:06	214.857	2.256	0.458	1.0332	6	1	0.015
2008/10/28	15:00:08	212.747	0.015	0.031	0.0005	6	0	0.000
2008/10/28	15:00:10	245.099	1.714	0.336	0.5759	6	2	0.029
2008/10/28	15:00:12	235.868	0.308	0.031	0.0095	7	3	0.038
2008/10/28	15:00:14	218.022	0.015	0.031	0.0005	6	0	0.000
2008/10/28	15:00:16	209.582	3.458	0.58	2.0056	7	5	0.063
2008/10/28	15:00:18	239.912	6.344	1.007	6.3884	7	8	0.101
2008/10/28	15:00:20	223.736	5.934	1.007	5.9755	9	6	0.059
2008/10/28	15:00:22	180.396	5.465	0.885	4.8365	8	6	0.066
2008/10/28	15:00:24	172.835	5.216	0.885	4.6162	7	5	0.063
2008/10/28	15:00:26	197.187	2.711	0.458	1.2416	6	4	0.059
2008/10/28	15:00:28	167.473	0.015	0.031	0.0005	5	1	0.018
2008/10/28	15:00:32	23.824	1.465	0.092	0.1348	5	1	0.018
2008/10/28	15:00:34	5.099	3.868	0.519	2.0075	5	3	0.053
2008/10/28	15:00:36	344	5.084	0.946	4.8095	6	5	0.073
2008/10/28	15:00:38	360	3.179	0.702	2.2317	7	5	0.063
2008/10/28	15:00:40	359.121	0.469	0.214	0.1004	6	2	0.029
2008/10/28	15:00:44	360	0.015	0.153	0.0023	5	0	0.000
2008/10/28	15:00:46	360	0.132	1.496	0.1975	6	2	0.029
2008/10/28	15:00:48	359.297	0.029	0.336	0.0097	7	2	0.025
2008/10/28	15:00:50	360	0.015	0.214	0.0032	7	1	0.013
2008/10/28	15:00:53	352.967	0.059	0.702	0.0414	8	1	0.011
2008/10/28	15:00:55	359.297	0.073	0.885	0.0646	8	2	0.022
2008/10/28	15:00:57	359.121	0.059	0.702	0.0414	7	2	0.025
2008/10/28	15:00:59	0.176	0.19	1.923	0.3654	7	2	0.025
2008/10/28	15:01:01	346.11	0.176	2.778	0.4889	9	4	0.039

2008/10/28	15:01:03	306.198	0.176	2.717	0.4782	9	2	0.020
START FOURTH RUN								
2008/10/28	15:01:05	298.462	0.278	4.06	1.1287	10	5	0.044
2008/10/28	15:01:07	305.143	0.132	1.679	0.2216	11	4	0.032
2008/10/28	15:01:09	303.912	0.293	4.792	1.4041	13	6	0.041
2008/10/28	15:01:11	294.33	0.557	10.165	5.6619	12	6	0.044
2008/10/28	15:01:13	290.549	0.425	8.089	3.4378	14	8	0.050
2008/10/28	15:01:15	295.033	0.205	3.877	0.7948	14	4	0.025
2008/10/28	15:01:17	276.484	0.586	11.386	6.6722	14	6	0.038
2008/10/28	15:01:19	281.758	0.879	18.895	16.609	16	21	0.115
2008/10/28	15:01:21	278.418	0.762	15.476	11.793	15	12	0.070
2008/10/28	15:01:23	286.857	0.733	15.659	11.478	17	19	0.098
2008/10/28	15:01:25	281.934	1.026	20.91	21.454	17	25	0.129
2008/10/28	15:01:27	293.451	0.894	18.895	16.892	17	24	0.124
2008/10/28	15:01:29	291.604	0.982	20.482	20.113	17	20	0.103
2008/10/28	15:01:31	288.264	0.996	21.337	21.252	17	24	0.124
2008/10/28	15:01:33	288.615	0.864	17.735	15.323	16	19	0.104
2008/10/28	15:01:35	285.363	0.879	18.712	16.448	17	28	0.145
2008/10/28	15:01:37	288.352	0.952	21.215	20.197	17	23	0.119
2008/10/28	15:01:39	293.626	0.879	20.726	18.218	17	39	0.202
2008/10/28	15:01:41	288.703	0.821	17.125	14.06	16	22	0.121
2008/10/28	15:01:43	290.813	0.308	5.525	1.7017	14	15	0.094
2008/10/28	15:01:45	287.033	0.806	14.499	11.686	16	7	0.038
2008/10/28	15:01:47	283.253	1.04	22.802	23.714	17	33	0.171
2008/10/28	15:01:49	284.571	1.04	23.413	24.35	17	37	0.191
2008/10/28	15:01:51	288.791	0.982	21.642	21.252	15	30	0.176
2008/10/28	15:01:53	299.516	0.894	19.994	17.875	17	26	0.135
2008/10/28	15:01:55	279.385	1.026	22.436	23.019	17	32	0.166
2008/10/28	15:01:57	291.165	0.952	21.215	20.197	16	27	0.148
2008/10/28	15:01:59	286.769	0.791	17.308	13.691	16	25	0.137
2008/10/28	15:02:01	286.418	0.806	18.651	15.033	18	31	0.151
2008/10/28	15:02:03	289.758	0.864	19.75	17.064	17	34	0.176
2008/10/28	15:02:05	288.176	1.055	23.962	25.28	16	34	0.187
2008/10/28	15:02:07	282.637	0.938	21.947	20.586	17	35	0.181
2008/10/28	15:02:10	290.198	0.879	21.032	18.487	18	37	0.181
2008/10/28	15:02:12	297.934	1.07	24.328	26.031	17	37	0.191
2008/10/28	15:02:14	301.626	0.85	19.994	16.995	15	29	0.170
2008/10/28	15:02:16	314.286	0.308	5.83	1.7956	13	5	0.034
END FOURTH RUN								
2008/10/28	15:02:18	305.495	0.044	0.641	0.0282	10	4	0.035
2008/10/28	15:02:20	301.275	0.205	3.266	0.6695	9	3	0.029
2008/10/28	15:02:22	284.396	0.147	2.228	0.3275	8	3	0.033
2008/10/28	15:02:24	272.44	0.103	1.496	0.1541	8	2	0.022
2008/10/28	15:02:26	213.626	0.015	0.092	0.0014	7	0	0.000
2008/10/28	15:02:28	184.703	0.029	0.275	0.008	6	1	0.015
2008/10/28	15:02:30	178.198	0.015	0.092	0.0014	5	0	0.000
2008/10/28	15:02:32	167.209	0.015	0.031	0.0005	4	1	0.022
2008/10/28	15:02:40	167.56	0.015	0.031	0.0005	6	0	0.000
2008/10/28	15:02:42	150.857	0.015	0.031	0.0005	7	1	0.013
2008/10/28	15:02:44	158.418	0.059	0.763	0.045	6	1	0.015
2008/10/28	15:02:46	175.824	0.088	1.374	0.1209	5	1	0.018
2008/10/28	15:02:48	171.604	0.015	0.031	0.0005	5	1	0.018

2008/10/28	15:02:52	223.121	0.044	0.519	0.0228	4	0	0.000
2008/10/28	15:02:54	206.242	0.029	0.397	0.0115	4	1	0.022
2008/10/28	15:02:56	203.429	0.015	0.092	0.0014	4	1	0.022
2008/10/28	15:02:58	231.121	0.015	0.031	0.0005	3	0	0.000
2008/10/28	15:03:00	230.769	0.015	0.092	0.0014	4	0	0.000
2008/10/28	15:03:02	219.077	0.015	0.031	0.0005	5	1	0.018
2008/10/28	15:03:04	220.659	0.161	2.289	0.3685	7	2	0.025
2008/10/28	15:03:06	183.56	0.015	0.031	0.0005	6	1	0.015
2008/10/28	15:03:08	177.758	0.015	0.153	0.0023	5	1	0.018
2008/10/28	15:03:10	183.736	0.029	0.214	0.0062	6	1	0.015
2008/10/28	15:03:12	184.615	0.117	1.557	0.1822	6	0	0.000
2008/10/28	15:03:14	231.121	0.015	0.092	0.0014	5	0	0.000
2008/10/28	15:03:16	211.78	0	0.092	0	5	1	0.018
2008/10/28	15:03:18	223.912	0.029	0.458	0.0133	5	1	0.018
2008/10/28	15:03:20	216.176	0.103	1.496	0.1541	5	1	0.018
2008/10/28	15:03:23	199.297	0.073	1.068	0.078	9	2	0.020
2008/10/28	15:03:25	184.879	0	0.092	0	7	1	0.013
2008/10/28	15:03:27	219.692	0.073	1.007	0.0735	7	2	0.025
2008/10/28	15:03:29	204.747	0.088	1.129	0.0994	7	2	0.025
2008/10/28	15:03:31	199.648	0.015	0.092	0.0014	7	0	0.000
2008/10/28	15:03:33	227.341	0.059	0.885	0.0522	7	0	0.000
2008/10/28	15:03:35	222.418	0.015	0.092	0.0014	6	1	0.015
2008/10/28	15:03:37	193.582	0.015	0.092	0.0014	8	1	0.011
2008/10/28	15:03:39	173.099	0.103	1.374	0.1415	8	2	0.022
2008/10/28	15:03:41	181.099	0.015	0.031	0.0005	7	1	0.013
2008/10/28	15:03:43	157.451	0.264	3.755	0.9913	8	2	0.022
2008/10/28	15:03:45	167.385	0.073	1.068	0.078	8	2	0.022
2008/10/28	15:03:47	199.736	0.015	0.092	0.0014	7	1	0.013
2008/10/28	15:03:49	199.648	0.103	1.252	0.129	8	2	0.022
2008/10/28	15:03:51	204.132	0.015	0.031	0.0005	6	2	0.029
2008/10/28	15:03:53	190.681	0.015	0.092	0.0014	5	2	0.035
2008/10/28	15:03:55	190.593	0.015	0.092	0.0014	7	1	0.013
2008/10/28	15:03:57	184	0.073	0.885	0.0646	7	2	0.025
2008/10/28	15:03:59	212.132	0.132	2.045	0.2699	8	3	0.033
2008/10/28	15:04:01	183.121	0.029	0.397	0.0115	7	2	0.025
2008/10/28	15:04:03	188.747	0.073	0.946	0.0691	6	1	0.015
2008/10/28	15:04:05	176.879	0.029	0.397	0.0115	7	2	0.025
2008/10/28	15:04:07	188.396	0.015	0.092	0.0014	5	1	0.018
2008/10/28	15:04:09	226.813	0.015	0.092	0.0014	7	1	0.013
2008/10/28	15:04:11	171.341	0.015	0.092	0.0014	6	1	0.015
2008/10/28	15:04:13	181.363	0.015	0.092	0.0014	7	1	0.013
2008/10/28	15:04:15	206.154	0.015	0.092	0.0014	7	0	0.000
2008/10/28	15:04:17	204.835	0.015	0.153	0.0023	7	0	0.000
2008/10/28	15:04:19	193.495	0.044	0.519	0.0228	6	2	0.029
2008/10/28	15:04:21	180.132	0.015	0.031	0.0005	6	0	0.000
2008/10/28	15:04:23	209.67	0.015	0.092	0.0014	6	0	0.000
2008/10/28	15:04:25	190.681	0.029	0.275	0.008	7	1	0.013
2008/10/28	15:04:27	188.22	0.015	0.031	0.0005	7	1	0.013
2008/10/28	15:04:29	190.066	0.029	0.214	0.0062	7	1	0.013
2008/10/28	15:04:32	193.319	0.015	0.031	0.0005	6	0	0.000
2008/10/28	15:04:34	203.077	0.015	0.031	0.0005	6	1	0.015
2008/10/28	15:04:36	203.516	0.015	0.031	0.0005	5	0	0.000
2008/10/28	15:04:38	214.769	0.015	0.092	0.0014	6	1	0.015
2008/10/28	15:04:40	198.418	0.015	0.092	0.0014	5	1	0.018
2008/10/28	15:04:42	204.835	0.015	0.092	0.0014	7	0	0.000

