DESIGN AND CONSTRUCTION OF A VERTICAL AXIS WINDMILL

By

KOWU AGBEZUDOR

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DECLARATION

I hereby declare that this thesis is my own original work undertaken at the Department of Mechanical Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, under the supervision of Prof. Francis K. Forson.

KOWU AGBEZUDOR ………………………….. …………………….
(Candidate) Signature Date

Certify by

Prof. Francis K. Forson ……………………… …………………….
Supervisor Signature Date

Certify by

Dr. S.M. Sackey ………………………. ………………………
Head of Department Signature Date
(Mechanical Engineering)

ABSTRACT

Ghana is an agricultural country where majority of the people live in villages and have agriculture as their means of livelihood. Since rainfall pattern is unreliable, erratic in nature and the amount is also sometimes insufficient for the cultivation of crops, irrigation will help in the general development of the country's agriculture. This will in turn improve the standard of living of the people. Wind mill will principally be of interest as an option for pumping water in relatively remote and deprived areas.

This research work highlights on the design and construction of a windmill using bamboo. The windmill went through vigorous design procedures and construction stages. The detailed working drawings of the windmill were produced and a bamboo chemical treatment set up was constructed. The rotor assembly which is made up of a straight treated bamboo 3m in length has one end of the bamboo secured to the flywheel and hub by a special locking mechanism and the other end is fixed to another bamboo which constitutes the circumference of the rotor assembly.

During the design analysis of the windmill, the following pertinent design parameters were obtained: swept area of the rotor 0.64 m^2, free stream velocity 5 m/s, tip speed ratio 0.18, radius of rotation 2.41 m, high drag coefficient 1.4, low drag coefficient 0.413, angular speed of rotor assembly 0.448 rad/s, inertia of rotor assembly 439.4 kgm^2, aerodynamic power 90.923 W, power dissipated by rotating components 44.121 W and net mechanical power available 46.803 W.

This bamboo-mat sail of the windmill was locally made using the local materials, skills and tools. The durability and reliability of the windmill was ensured by using quality and chemical-resistant materials. The designed windmill has a very good starting torque performance with its operating characteristics independent of the wind direction. The design is simple and the construction/fabrication technology required is less sophisticated. This makes it suitable for small scale application in wind energy conversion to mechanical energy, especially in remote areas with better wind regimes and it can also be coupled to a hybrid system to alternate between a system for electricity generation or used as a water pump.

It is recommended amongst other things that the windmill should be tested to check any defects in the static structural strength design calculations and to reveal any unusual effect which may lead to unexpected failure.

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ACKNOWLEDGMENT

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DEDICATION

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CHAPTER ONE

INTRODUCTION

This chapter discusses the background information, the objectives of the research, the significance of the research and method and the scope of the research.

1.1 Background

It is believed that the largest available source of fresh water lies underground and the total ground water potential is estimated to be one third the capacity of oceans (Punmia, 1985). Pumpage from wells constitutes the majority of artificial discharge of ground water.

Ghana is an agricultural country where majority of the people live in villages and have agriculture as their means of livelihood. Since rainfall pattern is unreliable, erratic in nature and the amount is also sometimes insufficient for the cultivation of crops, irrigation will help in the general development of the country's agriculture. This will in turn improve the standard of living of the people. There are instances in the world where the most dry areas and places where people living in abject poverty in dry areas have become prosperous and civilized, mainly due to the introduction of irrigation activities.

Wind power will principally be of interest as an option for pumping water in relatively remote areas where a prime-mover would have to be installed close to the water source and conveniently fuelled. The principal element of wind pump cost is financing the capital investment. Wind pumps are also sensitive to financial constraints, principal discount rate and amortization period. With even a modest wind regime, they appear to be perhaps one of the most economical options for lifting water given the present-day high fuel prices in Ghana. In general, farm wind pumps are sufficiently reliable and inexpensive to maintain and have a long operational life. Studies conducted recently in Ghana revealed that in places along the coastal savanna belt which exhibit fairly favourable wind regimes, wind could be harnessed for pumping water (Twum, 1991).**)**

Research conducted by reputable organizations and individual scientists indicate that Bamboo has an enormous potential for alleviating many of the social and environmental problems of the developing world today (Quintans, 1998). The global market potential for bamboo is estimated at more than $2 billion annually (ENS, 2004). It is a versatile, fast growing and renewable resource with over thousand non-timber and timber uses. For example, Bamboo has been used for environmental restoration and in the production of handicrafts, artifacts, furniture, for roofing and flooring buildings and the like. In Ghana, bamboo and rattan resources constitute the two largest non-timber forest products but their use in wind-turbine construction is not tapped.

Ghana's forest resources continue to deplete at an alarming rate (GNA, 2005), whilst the commercial importance and industrial application of Bamboo are unpopular although there are a number of general uses particularly at the rural level where commercial processing has recently begun. Furthermore, the bamboo sector lacks substantive basic information on the problems and opportunities to enable implementation of appropriate interventions for efficient utilization of the resource to enhance the sector (Obiri and Oteng-Amoako, 2007).

One of the most critical challenges encountered by the processing enterprise in Ghana is effective preservation as this significantly affects product quality, durability and production cost. According to the large-scale processors, known effective chemicals such as hydrogen peroxide are expensive and can render production unprofitable if applied at the large-scale industrial level

(Obiri and Oteng-Amoako, 2007). It is however known that if treated and preserved very well, bamboo assumes better attributes including increased tensile strength, durability and lighter weight and can resist corrosion better than metal (Rottke, 2002). Wind turbines have consistently been designed and constructed with metal which suffers all of these problems. A number of researchers have worked on design and construction of wind turbines with metal poles and sheets but not much has been done regarding the use of bamboo.

1.2 Goal and Objectives

The main objective of this thesis is to design and construct a vertical axis wind turbine rotor made of bamboo and metal.

The goal would be achieved with the following specific objectives.

1. To design a vertical axis wind turbine rotor using bamboo and metal
2. To construct the designed wind turbine rotor

1.3 Justification

Ghana is finding it very difficult to meet its electricity needs due to increase in population and industrialization. Grid electricity demand is likely to grow from about 6,900 GWh in year 2000 to about 18,000 GWh by 2015, and eventually reaching about 24,000 GWh by 2020. (Energy Commission, 2006). The 2006 installed electricity generating capacity of 1760 MW would have to be doubled by the year 2020 if Ghana is to be assured of secured uninterrupted electricity supply (Ghana Energy Commission, 2006). Relying on Hydro and thermal power alone to achieve this target would be very difficult since Ghana has been experiencing unsteady water inflows into the Akosombo Dam and economic activities might come to a halt if Ghana should experience severe drought.

Renewable energy, and for that matter wind power, has been increasing steadily having doubled in three years between 2005 and 2008 (Osei Yeboah, 2010). Wind power has been fairing well globally which has led countries like United States, China and Spain to increase their capacities.

In 2008, wind power accounted for about 19% of the electricity generation in Denmark, about 10% in Spain and Portugal and 7% in Germany and the Republic of Ireland (GWEC, Greenpeace & WPW 2008).