2008/10/28	15:04:44	193.231	0.015	0.092	0.0014	8	0	0.000
2008/10/28	15:04:46	185.495	0.088	1.068	0.094	7	0	0.000
2008/10/28	15:04:48	251.604	0.088	1.374	0.1209	10	1	0.009
2008/10/28	15:04:52	218.286	0.015	0.031	0.0005	6	0	0.000
2008/10/28	15:04:54	195.253	1.626	0.153	0.2488	6	2	0.029
2008/10/28	15:04:56	186.813	11.238	0.458	5.147	7	6	0.075
2008/10/28	15:04:58	214.418	23.692	1.007	23.858	7	13	0.163
2008/10/28	15:05:00	192.44	18.462	0.641	11.834	8	15	0.165
2008/10/28	15:05:02	223.912	18.799	0.824	15.49	9	18	0.176
2008/10/28	15:05:04	225.846	18.564	0.824	15.297	8	17	0.187
2008/10/28	15:05:06	206.681	14.725	0.641	9.4387	7	11	0.138
2008/10/28	15:05:08	202.286	16.366	0.641	10.491	11	15	0.120
2008/10/28	15:05:10	225.319	19.223	0.885	17.012	8	20	0.220
2008/10/28	15:05:12	219.868	22.374	1.007	22.531	9	17	0.166
2008/10/28	15:05:14	218.901	16.806	0.702	11.798	8	13	0.143
2008/10/28	15:05:16	187.165	9.392	0.397	3.7286	6	11	0.161
2008/10/28	15:05:18	222.945	5.817	0.275	1.5997	6	5	0.073
2008/10/28	15:05:20	173.626	12.938	0.519	6.7148	9	8	0.078
2008/10/28	15:05:22	178.198	19.736	0.824	16.262	9	13	0.127
2008/10/28	15:05:24	194.989	17.158	0.702	12.045	8	13	0.143
2008/10/28	15:05:26	193.143	11.897	0.519	6.1745	9	17	0.166
2008/10/28	15:05:28	181.538	21.524	0.824	17.736	9	16	0.156
2008/10/28	15:05:30	190.33	13.319	0.641	8.5375	8	10	0.110
2008/10/28	15:05:32	202.11	21.348	0.824	17.591	8	16	0.176
2008/10/28	15:05:34	210.637	14.315	0.58	8.3027	8	12	0.132
2008/10/28	15:05:36	199.736	15.751	0.58	9.1356	7	14	0.176
2008/10/28	15:05:38	195.868	6.974	0.336	2.3433	8	7	0.077
2008/10/28	15:05:40	172.571	12.322	0.641	7.8984	6	14	0.205
2008/10/28	15:05:42	201.143	6.3	0.336	2.1168	6	7	0.103
2008/10/28	15:05:44	190.505	4.777	0.214	1.0223	8	6	0.066
2008/10/28	15:05:47	201.67	12.396	0.519	6.4335	7	6	0.075
2008/10/28	15:05:49	222.769	7.062	0.336	2.3728	7	6	0.075
2008/10/28	15:05:51	230.945	2.74	0.214	0.5864	6	1	0.015
2008/10/28	15:05:53	210.989	0	0.092	0	7	2	0.025
2008/10/28	15:05:55	207.033	3.795	0.214	0.8121	7	2	0.025
2008/10/28	15:05:57	199.56	12.527	0.58	7.2657	7	9	0.113
2008/10/28	15:05:59	226.022	8.22	0.458	3.7648	6	8	0.117
2008/10/28	15:06:01	199.648	8.425	0.397	3.3447	7	6	0.075
2008/10/28	15:06:03	187.956	10.242	0.519	5.3156	6	8	0.117
2008/10/28	15:06:05	217.495	11.194	0.458	5.1269	7	7	0.088
2008/10/28	15:06:07	181.89	7.223	0.336	2.4269	7	6	0.075
2008/10/28	15:06:09	195.253	7.722	0.275	2.1236	6	7	0.103
2008/10/28	15:06:11	184.879	6.168	0.336	2.0724	6	7	0.103
2008/10/28	15:06:13	201.495	3.722	0.153	0.5695	6	3	0.044
2008/10/28	15:06:15	191.824	0.938	0.092	0.0863	5	2	0.035
2008/10/28	15:06:17	186.813	0	0.031	0	5	0	0.000
2008/10/28	15:06:19	181.011	0.835	0.092	0.0768	7	1	0.013
2008/10/28	15:06:21	192	1.67	0.092	0.1536	7	3	0.038
2008/10/28	15:06:23	220.396	17.026	0.702	11.952	7	9	0.113
2008/10/28	15:06:25	192.264	10.593	0.519	5.4978	5	12	0.211
2008/10/28	15:06:27	215.648	17.231	0.702	12.096	6	10	0.147
2008/10/28	15:06:29	209.846	15.912	0.702	11.17	9	18	0.176
2008/10/28	15:06:31	208.088	19.443	0.702	13.649	8	17	0.187
2008/10/28	15:06:33	210.813	19.853	0.763	15.148	8	14	0.154
2008/10/28	15:06:35	200.615	12.791	0.58	7.4188	7	11	0.138

2008/10/28	15:06:37	191.121	5.832	0.275	1.6038	7	6	0.075
2008/10/28	15:06:39	197.626	18.725	0.702	13.145	7	9	0.113
2008/10/28	15:06:41	167.033	3.414	0.214	0.7306	7	7	0.088
2008/10/28	15:06:43	198.593	3.648	0.153	0.5581	7	2	0.025
2008/10/28	15:06:45	187.429	1.538	0.092	0.1415	8	1	0.011
2008/10/28	15:06:47	176.088	4.703	0.214	1.0064	7	3	0.038
2008/10/28	15:06:49	193.67	17.788	0.702	12.487	7	16	0.201
2008/10/28	15:06:52	206.242	3.751	0.275	1.0315	6	5	0.073
2008/10/28	15:06:54	188.659	9.128	0.397	3.6238	6	4	0.059
2008/10/28	15:06:56	230.242	18.901	0.763	14.421	9	15	0.147
2008/10/28	15:06:58	196.747	21.626	0.885	19.139	7	15	0.188
2008/10/28	15:07:00	208.264	10.901	0.519	5.6576	7	13	0.163
2008/10/28	15:07:02	200.967	15.824	0.702	11.108	6	13	0.191
2008/10/28	15:07:04	212.659	13.436	0.519	6.9733	7	8	0.101
2008/10/28	15:07:06	205.626	9.509	0.519	4.9352	5	8	0.141
2008/10/28	15:07:08	188.132	12.718	0.641	8.1522	9	17	0.166
2008/10/28	15:07:10	196.659	18.344	0.702	12.877	7	11	0.138
2008/10/28	15:07:12	181.802	14.447	0.641	9.2605	6	11	0.161
2008/10/28	15:07:14	191.385	7.458	0.336	2.5059	7	7	0.088
2008/10/28	15:07:16	192.703	7.956	0.397	3.1585	6	6	0.088
2008/10/28	15:07:18	188.747	12.44	0.58	7.2152	6	12	0.176
2008/10/28	15:07:20	201.758	8.337	0.397	3.3098	6	8	0.117
2008/10/28	15:07:22	197.011	16.674	0.702	11.705	8	15	0.165
2008/10/28	15:07:24	208.791	15.062	0.702	10.574	8	11	0.121
2008/10/28	15:07:26	211.165	17.245	0.702	12.106	7	13	0.163
2008/10/28	15:07:28	195.516	19.897	0.763	15.181	7	13	0.163
2008/10/28	15:07:30	184.088	16.073	0.824	13.244	9	18	0.176
2008/10/28	15:07:32	194.989	8.615	0.397	3.4202	6	10	0.147
2008/10/28	15:07:34	213.714	15.634	0.641	10.021	6	9	0.132
2008/10/28	15:07:36	194.022	4.103	0.214	0.878	6	4	0.059
2008/10/28	15:07:38	203.516	6.388	0.519	3.3154	6	5	0.073

Development of a Reciprocating Aerofoil Wind Energy Harvester

Russell Phillips, Danie Hattingh

Prototype tests and numerical simulations investigate the use of a unique type of cross flow wind turbine to extract high torque at slow rotational speeds. The low solidity combined with large blade area offer potential for improved efficiency over existing slow speed machines. Results show favourable efficiencies at tip speed ratios less than 0.5. The high starting and running torque as well as slow rotation render the machine suitable for compressing of air for energy storage systems. The slow speed and quiet operation make the machine suitable for use near residential areas. The ability to control the power input from the wind to the machine from zero to a maximum is achieved by limiting the deflection of the aerofoil tails and allows full power output control as well as storm protection.

NOMENCLATURE

C_p	Power coefficient
F	Lift force (N)
A	Aerfoil area (m^2) (span multiplied by chord)
C_L	Coefficient of lift
N	Rotational speed of turbine (rev/min)
D	Turbine diameter (m)
r	Turbine radius (m)
V_{rot}	Velocity vector at aerofoil due to rotation (m/s)
V	Wind velocity (m/s)
V_{tot}	Resultant of V_{rot} and V (m/s)
M	Moment arm of lift force (m)
H	Horizontal component of lift (N)
W	Work done (J)
P	Power (W)

Greek symbols

ρ	Air density (kg/m^3)
Θ	Turbine rotation angle (deg)

Φ Lift force direction (deg)

α Angle of attack (deg)

1. INTRODUCTION

During the past three decades horizontal axis wind turbines (HAWT) have evolved dramatically[1] into highly efficient machines capable of extracting up to 40% (C_p=0.4) of the kinetic energy of the wind passing through their swept area[2]. Their main purpose is generation of electricity. Their design optimization has been driven by financial pressure to make them as cost effective as possible[3] in terms of power output versus capital cost. Most large, modern HAWT's have three slender blades which rotate with a tip speed to wind speed ratio (TSR) greater than 5.[1] Blade slenderness held advantages in materials savings and increased efficiency. The Darrieus rotor, (a vertical axis wind turbine VAWT), is the only other type of wind turbine to have seen wide scale commercial use, however few are still in service and according to Gipe[1]; "work on Darrieus technology has practically ceased". Darrieus machines also evolved into high speed devices (TSR>5) with slender blades (low solidity). They are capable of power coefficients[4] close to those of HAWT's but suffer from poor starting torque and structural complications. Both machines described are high speed, low torque devices with high TSR and low solidity and are well suited to driving electrical generators, often directly coupled[5] for efficiency reasons. Little evidence exists of significant research being conducted since the late 19th century[1] to optimize slow turning, high torque wind turbines. The American farm windmill optimized by Thomas Perry for water pumping is the last record of significant research[1]. This device is a common sight on South African farms with its numerous curved metal blades arranged in an annular ring. It is characterized by high solidity (80%)[1], relatively low TSR (1.9)[1], high starting and running torque and a C_p of approximately 0.15[1]. It was never considered efficient enough for electricity generation and hence saw little development after Perry.[1] Many developing nations (including South Africa) have no grid "feed in policy" for wind turbine owners[6]. Owners therefore can only make use of the electricity that they generate when it is available and cannot sell any surplus generated. If however a viable means of energy storage could be developed then the surplus energy could be utilized as and when it were required. Battery storage[7] is utilized to a small extent, however it is an expensive and seldom viable option. Storage of surplus wind energy harvested is also possible by pumping water to higher elevations and utilizing its energy via hydro turbines[8] at a later date. This is obviously limited to areas located near suitable high ground. Compression of air[9] is also a possible means of energy storage. The wind turbine requirements for water pumps and compressors are high torque and relatively slow rotation. The farm windmill would hence be well suited to the task, however it is possible that a device with similar torque and speed outputs could be developed with improved C_p.

2. BASIC THEORY

Lift based wind machines (such as the three described above) produce lift from the flow of air over their blades (which are of suitable cross section).[10]

$$F = C_L \frac{1}{2} \rho V^2 A \tag{1}$$

From equation (1) it is evident that an increase in total area would produce a proportional increase in lift force which would increase torque and ultimately power output. (Total area is the product of blade chord, span and number of blades). It would seem logical that a high solidity (such as the farm windmill) would yield high output (C_p) however this is not the case. The reason for this was determined by Albert Betz in 1926[2] and is well explained by quoting Gipe[1].”We must strike a balance between a rotor that completely stops the wind and one that allows the wind to pass through unimpeded”. Betz demonstrated mathematically that the optimum was reached when the rotor reduced the wind speed by one third. By conserving two thirds of the wind’s momentum after passing through the rotor an optimal quantity of the wind passed through the blades rather than being deflected around them. A rotor disc of high solidity would cause most of the wind to pass around it and little energy would be extracted from the wind by the blades. Betz concluded by using a linear momentum theory[2] that the maximum power that could be extracted by a propeller type turbine was 16/27 of the total wind power (59%). The basis of the invention on which the remainder of this paper is based is one which has the unique possibility of a combination of large area and low solidity. This combination is not possible with any other wind machines known to be in existence and has the potential of higher power coefficients particularly for slow TSR / high torque machines.

3. PRINCIPLE OF OPERATION

Figure 2 shows the final experimental platform constructed, consisting of three untwisted symmetrical section aerofoils (blades) mounted vertically 120^0 apart on radial arms connected to a central shaft. The aerofoils provided equal lift force in the positive and negative direction due to their symmetrical cross section. The aerofoils were freely pivoted on bearings at their ¼ chord at each of their ends. This position was chosen as controlling force on the symmetrical aerofoils would be least if hinged at ¼ chord[11]. The aerofoils were each fitted with a tail as shown in Figure 1, which would align the aerofoil with the local relative airflow (RAF) automatically.

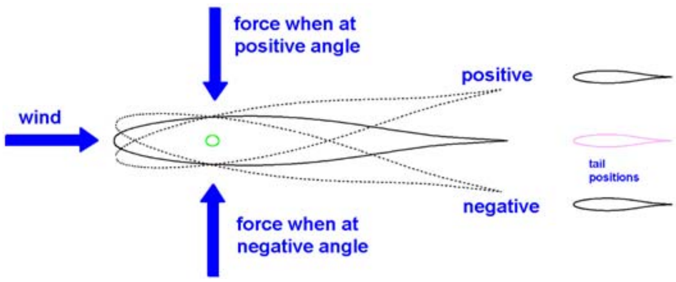

Figure 1: Symmetrical aerofoil forces

To ensure that the tails had a stable restoring tendency once deflected they were hinged at 20% of their chord and controlled via a cam arrangement such that they would control the main aerofoils to cause rotation of the central shaft. For rotation to occur anticlockwise when viewed from above the tails were made to deflect clockwise in relation to the main aerofoil in the front hemisphere of rotation and anticlockwise in relation to the main aerofoil in the rear hemisphere of rotation. It was found that deflection of the tails to approximately 10^0 in relation to the main aerofoils caused the main aerofoils to deflect to a similar but opposite angle in relation to the relative airflow (RAF).

Figure 2: Experimental platform

4. CALCULATIONS

The experimental platform had the following specifications:

- Aerofoil span 1300mm
- Aerofoil chord 400mm
- Turbine radius 840mm

It was found during testing that a TSR=0.478 yielded the best power coefficient for this particular arrangement. At an assumed wind speed of 16m/s and with a TSR=0.478 the rotational speed would be 89,94 rev/min where:

$$N = \frac{60V}{\pi D} \qquad (2)$$

The peripheral velocity of the blades due to rotation would be 7.65m/s where:

$$V_{rot} = \frac{\pi DN}{60} \qquad (3)$$

Figure 3 shows the method used to determine the resultant velocity of the RAF over the blade as well as the direction and magnitude of the lift force and its moment arm. V_{rot} was replaced with vertical and horizontal velocity components (V_{south} and V_{east}) which were summed with V to determine $V_{tot.}$ Equation (1) was used to calculate the lift force. The lift force was resolved into vertical and horizontal components. Torque was calculated using the product of the horizontal component of the lift force and the dimension M as follows:

The horizontal component of the lift force H:

$H = F\cos(90-\phi)$ for the front half (4)

$H = F\cos(90+\phi)$ for the back half (5)

The effective moment arm of this component:

$M = r(\sin\theta)$ (6)

The Torque produced would be the horizontal component of the lift force multiplied by the effective moment arm

$T = H \cdot M$ (7)

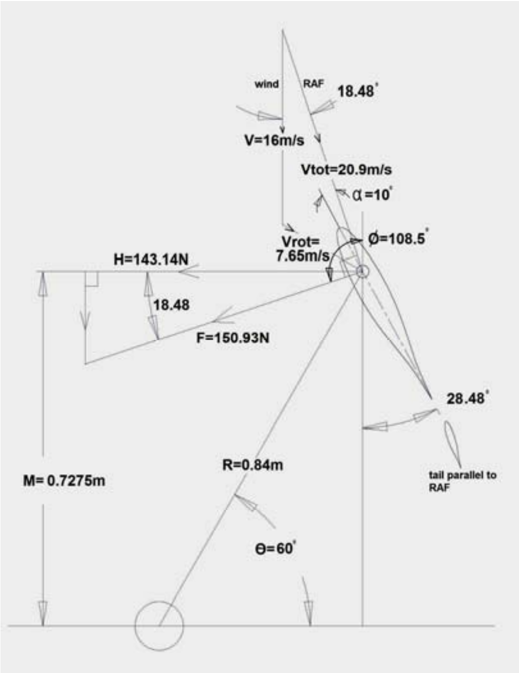

Figure 3: Direction of RAF and forces at 60^{o} turbine position

The orientation of the aerofoils during a full revolution when running at 87 rev/min and 16m/s wind speed would be as depicted in Figure 4. This was determined using Table 1.