Although advanced works have been done in wind, Ghana has no commercial wind power production. The interest in this area keeps on increasing since it has a lot of benefits and the fact that wind resource is often the most economic method of pumping water in rural areas where the average wind speed in the least windy month is greater than about 3 m/s, and no grid power is available. It requires no fuel, and generating electricity with wind power represents an environmentally sound technology with zero emission (even though there is some level of noise and visual impact) and lasts longer - about twenty (20) years. It is also highly reliable when regularly maintained. It is sustainable and less vulnerable to theft or damage than other systems. Again a wind turbine for generating electrical power can be locally manufactured thus creating indigenous skills and reducing foreign exchange requirements for costly diesel fuel and equipment (Kristoferson, 1993).

1.4 Methodology and Scope of Research

Literature search was done to unearth existing relevant work done in the field of wind turbine or power. Publications and knowledge on the existing wind farm or wind turbine and their theories were reviewed. Studies on bamboo varieties, characteristics and utilization and the possibilities of their use in wind turbine rotor were done. The setup for the treatment of bamboo was put up at the Department of Agricultural Engineering, KNUST workshop including the design and construction of the wind turbine.

1.5 Organisation of the Thesis

This thesis is organised into five chapters. The introduction which is the subject of chapter one consists of the background, the specific objectives, justification, the methodology and scope of the study and the organisation of the work. Chapter two discusses wind pumps and various types and characteristics of rotors, principles of wind energy conversion and the history and development of windmill around the world. The design calculations of the windmill are the focus of chapter three. Chapter four looks at the construction of the windmill project. Chapter five deals with the conclusions and recommendations.

CHAPTER TWO

LITERATURE REVIEW

This chapter discusses in general wind pumps and various types and characteristics of rotors, principles of wind energy conversion and the history and the technologies for wind energy conversion to mechanical energy around the world.

2.1 Wind turbine

A wind turbine is a device that converts kinetic energy from the wind (also called wind energy) into mechanical energy or wind power. If the mechanical energy is used to produce electricity, the device may be called wind turbine or wind power plant. If the mechanical energy is used to drive machinery, such as for grinding grain or pumping water, the device is called a windmill or wind pump. A wind pump is a windmill used for pumping water from wells, or for draining low-lying areas of land. Wind pumps are still used today as prime movers in areas where electric power is not available or too expensive.

2.2 History of Windmill development

It is generally agreed that windmills were used to pump water during the 9th century AD in what is now Afghanistan, Iran and Pakistan (Wikipedia, 2012). The use of windmills became widespread across the Muslim world and has spread to China and India as well. Windmills were later used extensively in Europe, particularly in the Netherlands and the East Anglia area of Great Britain, from the late Middle Ages onwards. The purpose was to drain land for agricultural or building purposes. Early immigrants to the New World brought with them the technology of windmills from Europe (Wikipedia, 2012).

On US farms, particularly in the Midwest, wind pumps were used to pump water from farm wells for animal husbandry. In California and some other states, the windmill was part of a self-contained domestic water system including a hand-dug well and a redwood water tower supporting a redwood tank and enclosed by redwood siding (tank house).

The self-regulating farm wind pump was invented by Daniel Halladay in 1854. Eventually steel blades and steel towers replaced wooden construction, and at their peak in 1930, an estimated 600,000 units were in use, with capacity equivalent to 150 megawatts. Early wind pumps directly operated the pump shaft from a crank attached to the rotor of the windmill; the installation of back-gearing between wind-rotor and pump-crank allowed the pump to function at lower wind speeds (Wikipedia, 2012).

The multi-bladed wind turbine on top of a lattice tower made of wood or steel became, for many years, a fixture of the landscape throughout rural America. These mills, made by a variety of manufacturers, featured a large number of blades that made them turn slowly with considerable torque at low winds and self-regulating at high winds. A tower-top gearbox and crankshaft converted the rotary motion into reciprocating strokes carried downward through a rod to the pump cylinder located below. Rising energy costs and improved pumping technology are issues of increasing interest in the use of this once declining technology (Wikipedia, 2012).

2.3 Worldwide use of wind pumps

Wind pumps are used extensively in Southern Africa, Australia, on farms and ranches in the central plains and South West of the United States. In South Africa and Namibia, thousands of wind pumps are still operating. These are mostly used to provide water for human use as well as drinking water for large sheep stocks.

Kenya has also benefited from the African development of wind pump technologies. At the end of the 1970's, the UK NGO Intermediate Technology Development Group provided engineering support to the Kenyan company Bob Harries Engineering Ltd for the development of the Kijito wind pumps. Bob Harries Engineering Ltd is still manufacturing the Kijito wind pumps and more than 300 wind pumps are operating in the whole of East Africa (Wikipedia, 2012).

The Netherlands is well known for its windmills. Most of these iconic structures situated along the edge of polders are actually wind pumps designed and used to drain the land. These are particularly important since much of the country lies below sea level.

Eight to ten-bladed windmills were used in the Region of Murcia, Spain to raise water for irrigation purposes. The drive from the windmill's rotor was led down through the tower and back out through the wall to turn a large wheel known as a noria. The noria supported a bucket chain which dangled down into the well. The buckets were traditionally made of wood or clay. These windmills were still in use until the 1950's, and many of the towers are still standing.

In the UK, the term wind pump is seldom used and they are better known as Drainage windmills. Many of these were built in The Broads and The Fens of East Anglia for the draining of land but most of them have since been replaced with diesel or electric-powered pumps. Many of the original windmills still stand in a derelict state although some have been restored.

In many parts of the world, a Rope pump is used in conjunction with wind turbines. This easy to construct pump works by pulling a knotted rope through a pipe (usually a simple PVC pipe) causing the water to be pulled up into the pipe. It has become common in Nicaragua and other places (Wikipedia, 2012).

The Anatomy of an installed wind pump consist principally of the rotor, the transmission, the tail stock, the tower , the pump rod, the well head components, the well, the rising main and the

pump as shown in figure 2.1. A borehole is by far the most common water source from which the wind pump will draw water. A classic multi blade farm wind pump has a piston pump pumping to an elevated storage tank. There are many other configurations possible, depending on the nature of the water source and the demand. These machines have rotor diameters of between 1.5 and 8 metres but they seldom exceed 4 or 5 metres. The power is transmitted from the rotor to the pump rods via a gearing system or via a direct drive mechanism. The movement of the pump rods cause the pump to lift water to the tank. Water can then be fed into the distribution network from the tank. The function of the tail vane is to keep the rotor orientated into the wind. Most wind pumps have a tail vane, which is designed, for automatic furling
speeds to prevent damage (Practical Action, 2012).

Principal benefits of Wind pumps

According to Kristoferson , (1993), the Principal benefits of Wind pumps are that:

- They are often the most economic method of pumping water in rural areas where the average wind speed in the least windy month is greater than about 3m/s and no grid power is available.
- They have no fuel requirements, contrary to engine-driven pumps which require expensive fuel that is difficult to obtain in rural areas.
- They represent an environmentally sound technology, though there is some noise and visual impact.
- They are highly reliable if given regular maintenance, and are also less vulnerable to theft or damage than other systems.
- They can last a long time, typically 20 years for a well-made, regularly maintained machine.
- They can be locally manufactured in most developing countries, creating indigenous skills and reducing foreign exchange requirements for costly diesel fuel engines.

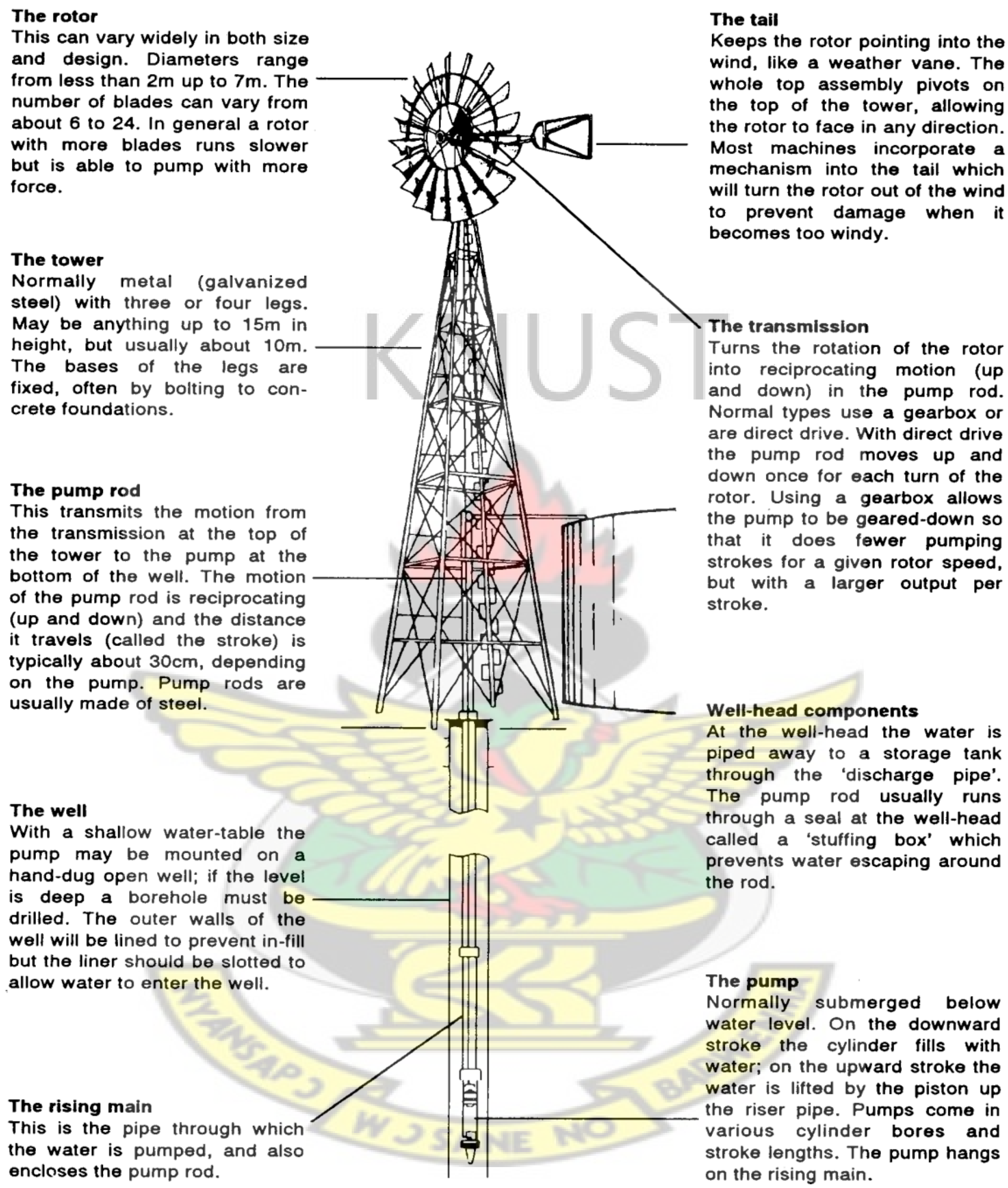


Figure 2.1 Anatomy of wind pump

Source: Kristoferson, (1993)

Effective Flow direction

Three special cases are shown in figure 2.2. These are:

- (A) is the axial flow which is common to all forms of airscrew
- (B) is diametric flow which occurs in such devices as the cup anemometer, and
- (C) when part of the wheel is shielded and can be described as tangential flow (Calvert, 1978).

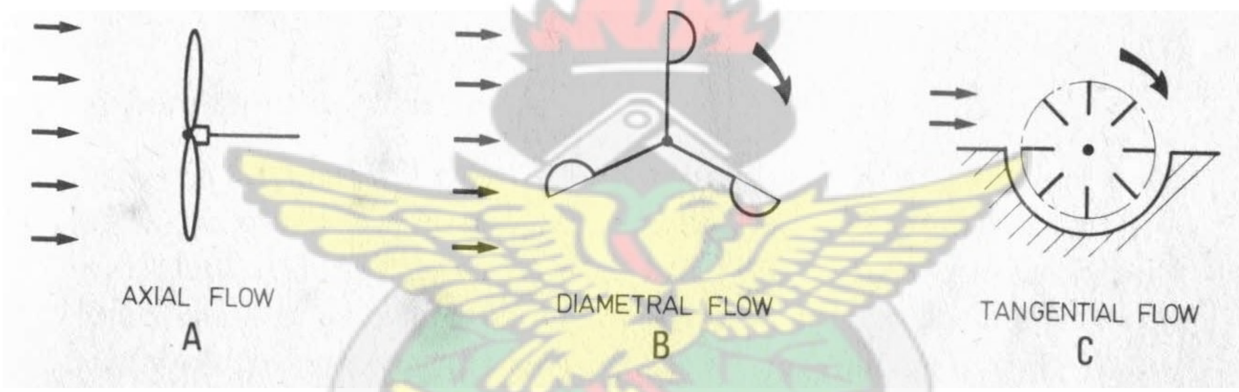


Figure 2.2 Axial, diametral and tangential flow mills

Source: Calvert, 1978

Wind Power Classification System

The Wind Power Classification System is represented by figure 2.3

Group 1 includes the great majority of the real-power-producing windmills of the world.

Group 2 includes some experimental devices such as the "venetian blind" windmill, and

Group 3 includes the Darius design and its derivatives.

Groups 4, 5, and 6 include Drag machines.