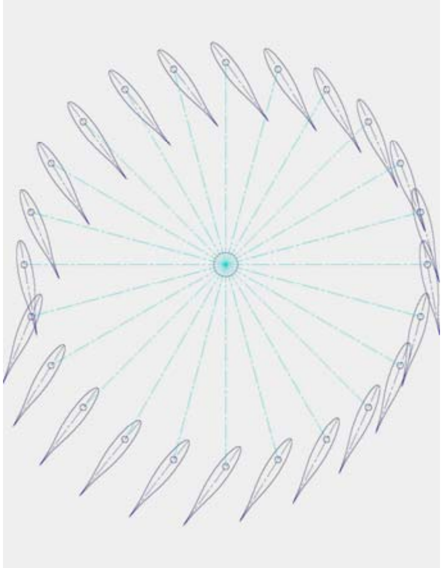

Figure 4: Aerofoil orientation

Equations 2-7 were used to calculate the values in Table 1.

Angular speed	86.94	rev/min
r	0.84	m
V_{rot}	7.6	m/s
V_{wind}	16	m/s
TSR	0.5	
α	10	deg

ϴ	V_{rot} (south comp)	V_{rot} (east comp)	V_{south} total	V_{tot}	RAF dir	Blade angle	Torque Nm
0	8	0	24	24	0	10	0
15	7	2	23	23	5	15	41
30	7	4	23	23	10	20	75
45	5	5	21	22	14	24	97
60	4	7	20	21	18	28	104
75	2	7	18	19	22	32	98
90	0	8	16	18	26	36	82
105	-2	7	14	16	28	38	82
120	-4	7	12	14	29	39	42
135	-5	5	11	12	27	37	26
150	-7	4	9	10	22	32	14
165	-7	2	9	9	13	23	6
180	-8	0	8	8	0	10	0
195	-7	-2	9	9	-13	-23	6
210	-7	-4	9	10	-22	-32	14
225	-5	-5	11	12	-27	-37	26
240	-4	-7	12	14	-29	-39	42

255	-2	-7	14	16	-28	-38	62
270	0	-8	16	18	-26	-36	82
285	2	-7	18	19	-22	-32	98
300	4	-7	20	21	-18	-28	104
315	5	-5	21	22	-14	-24	97
330	7	-4	23	23	-10	-20	75
345	7	-2	23	23	-5	-15	41
360	8	0	24	24	0	-10	0

Table 1: RAF velocity and blade orientation

Plotting torque values yielded a symmetrical graph as shown in Figure 5.

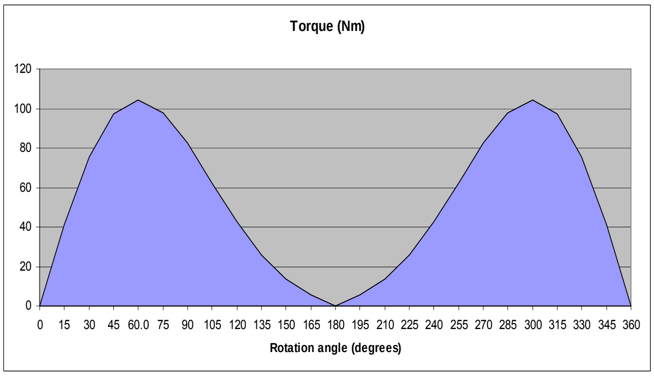

Figure 5: Torque output from main shaft

The work done by the wind turbine was calculated using equation 8.

$$W = T \cdot \theta \qquad (8)$$

The area of the graph in Figure 6 was equal to the work done per revolution.

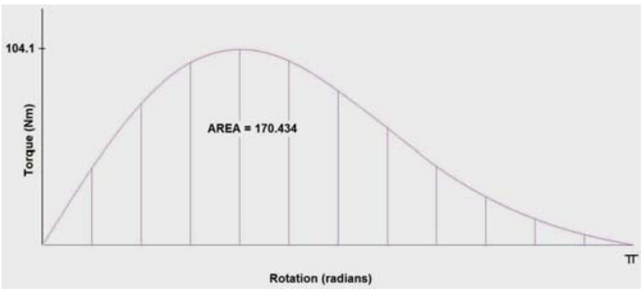

Figure 6: Torque graph area (half revolution)

$W = (170.434)2$

$W = 340.86 J / rev$

At 86.94 rev/min (1.449 rev/s):

$P = 493.9W$

This would be the theoretical power produced by one blade, neglecting blade drag losses as well as wake effects between blades. Due to the low solidity of the device and the low TSR the method used above should provide a reasonable approximation of power output. The calculations assume that sufficient resisting torque was applied to the output shaft to maintain the chosen speed.

5. TEST RESULTS

The experimental platform shown in Figure 1 was tested by mounting it on a moving vehicle and conducting tests in low ambient wind conditions, thereby simulating the reduced turbulence that the device would experience when mounted on a high mast. The moving platform also allowed data to be logged for performance over a wide range of wind speeds in a relatively short space of time. Power output was recorded from the actual electrical power output of the generator. For power coefficient calculations these values required correction for the losses in the mechanical gearing and electrical losses in the generator. An overall efficiency was ascertained by separate tests on these components.

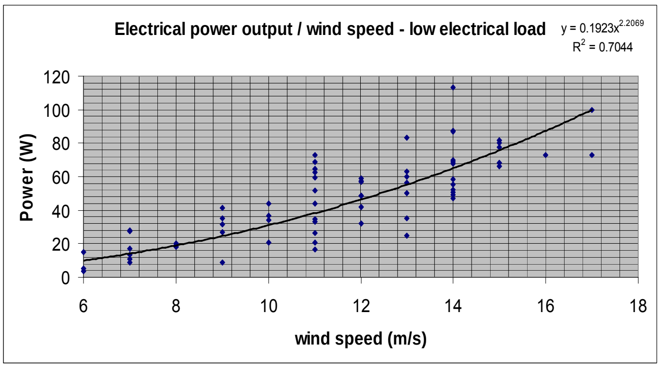

Figure 7: Power output at 25.4Ω electrical load

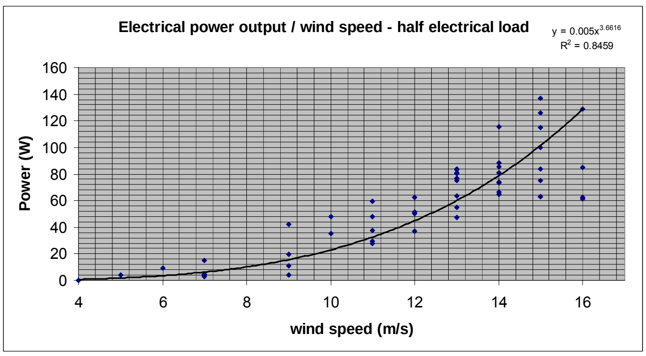

Figure 8: Power output at 12.7Ω electrical load

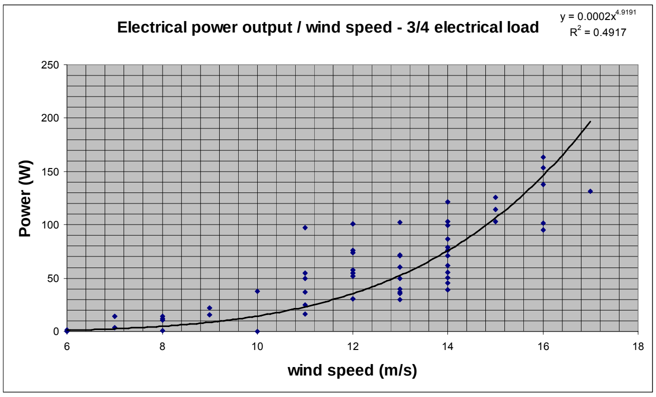

Figure 9: Power output at 6.35Ω electrical load

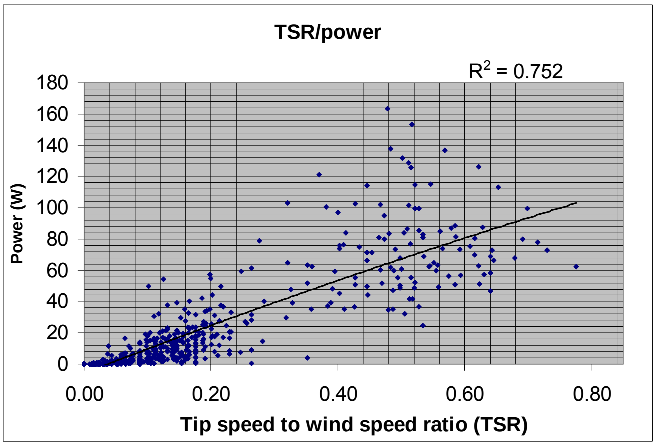

Figure 10: TSR / power results

The maximum electrical power[13] output of 164W was achieved at a TSR of 0.478. The combined efficiency of the mechanical gearing and the electrical generator under similar loadings and speed was determined by separate experimentation to be 20%.

Correcting the output power to obtain the actual power in the main shaft:

$$P_{shaft} = \frac{164}{0.2}$$

$$P_{shaft} = 820W$$

6. CONCLUSION

The maximum power obtained yielded a power coefficient[12] of C_p=0.15 which was calculated with the wind speed of 16m/s as follows:

$$C_P = \frac{P_{shaft}}{P_{wind}} \quad (9)$$

$$C_P = \frac{P_{shaft}}{\frac{1}{2}\rho . v^3 . A.}$$

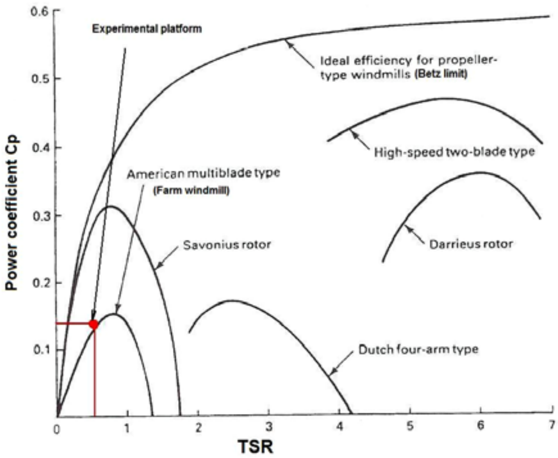

Figure 11: Power coefficients / TSR

The power coefficients of various types of wind turbines are shown in Figure 11 as well as that of the experimental platform. The performance obtained was very similar to the farm windmill but at a lower TSR. The blade chord used was 400mm. To extract the full potential of the low solidity / large area discussed in (1) the blade chord could be increased significantly. This and other refinements are likely to increase performance over that obtained. Figure 12 shows the arrangement of a compressed air energy storage system[14] which should be ideally suited to the wind turbine described in this research.