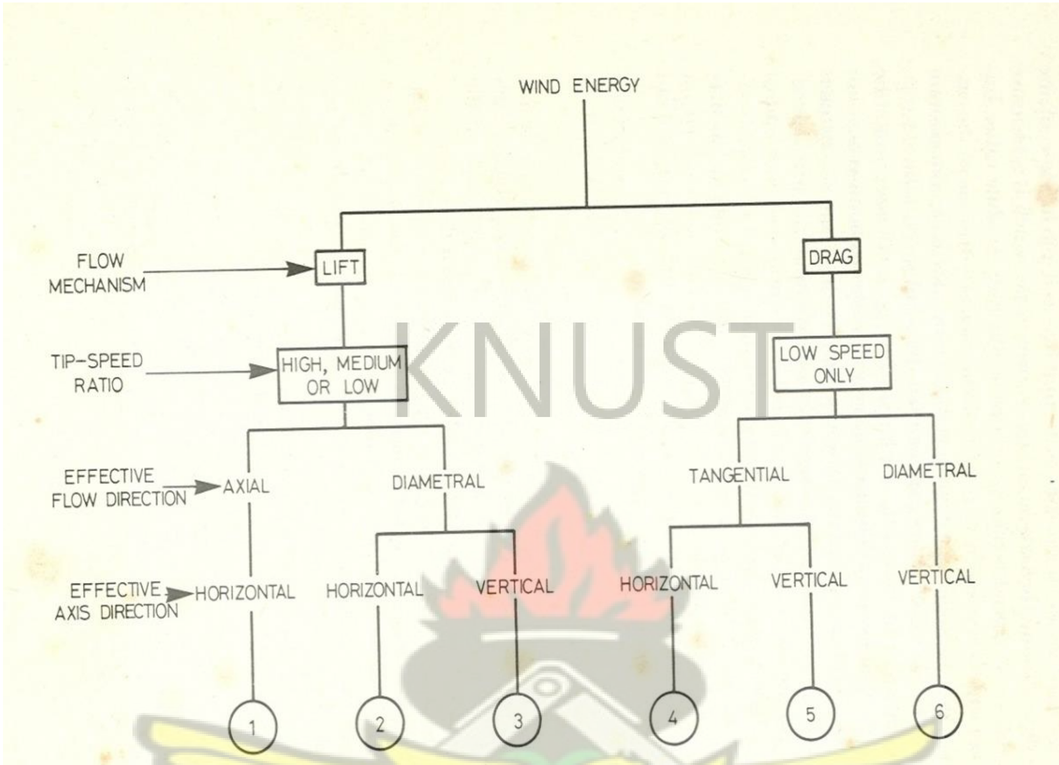


Figure 2.3 Wind power classification system

Source: Calvert, 1978

Drag-generated work arises when the blade moves in the same direction as the wind but at a lower speed. Since the blade must somehow get back to its starting point it must, for half the time, be moving against the direction of the wind. Thus the net force available is the difference between that experienced by the blade on its downstream and its upstream journey. The drag difference may be brought about by difference of shape between the front and back of the blade, as in the cup anemometer or by shielding one half of the wheel from the wind. These two types of machines may be called the *differential drag* and the *shielded paddle*, respectively.

The Group 4, horizontal axis, shielded paddles were formerly reported from Nebraska (i.e.

named the Nebraskan Go-Devil) and vertical axis types (Group 5) from Siestan. These latter ones are believed to be the oldest windmills on earth.

One vertical axis differential drag machine (Group 6) is the above-mentioned cup anemometer, a device established since 1846. The Savonius rotor which also comes in Group 6 is used as a current-meter deep in the ocean. A minute version of the shielded paddle has been developed as a yacht log (or speedometer). The shielding arises here from it being recessed into the hull with only the blade tips emerging.

It is interesting to note that lift machines are, and always have been, dominant in real power production; drag machines (or very low speed lift machines) are dominant in instrumentation. Classification here, in respect of wind seeking, can range from "not sought for" (which is the situation where the useful wind comes always from one direction), to "not necessary" (i.e. when the machine - essentially on a vertical axis - can accept wind from any direction without adjustment). In-between are *manual devices* where the whole or part of the mill must be winched into the wind by hand and *mechanical devices* where the mill automatically follows the wind. These may be subdivided into fan tail, tail vane, and downstream rotor (Calvert, 1978).

Storage of Wind Energy

A good system of energy storage is especially important where wind energy is concerned. Because of the strongly fluctuating supply of wind (and therefore the output of the windmill), storage is necessary to meet the demands (Brughuis, 1991).

According to Brughuis F. (1991), some means of wind energy storage are:

- Batteries: The lead (-acid) and the nickel/cadmium batteries are often used in combination with small wind-driven generators.

- Electrolysis of water into hydrogen and oxygen used with wind-driven generators: The hydrogen is stored in a tank and can be used for heating or as fuel for a motor at any chosen moment. This method is expensive and energy-inefficient.

- Pumped-up water in a reservoir: Usually in combination with water-pumping windmills.

- Flywheels: This is a seldom-practiced method because of the needed 'high technology'. This method is not very suitable for Third World countries.

- Contribution to electricity supply. Power generated could be harnessed and channelled to the public electricity supply system.

2.4 Wind pump types

Three types of wind turbines used in pumping water and for irrigation purposes are multi-blade wind pump, the Tjasker and Thai wind pumps.

2.4.1 A multi-bladed wind pump

"American" multi-bladed wind pumps, figures 2.4 and 2.5, can be found worldwide and are manufactured in the United States, Argentina, China, New Zealand, and South Africa. A 16 ft (4.8 m) diameter wind pump can lift up to 1600 US gallons (about 6.4 metric tons) of water per hour to an elevation of 100 ft with a 15 to 20 mph wind (24–32 km/h). The Aermotor Windmill Company, manufacturer of the wind powered water pumps, is one of the oldest manufacturer American. A properly designed Wind pump begins working in a 3-4 mph (5 to 6.5 km/h) wind. Wind pumps require little maintenance - only a change of gear box oil is required annually. An estimated 60,000 wind pumps are still in use in the United States. They are particularly attractive for use at remote sites where electric power is not available and maintenance is difficult to provide (Wikipedia, 2012).

Figure 2.4 Multi-blade wind pump

Source: Wikipedia, (2012).

Figure 2.5 Multi-blade wind turbine

Source: Wikipedia (2012)

2.4.2 The Tjasker wind pump

In the Netherlands, the tjasker , figure 2.6, is a small type of windmill used solely for drainage purposes. It is distinctive for its simple construction, featuring only a single inclined shaft that carries the sails on one end and an Archimedes' screw on the other, in this way avoiding the need for any gearing. This was used for raising water in areas where only a small lift of water was required. The wind-shaft sat on a tripod which allowed it to pivot. The archimedean screw raised water into a collecting ring, where it was drawn off into a ditch at a higher level, thus draining the land (Wikipedia, 2012).

Figure 2.6 Multi-blade Tjasker wind pump

Source: Wikipedia (2012).

2.4.3 Thai wind pumps

In Thailand, wind pumps, figure 2.7, were traditionally built on Chinese wind pump designs. These pumps were constructed from wire-braced bamboo poles carrying fabric or bamboo-mat

Sails. A paddle pump or water ladder is fixed to a Thai bladed rotor and the water lift required is typically less than 1 meter(Wikipedia, 2012).