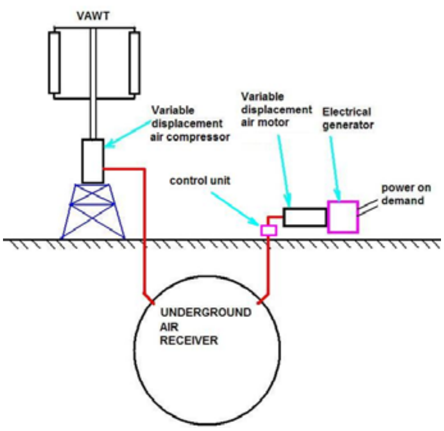

Figure 12: Compressed air energy storage system

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TIME	Input Torque (Nm)	Input Power (W)	Voltage	Amps	Output Power W	Rot spd RPM	Eff	Eff %
low electrical load 10kg pull								
12:31:04	14.5	53.0	24.615	0.82	20.28	35.00	0.38	38.2
12:31:06	14.5	92.4	22.623	0.7	15.88	61.00	0.17	17.2
12:31:08	14.5	78.8	20.22	1.07	21.59	52.00	0.27	27.4
12:31:10	14.5	72.7	20.733	0.64	13.29	48.00	0.18	18.3
12:31:12	14.5	77.3	22.256	0.7	15.62	51.00	0.20	20.2
12:31:14	14.5	86.4	20.132	0.7	14.13	57.00	0.16	16.4
12:31:16	14.5	86.4	19.311	0.64	12.38	57.00	0.14	14.3
12:31:18	14.5	77.3	26.637	0.76	20.32	51.00	0.26	26.3
12:31:20	14.5	62.1	18.608	0.58	10.79	41.00	0.17	17.4
12:31:23	14.5	74.2	22.696	0.82	18.7	49.00	0.25	25.2
12:31:25	14.5	89.4	18.974	0.82	15.63	59.00	0.17	17.5
12:31:27	14.5	81.8	20.103	0.7	14.11	54.00	0.17	17.2
12:31:29	14.5	77.3	25.538	1.01	25.72	51.00	0.33	33.3
12:31:31	14.5	68.2	21.201	0.64	13.59	45.00	0.20	19.9
12:31:33	14.5	74.2	19.385	0.64	12.43	49.00	0.17	16.7
12:31:35	14.5	74.2	19.722	0.64	12.64	49.00	0.17	17.0
12:31:37	14.5	66.7	17.788	0.7	12.49	44.00	0.19	18.7
12:31:39	14.5	62.1	24.601	0.95	23.27	41.00	0.37	37.5
12:31:41	14.5	81.8	18.168	0.58	10.54	54.00	0.13	12.9
12:31:43	14.5	77.3	16.982	0.7	11.92	51.00	0.15	15.4
12:31:45	14.5	63.6	24.513	0.76	18.7	42.00	0.29	29.4
12:31:47	14.5	65.2	21.143	0.64	13.55	43	0.21	20.8
12:31:49	14.5	80.3	17.978	0.58	10.43	53	0.13	13.0
12:31:51	14.5	72.7	18.081	0.7	12.69	48	0.17	17.5
12:31:53	14.5	57.6	16.821	0.7	11.81	38	0.21	20.5
12:31:55	14.5	75.8	19.487	0.58	11.3	50.00	0.15	14.9
12:31:57	14.5	83.3	18.242	0.64	11.69	55.00	0.14	14.0
12:31:59	14.5	66.7	19.531	0.64	12.52	44.00	0.19	18.8
12:32:01	14.5	65.2	18.799	0.64	12.05	43.00	0.18	18.5
12:32:03	14.5	78.8	25.114	0.7	17.63	52.00	0.22	22.4
12:32:05	14.5	72.7	20.762	0.7	14.57	48.00	0.20	20.0
12:32:07	14.5	56.1	17.084	0.7	11.99	37.00	0.21	21.4
12:32:09	14.5	66.7	16.322	0.58	9.467	44.00	0.14	14.2
12:32:11	14.5	66.7	17.465	0.52	9.064	44.00	0.14	13.6
12:32:13	14.5	54.5	17.172	0.58	9.96	36.00	0.18	18.3
12:32:15	14.5	71.2	17.07	0.64	10.94	47.00	0.15	15.4
12:32:17	14.5	74.2	17.026	0.52	8.836	49.00	0.12	11.9
12:32:19	14.5	62.1	18.711	0.82	15.42	41.00	0.25	24.8
12:32:21	14.5	6.1	0.015	-0.09	-0	4.00	0.00	0.0
							ave	**19.4**
low electrical load 15kg pull								
12:34:09	21.7	9.1	15.326	0.46	7.019	4.00	0.77	77.2
12:34:11	21.7	175.0	39.238	1.13	44.3	77.00	0.25	25.3
12:34:13	21.7	195.5	40.41	1.25	50.59	86.00	0.26	25.9
12:34:15	21.7	186.4	32.747	1.25	41	82.00	0.22	22.0
12:34:17	21.7	193.2	31.429	1.44	45.1	85.00	0.23	23.3
12:34:19	21.7	209.1	42.403	1.31	55.68	92.00	0.27	26.6
12:34:21	21.7	179.6	33.744	1.19	40.16	79.00	0.22	22.4
12:34:23	21.7	211.4	39.546	1.31	51.92	93.00	0.25	24.6
12:34:25	21.7	193.2	32.264	1.62	52.2	85.00	0.27	27.0
12:34:27	21.7	197.7	41.377	1.5	61.9	87.00	0.31	31.3

12:34:29	21.7	220.5	43.165	1.25	54.04	97.00	0.25	24.5
12:34:31	21.7	181.8	32.982	1.37	45.32	80.00	0.25	24.9
12:34:33	21.7	197.7	33.744	1.37	46.36	87.00	0.23	23.4
12:34:35	21.7	206.8	37.993	1.25	47.57	91.00	0.23	23.0
12:34:37	21.7	193.2	39.355	1.31	51.67	85.00	0.27	26.7
12:34:39	21.7	220.5	41.04	1.92	78.92	97.00	0.36	35.8
12:34:41	21.7	200.0	34.154	1.37	46.93	88.00	0.23	23.5
12:34:43	21.7	190.9	30.872	1.25	38.65	84.00	0.20	20.2
12:34:45	21.7	215.9	43.326	1.62	70.1	95.00	0.32	32.5
12:34:47	21.7	188.7	34.359	1.25	43.02	83.00	0.23	22.8
12:34:49	21.7	202.3	31.399	1.44	45.06	89.00	0.22	22.3
12:34:51	21.7	202.3	31.282	1.31	41.07	89.00	0.20	20.3
12:34:53	21.7	181.8	34.608	1.19	41.18	80.00	0.23	22.6
12:34:55	21.7	2.3	0.015	-0.09	-0	1.00	0.00	-0.1
							ave	**26.2**
low electrical load 20kg pull								
12:36:39	36.2	11.4	8.132	0.21	1.74	3.00	0.15	15.3
12:36:41	36.2	291.7	31.458	1.13	35.52	77.00	0.12	12.2
12:36:43	36.2	443.2	44.176	1.37	60.7	117.00	0.14	13.7
12:36:45	36.2	500.0	56.337	1.92	108.3	132.00	0.22	21.7
12:36:47	36.2	515.2	59.941	2.35	140.9	136.00	0.27	27.3
12:36:49	36.2	587.2	48.059	2.11	101.2	155.00	0.17	17.2
12:36:51	36.2	553.1	59.473	1.92	114.4	146.00	0.21	20.7
12:36:53	36.2	606.1	53.143	1.86	98.95	160.00	0.16	16.3
12:36:55	36.2	537.9	48.996	2.17	106.2	142.00	0.20	19.7
12:36:57	36.2	534.1	56.542	1.86	105.3	141.00	0.20	19.7
12:36:59	36.2	522.8	53.773	2.47	133	138.00	0.25	25.4
12:37:01	36.2	541.7	54.593	1.86	101.7	143.00	0.19	18.8
12:37:03	36.2	568.2	48.967	1.92	94.16	150.00	0.17	16.6
12:37:05	36.2	507.6	42.74	1.68	71.76	134.00	0.14	14.1
12:37:07	36.2	465.9	53.905	1.8	97.08	123.00	0.21	20.8
12:37:09	36.2	583.4	58.916	2.23	131.3	154.00	0.23	22.5
12:37:11	36.2	18.9	0	0.03	0	5.00	0.00	0.0
							ave	**17.8**
half electrical load 10kg pull								
12:38:36	14.5	48.5	12.982	0.95	12.28	32	0.25	25.3
12:38:38	14.5	53.0	15.106	1.01	15.21	35	0.29	28.7
12:38:40	14.5	18.2	11.136	0.82	9.176	12	0.50	50.5
12:38:42	14.5	25.8	13.861	1.01	13.96	17	0.54	54.2
12:38:44	14.5	28.8	11.487	0.89	10.17	19	0.35	35.3
12:38:46	14.5	59.1	12.293	0.82	10.13	39	0.17	17.1
12:38:48	14.5	37.9	11.839	0.95	11.2	25	0.30	29.6
12:38:50	14.5	45.5	14.579	1.01	14.68	30	0.32	32.3
12:38:52	14.5	18.2	11.751	0.89	10.4	12	0.57	57.2
12:38:54	14.5	56.1	11.341	0.82	9.345	37	0.17	16.7
12:38:56	14.5	37.9	11.868	0.95	11.23	25	0.30	29.6
12:38:58	14.5	47.0	11.985	0.89	10.61	31	0.23	22.6
12:39:00	14.5	28.8	11.502	0.95	10.88	19	0.38	37.8
12:39:02	14.5	47.0	14.491	1.07	15.48	31	0.33	32.9
12:39:04	14.5	24.2	13.26	0.95	12.54	16	0.52	51.7
12:39:06	14.5	45.5	11.678	0.82	9.623	30	0.21	21.2
12:39:08	14.5	27.3	13.788	0.95	13.04	18	0.48	47.8
12:39:10	14.5	50.0	12.557	1.01	12.64	33	0.25	25.3
12:39:13	14.5	24.2	11.399	0.82	9.393	16	0.39	38.7
12:39:15	14.5	30.3	12.176	0.82	10.03	20	0.33	33.1

12:39:17	14.5	30.3	10.564	0.76	8.06	20	0.27	26.6
12:39:19	14.5	19.7	10.505	0.82	8.656	13	0.44	43.9
12:39:21	14.5	19.7	11.531	0.82	9.502	13	0.48	48.2
12:39:23	14.5	31.8	12.132	0.82	9.997	21	0.31	31.4
12:39:25	14.5	42.4	12.205	0.95	11.55	28	0.27	27.2
12:39:27	14.5	30.3	14.168	1.13	16	20	0.53	52.8
12:39:29	14.5	30.3	12.454	0.89	11.02	20	0.36	36.4
12:39:31	14.5	16.7	11.619	0.89	10.28	11	0.62	61.7
12:39:33	14.5	21.2	10.535	0.76	8.038	14	0.38	37.9
12:39:35	14.5	18.2	12.381	0.95	11.71	12	0.64	64.4
12:39:37	14.5	30.3	12.22	0.89	10.81	20	0.36	35.7
12:39:39	14.5	18.2	10.813	0.76	8.25	12	0.45	45.4
12:39:41	14.5	30.3	13.363	0.95	12.64	20	0.42	41.7
12:39:43	14.5	13.6	12.088	0.82	9.961	9	0.73	73.0
12:39:45	14.5	19.7	10.945	0.82	9.019	13	0.46	45.8
12:39:47	14.5	15.2	10.227	0.82	8.427	10	0.56	55.6
12:39:49	14.5	21.2	13.89	0.95	13.14	14	0.62	61.9
12:39:51	14.5	34.9	12.908	0.95	12.21	23	0.35	35.0
12:39:53	14.5	16.7	10.623	0.76	8.105	11	0.49	48.6
12:39:55	14.5	18.2	10.227	0.7	7.179	12	0.39	39.5
12:39:57	14.5	15.2	11.59	0.82	9.55	10	0.63	63.0
12:39:59	14.5	18.2	11.004	0.82	9.067	12	0.50	49.9
12:40:01	14.5	15.2	11.15	0.76	8.507	10	0.56	56.1
12:40:03	14.5	24.2	10.857	0.76	8.284	16	0.34	34.2
12:40:05	14.5	15.2	10.447	0.82	8.608	10	0.57	56.8
12:40:07	14.5	16.7	10.916	0.82	8.995	11	0.54	54.0
12:40:09	14.5	18.2	13.744	0.95	13	12	0.72	71.5
12:40:11	14.5	16.7	13.875	1.07	14.82	11	0.89	88.9
12:40:13	14.5	24.2	13.377	0.95	12.65	16	0.52	52.2
12:40:15	14.5	16.7	11.092	0.82	9.14	11	0.55	54.8
12:40:17	14.5	18.2	14.227	0.95	13.46	12	0.74	74.0
12:40:19	14.5	16.7	12.645	0.89	11.19	11	0.67	67.1
12:40:21	14.5	15.2	10.125	0.7	7.108	10	0.47	46.9
12:40:23	14.5	16.7	9.993	0.76	7.625	11	0.46	45.7
12:40:26	14.5	18.2	10.74	0.82	8.85	12	0.49	48.7
12:40:28	14.5	19.7	14.403	1.07	15.38	13	0.78	78.1
12:40:30	14.5	16.7	10.432	0.82	8.596	11	0.52	51.6
12:40:32	14.5	15.2	11.385	0.76	8.687	10	0.57	57.3
12:40:34	14.5	15.2	10.916	0.76	8.329	10	0.55	55.0
12:40:36	14.5	16.7	11.018	0.76	8.407	11	0.50	50.4
12:40:38	14.5	16.7	11.165	0.82	9.2	11	0.55	55.2
12:40:40	14.5	16.7	11.736	0.89	10.39	11	0.62	62.3
12:40:42	14.5	15.2	10.681	0.82	8.801	10	0.58	58.1
12:40:44	14.5	12.1	4.454	0.34	1.497	8	0.12	12.3
							ave	**46.0**

half electrical load 15kg pull

12:42:08	21.7	6.8	7.341	0.58	4.258	3	0.62	62.4
12:42:10	21.7	127.3	24.454	1.62	39.57	56	0.31	31.1
12:42:12	21.7	115.9	20.703	1.5	30.97	51	0.27	26.7
12:42:14	21.7	109.1	19.341	1.68	32.47	48	0.30	29.8
12:42:16	21.7	115.9	22.637	1.68	38.01	51	0.33	32.8
12:42:19	21.7	120.5	23.136	1.68	38.85	53	0.32	32.2
12:42:21	21.7	136.4	19.209	1.44	27.56	60	0.20	20.2
12:42:23	21.7	136.4	18.857	1.56	29.36	60	0.22	21.5
12:42:25	21.7	138.6	20.864	1.56	32.49	61	0.23	23.4

12:42:27	21.7	125.0	24.982	1.92	48.04	55	0.38	38.4
12:42:29	21.7	115.9	22.623	1.62	36.6	51	0.32	31.6
12:42:31	21.7	115.9	19.414	1.44	27.86	51	0.24	24.0
12:42:33	21.7	115.9	23.267	1.62	37.65	51	0.32	32.5
12:42:35	21.7	129.6	22.828	1.68	38.33	57	0.30	29.6
12:42:37	21.7	138.6	27.048	1.92	52.01	61	0.38	37.5
12:42:39	21.7	127.3	25.231	1.62	40.82	56	0.32	32.1
12:42:41	21.7	129.6	24	1.68	40.3	57	0.31	31.1
12:42:43	21.7	118.2	22.755	1.8	40.98	52	0.35	34.7
12:42:45	21.7	106.8	21.201	1.56	33.01	47	0.31	30.9
12:42:47	21.7	122.7	19.956	1.44	28.64	54	0.23	23.3
12:42:49	21.7	122.7	20.908	1.5	31.28	54	0.25	25.5
12:42:51	21.7	138.6	18.667	1.44	26.79	61	0.19	19.3
12:42:53	21.7	127.3	19.546	1.62	31.63	56	0.25	24.8
12:42:55	21.7	125.0	19.546	1.37	26.86	55	0.21	21.5
12:42:57	21.7	109.1	22.93	1.62	37.1	48	0.34	34.0
12:42:59	21.7	102.3	18.418	1.5	27.55	45	0.27	26.9
12:43:01	21.7	115.9	22.271	1.68	37.39	51	0.32	32.3
12:43:03	21.7	131.8	20.396	1.74	35.49	58	0.27	26.9
12:43:05	21.7	120.5	18.447	1.5	27.6	53	0.23	22.9
12:43:07	21.7	125.0	18.857	1.44	27.06	55	0.22	21.6
12:43:09	21.7	106.8	18.3	1.44	26.26	47	0.25	24.6
12:43:11	21.7	109.1	19.707	1.44	28.28	48	0.26	25.9
12:43:13	21.7	129.6	23.414	1.68	39.31	57	0.30	30.3
12:43:15	21.7	125.0	17.538	1.44	25.17	55	0.20	20.1
12:43:17	21.7	120.5	18.813	1.44	27	53	0.22	22.4
12:43:19	21.7	102.3	22.432	1.62	36.29	45	0.35	35.5
12:43:21	21.7	6.8	0.015	-0.03	-0	3	0.00	0.0
							ave	**28.1**

half electrical load 20kg pull

12:44:24	36.2	106.1	20.015	1.44	28.72	28	0.27	27.1
12:44:26	36.2	287.9	28.352	2.05	57.98	76	0.20	20.1
12:44:28	36.2	306.8	34.066	2.6	88.4	81	0.29	28.8
12:44:30	36.2	329.6	37.114	2.47	91.78	87	0.28	27.8
12:44:32	36.2	337.1	32.469	2.23	72.34	89	0.21	21.5
12:44:34	36.2	306.8	28.542	2.23	63.59	81	0.21	20.7
12:44:36	36.2	322.0	33.421	2.6	86.73	85	0.27	26.9
12:44:38	36.2	306.8	28.908	2.29	66.17	81	0.22	21.6
12:44:40	36.2	291.7	34.886	2.41	84.11	77	0.29	28.8
12:44:42	36.2	337.1	33.832	2.35	79.51	89	0.24	23.6
12:44:44	36.2	318.2	30.696	2.17	66.52	84	0.21	20.9
12:44:46	36.2	272.7	33.392	2.35	78.47	72	0.29	28.8
12:44:48	36.2	269.0	27.971	2.05	57.2	71	0.21	21.3
12:44:50	36.2	303.1	28.425	2.11	59.86	80	0.20	19.8
12:44:52	36.2	314.4	26.93	2.17	58.36	83	0.19	18.6
12:44:54	36.2	280.3	30.725	2.17	66.58	74	0.24	23.8
12:44:56	36.2	284.1	28.513	2.9	82.69	75	0.29	29.1
12:44:58	36.2	299.3	29.612	2.17	64.17	79	0.21	21.4
12:45:00	36.2	333.4	29.363	2.11	61.84	88	0.19	18.6
12:45:02	36.2	280.3	27.824	2.35	65.39	74	0.23	23.3
12:45:04	36.2	287.9	32.996	2.35	77.54	76	0.27	26.9
12:45:06	36.2	344.7	29.114	2.11	61.31	91	0.18	17.8
12:45:08	36.2	314.4	32.513	2.96	96.27	83	0.31	30.6
12:45:10	36.2	269.0	25.788	2.05	52.74	71	0.20	19.6
							ave	**23.6**