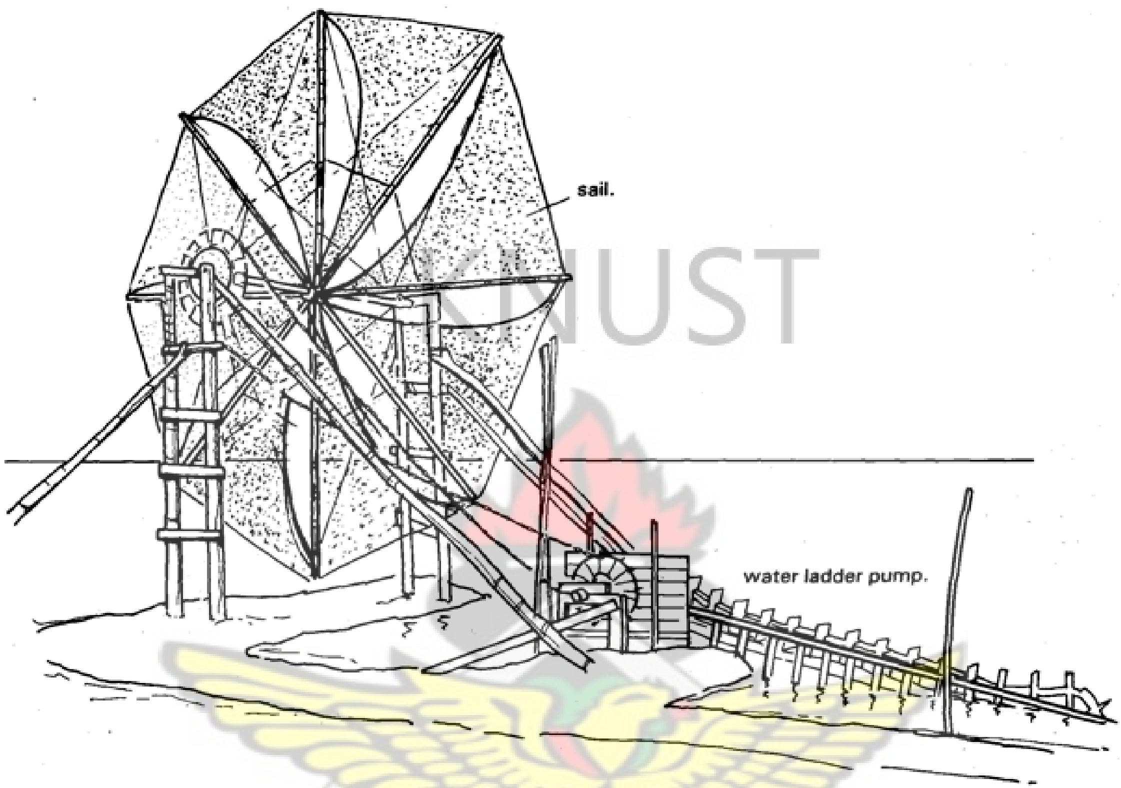


Figure 2.7 Thai wind pumps

Source: FAO, (1986)

2.5 Types and characteristics of rotors

There are two main families of wind machines: *vertical and horizontal axis machines* shown in figure 2.8 and figure 2.9 respectively. These can in turn use either lift or drag forces to harness the wind. Horizontal axis lift devices are more popular and widely used because the design and technologies are more widely understood and developed. Vertical axis drag devices are still unknown to many wind power users and technicians. Its technologies and designs are still in the process of being more widely understood.

In fact, other than a few experimental machines, virtually all windmills come under this category.

Technical parameters:

There are several technical parameters that are used to characterize windmill rotors.

The tip-speed ratio is defined as the ratio of the speed of the extremities of a windmill rotor to the speed of the free wind. Drag devices always have tip-speed ratios less than one and hence turn slowly, whereas lift devices can have high tip-speed ratios (up to13:1) and hence turn quickly relative to the wind (Practical Action, 2012).

The proportion of the power in the wind that the rotor can extract is termed the coefficient of performance (or power coefficient or efficiency symbolized by Cp). Its variation as a function of tip-speed ratio is commonly used to characterize different types of rotor. There is an upper limit of Cp = 59.3% (known as the Betz limit), although in practice real wind rotors have maximum Cp values in the range of 25%-45% (Practical Action, 2012).

Solidity is usually defined as the percentage of the area of the rotor which contains material rather than air. High-solidity machines carry a lot of material and have coarse blade angles. They generate much higher starting torque (torque is the twisting or rotary force produced by the rotor) than low-solidity machines but are inherently less efficient than low-solidity machines. The wind pump is generally of this type. Low-solidity machines tend to be used for electricity generation. High solidity machines will have a low tip-speed ratio and vice versa.

Advantages of Drag windmills over Lift windmills

- Ability to effectively capture turbulent winds which are typical in urban settings, especially in built-up areas.
- No need for a yaw mechanism to face the blade rotor into veering wind directions; therefore have higher efficiency and no orientation parts to maintain.

- Operation at lower rotational speeds, thereby reducing or eliminating turbine vibration and noise.
- Durability and reliability working in multi-directional (turbid) wind.
- Easier and less expensive repair and maintenance with generator on rooftops.
- Lower noise and vibration.

Figure 2.8 A vertical axis machine

Source: Wikipedia (2012)

Figure 2.9 A horizontal axis machine

Source: Wikipedia (2012)

2.6 Types of Pumps

Water is the most common fluid handled by wind pumps. Virtually, therefore, all types of wind pumps may be considered as potentially suitable for water lifting. However, pumps used with wind-powered pumping systems are generally found to be of three types: *reciprocating, rotary and diaphragm.* Both reciprocating and rotary pumps are of the positive displacement type. A positive displacement type of pump is that in which a measured quantity of water is entrapped in a space, its pressure is raised and then it is delivered.

2.6.1 Reciprocating pumps

In order to start reciprocating pumps in reasonably low wind speed, it is necessary to obtain sufficient starting torque which is possible by using high-rotor solidity. Hence many windmills have a large number of vanes or sails to provide high starting torque. All types of reciprocating pumps are self priming in that they do not need to be filled with fluid before pumping. Its diameter and the length of the pumping stroke inside it are majors in determining the windmill's pumping capacity. The stroke of a windmill is the distance which the plunger moves up and down. A short stroke enables the mill to begin pumping in a light breeze but in strong breeze a long stroke causes more water to be pumped.

A very good aerodynamic design must be simple and effective, utilizing low wind velocities (which occurs far more often than higher velocities) to deliver a high starting torque and to begin running at very low wind speeds.

2.6.2 Rotary pump

This is commonly used in China and South-east Asia for a head up to 3m and consists of rectangular wooden pallets or paddles mounted on a continuous wooden chain that runs up an inclined square section open wooden trough. The paddles and chain pass around a large wood at the base of a trough which is submerged in water. This type of pump is commonly used with Chinese vertical-axis wind pump systems and Thai high-speed wooden rotors and Thai sail rotors.

2.6.3 Diaphragm pump

This consists of a cylinder closed at the lower end with a circular diaphragm of rubber or some other flexible material fixed at the top end. A reciprocating connecting rod is fixed to the centre of the diaphragm and upon vertical movement, causes volumetric displacement in the cylinder. An arrangement of valves allows water movement in only one direction through the cylinder.

2.7 Matching rotor and pump

When installing a wind pump it is important to match the characteristics of the pump and the wind machine. A good interaction between pump and rotor is essential. The most common type of pump used for water pumping (especially for borehole water pumping) in conjunction with a windmill is the reciprocating or piston pump.