3/4 electrical load 10kg pull

12:46:23	14.5	10.6	7.077	0.95	6.695	7	0.63	63.1
12:46:25	14.5	10.6	6.989	0.89	6.185	7	0.58	58.3
12:46:27	14.5	10.6	6.711	0.89	5.939	7	0.56	56.0
12:46:29	14.5	10.6	7.209	0.95	6.82	7	0.64	64.3
12:46:31	14.5	10.6	7.722	1.07	8.247	7	0.78	77.8
12:46:33	14.5	10.6	7.912	1.07	8.45	7	0.80	79.7
12:46:35	14.5	10.6	6.769	0.89	5.991	7	0.56	56.5
12:46:37	14.5	12.1	7.179	0.95	6.791	8	0.56	56.0
12:46:39	14.5	12.1	7.15	1.01	7.2	8	0.59	59.4
12:46:41	14.5	10.6	6.974	0.95	6.597	7	0.62	62.2
12:46:43	14.5	10.6	7.179	0.95	6.791	7	0.64	64.0
12:46:45	14.5	12.1	8.542	1.13	9.644	8	0.80	79.6
12:46:47	14.5	12.1	7.15	1.01	7.2	8	0.59	59.4
12:46:49	14.5	10.6	8.147	1.07	8.701	7	0.82	82.0
12:46:51	14.5	12.1	7.941	1.07	8.481	8	0.70	70.0
12:46:53	14.5	12.1	6.974	0.95	6.597	8	0.54	54.4
12:46:55	14.5	10.6	6.52	0.82	5.372	7	0.51	50.7
12:46:57	14.5	12.1	8.308	1.13	9.38	8	0.77	77.4
12:46:59	14.5	12.1	8.176	1.07	8.732	8	0.72	72.0
12:47:01	14.5	12.1	8.088	1.07	8.638	8	0.71	71.3
12:47:03	14.5	12.1	6.96	0.95	6.584	8	0.54	54.3
12:47:05	14.5	12.1	7.414	0.95	7.014	8	0.58	57.9
12:47:07	14.5	12.1	7.531	1.01	7.584	8	0.63	62.6
12:47:09	14.5	10.6	6.872	0.95	6.501	7	0.61	61.3
12:47:11	14.5	10.6	8.425	1.13	9.512	7	0.90	89.7
12:47:13	14.5	12.1	8.425	1.13	9.512	8	0.78	78.5
12:47:15	14.5	10.6	7.604	1.07	8.121	7	0.77	76.6
12:47:17	14.5	12.1	6.974	0.95	6.597	8	0.54	54.4
12:47:19	14.5	12.1	6.535	0.89	5.783	8	0.48	47.7
12:47:21	14.5	10.6	7.033	0.95	6.653	7	0.63	62.7
12:47:23	14.5	10.6	7.062	0.95	6.681	7	0.63	63.0
12:47:26	14.5	10.6	6.505	0.89	5.757	7	0.54	54.3
12:47:28	14.5	10.6	7.077	0.95	6.695	7	0.63	63.1
12:47:30	14.5	12.1	6.667	0.89	5.9	8	0.49	48.7
12:47:32	14.5	10.6	6.52	0.95	6.168	7	0.58	58.2
12:47:34	14.5	12.1	8.234	1.13	9.296	8	0.77	76.7
12:47:36	14.5	10.6	6.418	0.89	5.68	7	0.54	53.5
12:47:38	14.5	10.6	6.769	0.95	6.403	7	0.60	60.4
12:47:40	14.5	10.6	7.223	1.01	7.274	7	0.69	68.6
12:47:42	14.5	10.6	5.949	0.82	4.902	7	0.46	46.2
12:47:44	14.5	10.6	7.077	0.95	6.695	7	0.63	63.1
12:47:46	14.5	10.6	7.604	1.01	7.657	7	0.72	72.2
12:47:48	14.5	10.6	6.051	0.89	5.355	7	0.50	50.5
12:47:50	14.5	10.6	7.81	1.01	7.865	7	0.74	74.1
12:47:52	14.5	10.6	6.623	0.89	5.861	7	0.55	55.3
12:47:54	14.5	12.1	7.78	1.07	8.309	8	0.69	68.5
12:47:56	14.5	10.6	7.751	1.07	8.278	7	0.78	78.0
12:47:58	14.5	10.6	6.476	0.89	5.731	7	0.54	54.0
12:48:00	14.5	10.6	7.546	0.95	7.139	7	0.67	67.3
12:48:02	14.5	12.1	7.092	0.95	6.709	8	0.55	55.3
12:48:04	14.5	10.6	7.37	0.95	6.972	7	0.66	65.7
12:48:06	14.5	12.1	7.824	1.01	7.879	8	0.65	65.0
12:48:08	14.5	10.6	6.037	0.89	5.343	7	0.50	50.4
12:48:10	14.5	12.1	6.095	0.89	5.394	8	0.44	44.5

12:48:12	14.5	10.6	6.315	0.89	5.589	7	0.53	52.7
12:48:14	14.5	10.6	5.773	0.82	4.757	7	0.45	44.8
12:48:16	14.5	10.6	6.52	0.89	5.77	7	0.54	54.4
12:48:18	14.5	10.6	5.861	0.76	4.472	7	0.42	42.2
12:48:20	14.5	10.6	7.795	1.13	8.801	7	0.83	83.0
12:48:22	14.5	12.1	6.857	0.95	6.487	8	0.54	53.5
12:48:24	14.5	10.6	7.062	0.95	6.681	7	0.63	63.0
12:48:26	14.5	12.1	6.535	0.89	5.783	8	0.48	47.7
12:48:28	14.5	10.6	6.769	0.95	6.403	7	0.60	60.4
12:48:30	14.5	10.6	6.608	0.89	5.848	7	0.55	55.1
12:48:32	14.5	10.6	8.044	1.01	8.1	7	0.76	76.4
12:48:34	14.5	10.6	7.385	1.01	7.437	7	0.70	70.1
12:48:36	14.5	10.6	6.256	0.82	5.155	7	0.49	48.6
12:48:38	14.5	10.6	7.736	1.01	7.79	7	0.73	73.4
12:48:40	14.5	10.6	6.418	0.89	5.68	7	0.54	53.5
12:48:42	14.5	10.6	6.139	0.89	5.433	7	0.51	51.2
12:48:44	14.5	10.6	5.846	0.82	4.817	7	0.45	45.4
12:48:46	14.5	10.6	7.341	1.01	7.392	7	0.70	69.7
12:48:48	14.5	10.6	6.344	0.95	6.001	7	0.57	56.6
12:48:50	14.5	10.6	6.271	0.82	5.167	7	0.49	48.7
12:48:52	14.5	10.6	6.212	0.76	4.74	7	0.45	44.7
12:48:54	14.5	10.6	6.462	0.82	5.325	7	0.50	50.2
12:48:56	14.5	10.6	5.963	0.89	5.277	7	0.50	49.8
12:48:58	14.5	10.6	6.623	0.89	5.861	7	0.55	55.3
12:49:00	14.5	10.6	7.267	1.07	7.761	7	0.73	73.2
12:49:02	14.5	10.6	5.89	0.82	4.853	7	0.46	45.8
12:49:04	14.5	9.1	6.154	0.76	4.696	6	0.52	51.6
12:49:06	14.5	10.6	7.927	1.07	8.466	7	0.80	79.8
12:49:08	14.5	9.1	6.608	0.95	6.251	6	0.69	68.8
12:49:10	14.5	10.6	6.242	0.82	5.143	7	0.48	48.5
12:49:12	14.5	10.6	7.751	1.01	7.805	7	0.74	73.6
12:49:14	14.5	9.1	6.198	0.82	5.107	6	0.56	56.2
12:49:16	14.5	10.6	5.773	0.82	4.757	7	0.45	44.8
12:49:18	14.5	10.6	6.183	0.89	5.472	7	0.52	51.6
12:49:20	14.5	10.6	6.916	0.95	6.543	7	0.62	61.7
12:49:22	14.5	10.6	6.212	0.82	5.119	7	0.48	48.3
12:49:24	14.5	10.6	7.253	0.95	6.861	7	0.65	64.7
12:49:26	14.5	10.6	5.875	0.76	4.483	7	0.42	42.3
12:49:28	14.5	10.6	7.516	0.95	7.11	7	0.67	67.0
12:49:31	14.5	10.6	6.476	0.89	5.731	7	0.54	54.0
12:49:33	14.5	10.6	6.549	0.89	5.796	7	0.55	54.6
12:49:35	14.5	10.6	6.037	0.82	4.974	7	0.47	46.9
12:49:37	14.5	10.6	6.842	0.95	6.473	7	0.61	61.0
12:49:39	14.5	10.6	6.579	0.95	6.224	7	0.59	58.7
12:49:41	14.5	1.5	0.015	-0.03	-0	1	0.00	0.0
								59.8

3/4 electrical load 15 kg pull

12:50:23	21.7	2.3	4.015	0.52	2.084	1	0.92	91.7
12:50:25	21.7	61.4	11.883	1.68	19.95	27	0.33	32.5
12:50:27	21.7	90.9	11.766	1.56	18.32	40	0.20	20.2
12:50:29	21.7	56.8	11.209	1.56	17.45	25	0.31	30.7
12:50:31	21.7	81.8	14.579	1.92	28.04	36	0.34	34.3
12:50:33	21.7	70.5	11.033	1.5	16.51	31	0.23	23.4
12:50:35	21.7	86.4	12.015	1.68	20.17	38	0.23	23.4
12:50:37	21.7	70.5	11.883	1.62	19.23	31	0.27	27.3

12:50:39	21.7	77.3	14.242	1.86	26.52	34	0.34	34.3
12:50:41	21.7	72.7	10.462	1.56	16.29	32	0.22	22.4
12:50:43	21.7	77.3	12.777	1.74	22.23	34	0.29	28.8
12:50:45	21.7	70.5	12.806	1.74	22.28	31	0.32	31.6
12:50:47	21.7	70.5	11.707	1.68	19.66	31	0.28	27.9
12:50:49	21.7	63.6	10.271	1.44	14.74	28	0.23	23.2
12:50:51	21.7	72.7	11.121	1.56	17.32	32	0.24	23.8
12:50:53	21.7	54.5	13.143	1.8	23.67	24	0.43	43.4
12:50:55	21.7	68.2	12.645	1.86	23.54	30	0.35	34.5
12:50:57	21.7	72.7	10.711	1.56	16.68	32	0.23	22.9
12:50:59	21.7	70.5	11.678	1.62	18.9	31	0.27	26.8
12:51:01	21.7	84.1	11.253	1.5	16.83	37	0.20	20.0
12:51:03	21.7	75.0	12.352	1.74	21.49	33	0.29	28.7
12:51:05	21.7	77.3	10.769	1.5	16.11	34	0.21	20.8
12:51:07	21.7	63.6	11.443	1.62	18.51	28	0.29	29.1
12:51:09	21.7	79.6	12.073	1.62	19.53	35	0.25	24.6
12:51:11	21.7	72.7	10.96	1.56	17.06	32	0.23	23.5
12:51:13	21.7	81.8	11.399	1.62	18.44	36	0.23	22.5
12:51:15	21.7	70.5	13.289	1.8	23.93	31	0.34	34.0
12:51:17	21.7	77.3	10.462	1.56	16.29	34	0.21	21.1
12:51:19	21.7	59.1	12.029	1.68	20.2	26	0.34	34.2
12:51:21	21.7	81.8	13.993	1.92	26.91	36	0.33	32.9
12:51:23	21.7	63.6	12.103	1.68	20.32	28	0.32	31.9
12:51:25	21.7	77.3	9.626	1.44	13.81	34	0.18	17.9
12:51:27	21.7	72.7	11.238	1.56	17.5	32	0.24	24.1
12:51:29	21.7	84.1	11.531	1.68	19.36	37	0.23	23.0
12:51:31	21.7	70.5	11.927	1.62	19.3	31	0.27	27.4
12:51:33	21.7	81.8	13.67	1.86	25.45	36	0.31	31.1
12:51:35	21.7	70.5	11.106	1.56	17.29	31	0.25	24.5
12:51:37	21.7	88.6	11.223	1.56	17.47	39	0.20	19.7
12:51:39	21.7	63.6	11.062	1.62	17.9	28	0.28	28.1
12:51:41	21.7	81.8	13.538	1.74	23.56	36	0.29	28.8
12:51:43	21.7	61.4	10.051	1.56	15.65	27	0.26	25.5
12:51:45	21.7	86.4	10.403	1.44	14.93	38	0.17	17.3
12:51:47	21.7	59.1	11.81	1.68	19.83	26	0.34	33.6
12:51:49	21.7	61.4	11.282	1.56	17.57	27	0.29	28.6
12:51:51	21.7	63.6	12.923	1.74	22.49	28	0.35	35.3
12:51:53	21.7	72.7	12.527	1.8	22.56	32	0.31	31.0
12:51:55	21.7	65.9	10.095	1.5	15.1	29	0.23	22.9
12:51:57	21.7	77.3	11.883	1.68	19.95	34	0.26	25.8
12:51:59	21.7	65.9	12	1.68	20.15	29	0.31	30.6
12:52:02	21.7	77.3	12.22	1.74	21.26	34	0.28	27.5
12:52:04	21.7	61.4	10.388	1.44	14.91	27	0.24	24.3
12:52:06	21.7	84.1	12.264	1.62	19.84	37	0.24	23.6
12:52:08	21.7	65.9	13.67	1.8	24.62	29	0.37	37.4
12:52:10	21.7	77.3	11.429	1.56	17.79	34	0.23	23.0
12:52:12	21.7	63.6	11.751	1.62	19.01	28	0.30	29.9
12:52:14	21.7	81.8	10.857	1.56	16.9	36	0.21	20.7
12:52:16	21.7	75.0	10.315	1.44	14.8	33	0.20	19.7
12:52:18	21.7	75.0	12.454	1.8	22.43	33	0.30	29.9
12:52:20	21.7	72.7	12.176	1.68	20.44	32	0.28	28.1
12:52:22	21.7	84.1	10.945	1.56	17.04	37	0.20	20.3
12:52:24	21.7	2.3	0.015	-0.03	-0	1	0.00	0.0
								27.6

3/4 electrical load 20kg pull

12:53:14	36.2	90.9	13.128	1.8	23.64	24	0.26	26.0
12:53:16	36.2	189.4	16.293	2.29	37.29	50	0.20	19.7
12:53:18	36.2	204.6	18.608	2.66	49.42	54	0.24	24.2
12:53:20	36.2	162.9	18.755	2.6	48.67	43	0.30	29.9
12:53:22	36.2	155.3	14.637	2.29	33.5	41	0.22	21.6
12:53:24	36.2	193.2	16.454	2.35	38.67	51	0.20	20.0
12:53:26	36.2	200.8	17.216	2.41	41.51	53	0.21	20.7
12:53:28	36.2	174.3	15.575	2.23	34.7	46	0.20	19.9
12:53:30	36.2	162.9	16	2.23	35.65	43	0.22	21.9
12:53:32	36.2	185.6	15.516	2.17	33.62	49	0.18	18.1
12:53:34	36.2	189.4	17.055	2.35	40.08	50	0.21	21.2
12:53:36	36.2	159.1	14.755	2.11	31.07	42	0.20	19.5
12:53:38	36.2	162.9	18.256	2.6	47.37	43	0.29	29.1
12:53:40	36.2	200.8	16.733	2.29	38.3	53	0.19	19.1
12:53:42	36.2	227.3	17.963	2.72	48.81	60	0.21	21.5
12:53:44	36.2	170.5	15.751	2.17	34.13	45	0.20	20.0
12:53:46	36.2	166.7	16.967	2.41	40.91	44	0.25	24.5
12:53:49	36.2	185.6	15.179	2.17	32.89	49	0.18	17.7
12:53:51	36.2	181.8	14.095	2.11	29.68	48	0.16	16.3
12:53:53	36.2	159.1	15.414	2.17	33.4	42	0.21	21.0
12:53:55	36.2	162.9	14.799	2.53	37.5	43	0.23	23.0
12:53:57	36.2	189.4	17.26	2.47	42.68	50	0.23	22.5
12:53:59	36.2	170.5	15.092	2.11	31.78	45	0.19	18.6
12:54:01	36.2	159.1	17.612	2.6	45.7	42	0.29	28.7
12:54:03	36.2	189.4	16.542	2.35	38.87	50	0.21	20.5
12:54:05	36.2	189.4	16.44	2.29	37.63	50	0.20	19.9
12:54:07	36.2	151.5	16.015	2.23	35.68	40	0.24	23.5
12:54:09	36.2	159.1	15.736	2.17	34.1	42	0.21	21.4
12:54:11	36.2	181.8	13.934	2.05	28.5	48	0.16	15.7
12:54:13	36.2	162.9	15.692	2.41	37.83	43	0.23	23.2
12:54:15	36.2	174.3	15.443	2.11	32.52	46	0.19	18.7
12:54:17	36.2	200.8	17.641	2.47	43.63	53	0.22	21.7
12:54:19	36.2	197.0	19.297	2.6	50.08	52	0.25	25.4
12:54:21	36.2	155.3	16.85	2.35	39.6	41	0.25	25.5
12:54:23	36.2	147.7	15.853	2.23	35.32	39	0.24	23.9
12:54:25	36.2	197.0	19.473	2.66	51.72	52	0.26	26.3
12:54:27	36.2	189.4	17.201	2.47	42.54	50	0.22	22.5
12:54:29	36.2	155.3	16.249	2.23	36.2	41	0.23	23.3
12:54:31	36.2	174.3	15.692	2.17	34	46	0.20	19.5
12:54:33	36.2	204.6	15.253	2.17	33.05	54	0.16	16.2
12:54:35	36.2	170.5	16.029	2.29	36.69	45	0.22	21.5
12:54:37	36.2	3.8	0.015	-0.03	-0	1	0.00	0.0
								21.3

G.P.-S. 019-0126

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Form P I

PATENTS ACT, 1978

APPLICATION FOR A PATENT AND ACKNOWLEDGEMENT OF RECEIPT

[Section 30 (I)-Regulation 22]
(See notes overleaf)

Revenue stamps or revenue franking machine impression
Official date stamp

The grant of a patent is hereby requested by the undermentioned applicant on the basis of the present application filed in duplicate.

Official Application No. [redacted] 2007/00927

(i) Applicant's or agent's reference

(ii) 71 Full name(s) of applicant(s): PHILLIPS : Russell Leslie

(iii) Address(es) of applicant(s): 52 Prospect rd, Walmer PORT ELIZABETH, 6070

(iv) 54 Title of invention: RECIPROCATING AEROFOIL WIND ENERGY HARVESTER

(v) The applicant claims priority as set out on the accompanying form P 2.

(vi) This application is for a patent of addition to Patient Application No. [redacted]

(vii) This application is a fresh application in terms of section 37 and based on Application No. 21 [redacted]

(viii) This application is accompanied by:

1. A single copy of a provisional or two copies of a complete specification of 1 pages.
2. Drawings of 1 sheets.
3. Publication particulars and abstract (form P 8 in duplicate).
4. A copy of Figure .... of drawings (if any) for the abstract.
5. An assignment of invention.
6. Certified priority document(s) (state number).
7. Translation of the priority document(s).
8. An assignment of priority rights..
9. A copy of the form P 2 and the specification of S.A. Patent Application [redacted]
10. A declaration and Power of Attorney on form P 3.
11. Request for ante-dating on form P 4.
12. Request for classification on form P 9.
13.

(ix) 74 Address for service: P.O. BOX 5503, WALMER, 6065

Dated this 25th day of July 2006

Signature of applicant(s) or agent

The duplicate will be returned to the applicant's address for service as proof of lodging but is not valid unless endorsed with official stamp.

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