The piston pump tends to have a high torque requirement on starting. This is because, when starting, the rotor has to provide enough torque to overcome the weight of the pump rods and water in the rising main. Once the rotor is turning, the torque requirement decreases because of the momentum of the revolving rotor. The wind speed can then drop to about 2/3 of the start-up wind speed before the wind pump will stop.

It is obviously important to match the water pumping demand with the available wind and hence decide upon a suitable rotor size. To calculate the demand, the following data is needed:

• The head to which the water is to be pumped (in metres)

• Volume of water to be pumped per day (in metres cubed)

For water at sea level, the approximate energy requirement can be calculated using the following equation: E = 0.002725 x volume x head (in kilowatt-hours) (Practical Action, 2012).

Typical pumping heads can vary between a few metres to 100m (and occasionally more), whilst the volume of water required can vary from a few cubic metres a day for domestic use to a few hundred cubic metres for irrigation.

2.8 Principles of Wind Energy Conversion

Factors that need to be examined before introducing windmills include:

- The required power

- Data of wind-speeds at the spot
- In case of local production, the required and available materials, tools and technical know-how
- Provision for maintenance and repairs
- The participation of the local people.

These factors determine the feasibility of wind energy in comparison with alternatives, like diesel- or kerosene-motors and solar-energy (Brughuis, 1991).

2.9 The Vertical Axis Wind Turbines

Vertical axis wind turbines are different from traditional wind turbines because their main axis is perpendicular to the ground. Their configurations make them ideal for both rural and urban settings and offer the owner an opportunity to offset the rising cost of electricity and to preserve the environment.

2.10 Design of a wind pump (KNUST wind pump (1991))

An example of the Vertical axis wind turbines is the KNUST Wind pump designed and constructed by Kowu Agbezudor in 1991. Figure 2.10 shows the designed wind pump and the constructed windmill.

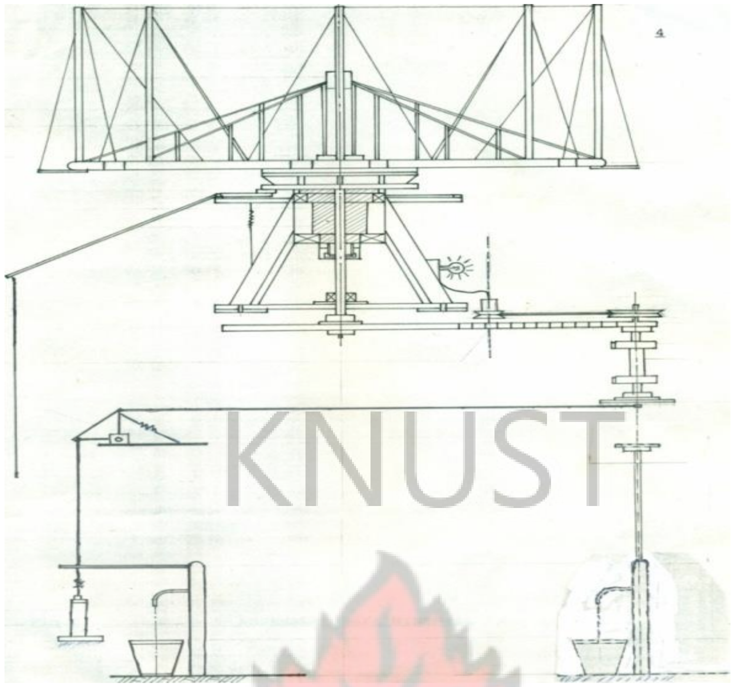


Figure 2.10 KNUST wind pump (designed by Kowu Agbezudor in 1991)

Source: Agbezudor & Amedorme, (2013)

Figure 2.11 Assembled KNUST sail wind mill

Source: Agbezudor & Amedorme, (2013)

2.10.1 The KNUST Rotor

The structure is an octagonal rim of galvanized steel pipes welded to a central hub by the same pipes. To ensure a level or flat bottom of the rotor, iron rods of about 5mm diameter are used to reinforce it. These rods or struts are attached to the pipes joining the octagon to the central hub and the extended hub. At the ends of the joints of the octagon are erected eight pipes of which each is of height 2 m for attachment of the sails. The diameter of the rotor is 6 m and that of the central hub is 300 mm. This hub has holes which coincide with those on another hub. These two hubs are joined together with bolts and nuts which allow the rotor to rotate with the hollow shaft in the bearing housing. Strong wires are used to reinforce the vertical pipes to make them more resistant to the wind force to be exerted on the sails which they hold.

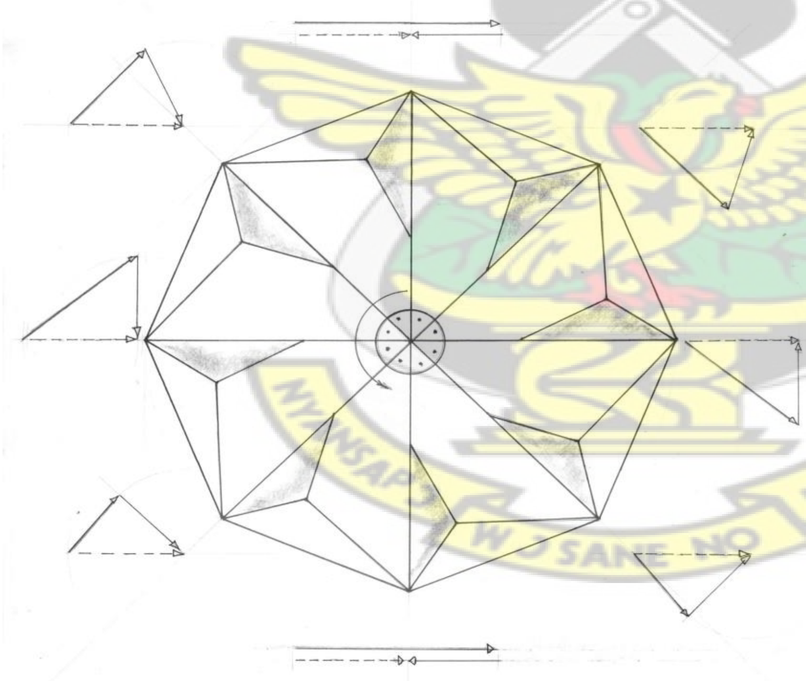


Figure 2.12 The KNUST rotor

Source: Agbezudor & Amedorme, (2013)

In figure 2.12, the light arrows show the direction of travel of the aerofoil at the instant they are in the positions shown.

The dotted arrow shows the direction of the actual wind.

The heavy arrow shows the direction of the "relative wind".

The length of any of the arrows represents the speed (velocity is a vector quantity) of either the aerofoil, the actual or the "relative wind"- Note that while the length of the aerofoil and actual wind arrows stay the same, the length and hence the speed of the relative wind changes (Hurley, 1980).

2.10.1.1 Rotor Reinforcement

The radial pipes of the rotor are extended 300 mm outward by welding angle bars to them. The vertical galvanized pipes are connected to the radial and octagonal pipes and to the extensions by strong wires which are made taut. These increase structural strength and prevent the poles from bending and tearing the sails apart.

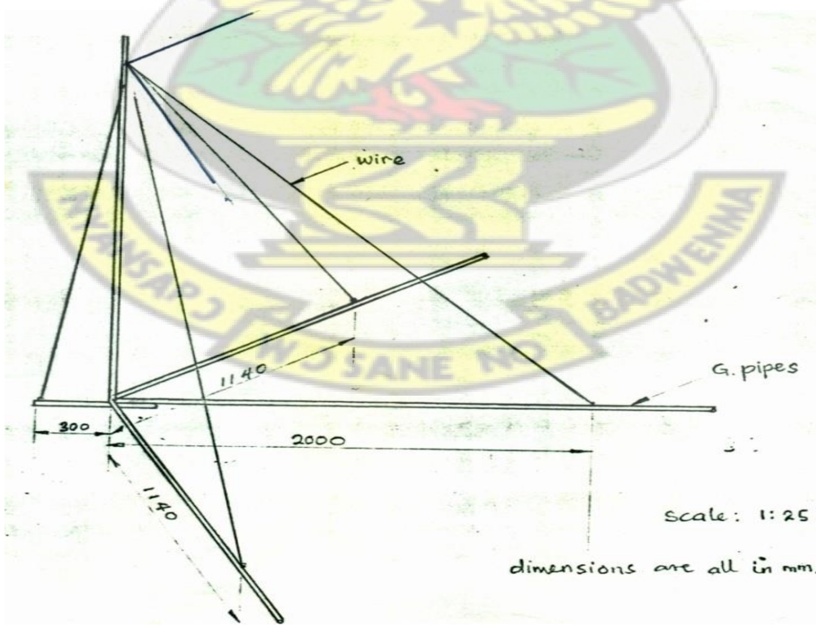


Figure 2.13 Reinforcement of the Rotor frame

Source: Agbezudor & Amedorme (2013)

2.10.2 The Sails

The guiding principle in the setting of the sails is that it is important for the spent air to be able to leave the wind-wheel without obstructing their flow to the following sails. It is also important to note that the main turning effect is due to the difference in drag between the concave and convex faces of the cups.

The sails are made of tarpaulin. They are cut and shaped into right-angle triangles of perpendicular sides of about 2.3m X 2.5m.

The edges are sewn to prevent the sails from tearing prematurely. The sails are riveted at the edges and their centroids. Each sail has about 22 rivets in all. The sails are to be tied to the rotor by nylon cords and shaped in the form of a cup by means of three nylon cords radiating and passing through the centroid to the corners (figure 2.14).

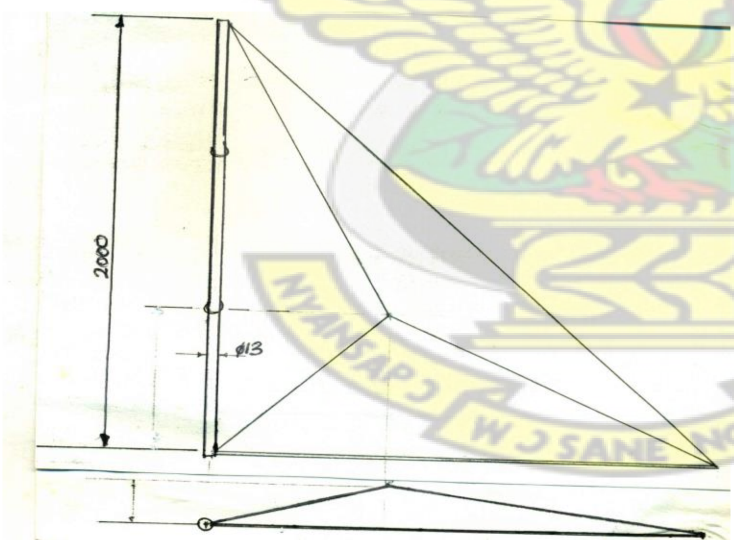


Figure 2.14 Sail configuration

Source: Agbezudor & Amedorme (2013)

To set the sails in position, the following steps may be followed:

1 Cut three cords and tie one end of the cords at one point such that the three cords radiate from a common point.

2 Tie the sails onto the poles as shown if figure 2.14

3 Tie the nylon cord to the corners of the poles such that it radiates from the centroid. They must be under tension. (Note: this has no effect on the sails at this stage).

4 Pass a cord through the centroid of the tarpaulin and tie one of the ends of the cord to the nut or joint at the common point of (3). Now tie the other end of the cord to the foot of the next pole (i.e. the pole behind the tarpaulin). Tensioning this cord causes the sails to be shaped in the form of a cup

2.10.3 The Tower (Supporting Frame)

It serves as a point of attachment for the various components such as the main shaft, transmission, bearings, etc. The rotor is usually placed on a tower to:

1. Get out the lee (shatter) of the obstacles like overgrowth,
2. Prevent the turning blade from hitting anyone (Brughuis, 1986).

Regardless of the platform type, there are several possible tower forms that can be used. Essentially, these are: Lattice steel (truss) tower (3 or 4 legs); Single column (steel or concrete) and Multiple column (3 or 4 legs) (fig 7) (BWEA, 1982). The Windmill tower is of type 3.

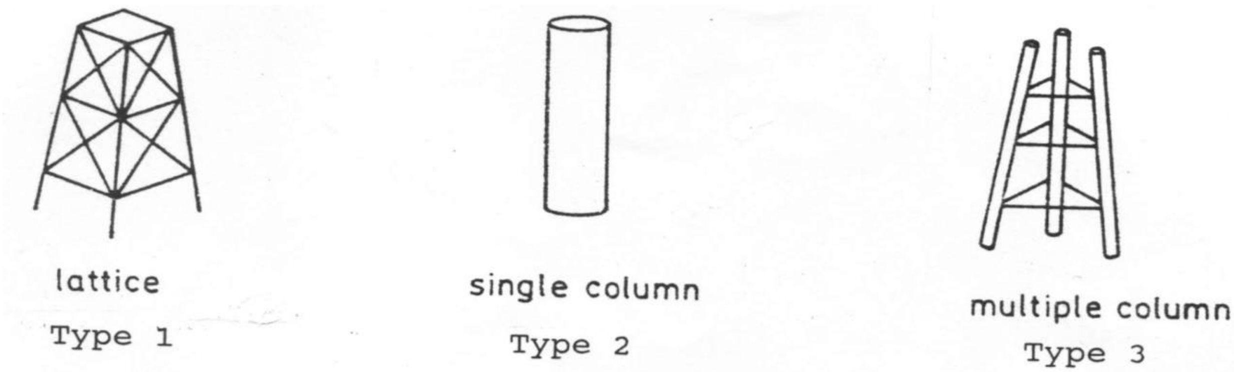


Figure 2.15 Examples of tower forms

Source: BWEA, (1982)

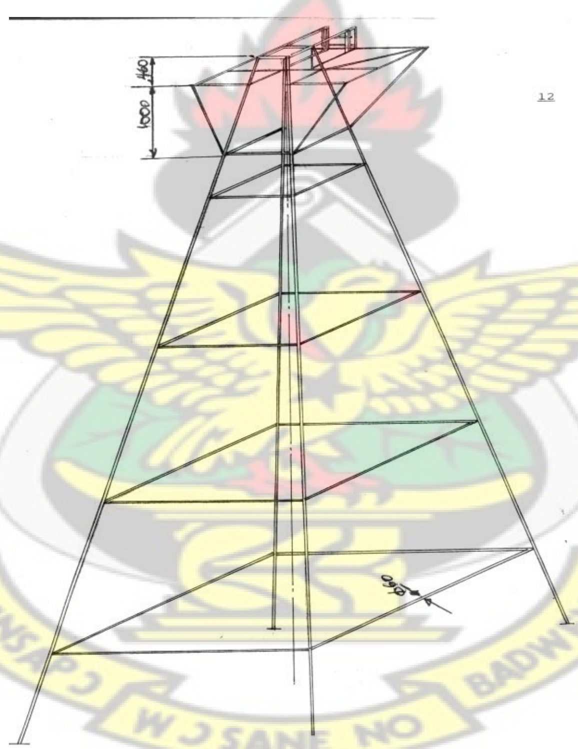


Figure 2.16 The windmill tower

Source: Agbezudor & Amedorme (2013)

The supporting frame is made up of galvanized steel pipes of diameter 60mm. These are joined together by welding to attain a height of 10m above ground level. The initial height which has been constructed for test purposes is about 2.5m (figure 2.16). There is a platform about 1m from the top of the supporting frame. This consists of a rectangular frame of angle bars, on which mahogany boards are placed. The platform is a little over 1m below the rotor hub. At the top of the supporting frame, a seat is provided for the attachment of the bearing housing.

2.10.4 The Transmission

The transmission is made up of a chain and sprocket (to step up the speed) and the bell crank mechanism (to change the rotational motion to reciprocating motion). The speed ratio is about 1:10.

2.10.5 The Connecting Rod

It connects the transmission hub to the bell crank by means of ball and socket joints at both sides (the ball and socket joints used are scraps).

2.10.6 The Transmission Hub

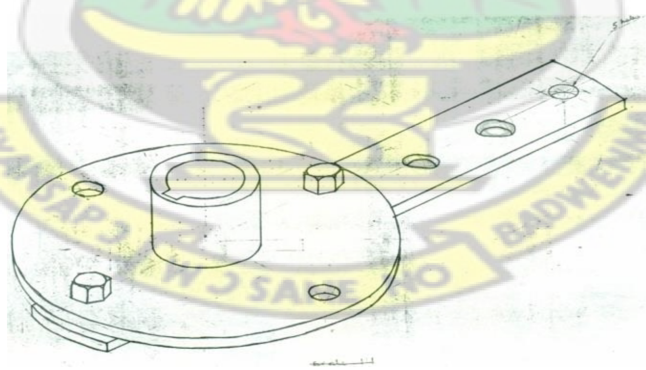


Figure 2.17 Transmission Hub

Source: Agbezudor & Amedorme (2013)

The hub is keyed and machined to make its walls as thin as possible and has an inner diameter of

30 mm. A bar is bolted to the hub to extend its flange and prevent the machining of an exceptionally large hub (figure 2.17).

2.10.7 The Bell Crank Mechanism

This consists of two flat bars, 20mm X 3mm, welded to the crank which passes through two wooden bearings. The wooden bearings are bolted to angle bars 50mm X 50mm which are also able to be bolted to the sliding seat (figure 2.18). This mechanism helps produce the reciprocating motion at the pump's handle.

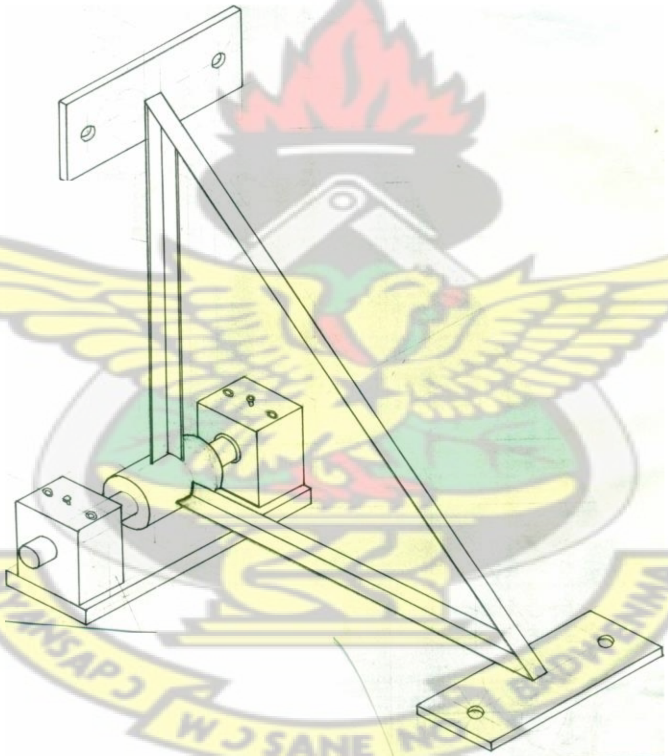


Figure 2.18 The Bell Crank Mechanism

Source: Agbezudor & Amedorme (2013)

2.10.8 Pump Handle Connection

The handle of the pump was spring-loaded so that the spring provides the down stroke whilst the windmill took care of the up stroke.

Two eye bolts of size M15 are used to hold the spring in position. One of the bolts is screwed to the pump and the other to a tapped plate. The force in the spring can be adjusted by screwing or unscrewing the bolt in the plate.

The tapped plate is welded to two galvanized pipes whose lower portion is also welded to another plate to be fixed to the concrete slab.

Another spring connected directly to the bell crank helps return both the bell crank and the pump handle to their equilibrium position (this works against gravity and reduces the extra work the mill would have done against gravity).

2.10.9 The Main Bearing Housing

This is a four-legged structure made from mild steel. A hollow shaft which is flanged at the top runs through two bearings - a roller bearing at the top and a taper bearing at the bottom. The flange is about 300 mm in diameter and has holes for coupling the rotor. The feet of the bearing housing are bolted to the seat of the supporting frame.

2.10.10 Power Shaft/Driven Shaft

The forces on the shaft include:

a) Trust forces due to the wind on the sails.

b) The tension in the chains.

c) Reaction at the bearings and

d) The thrust forces due to the weight of the rotor.

The power shaft has a diameter of 30 mm. It also has two keyways at one end (for keying to the rotor and one at the other end (for flange and bigger sprocket).

The driven shaft is of a diameter 35 mm. One end takes a tapper bearing and a flange (as part of the transmission hub and also acts as a point of attachment to a rotary pump) and the other end takes the smaller sprocket and a pulley for possible generation of electricity.

2.10.11 SAFETY CONSIDERATIONS

Windmills without a safety system usually have a short life. An exception can be made for very small windmills with a diameter of less than one meter which can be so strong or have a tower which is so low, that they can survive heavy storms. Normally a well designed safety system is required which must perform three functions:

a. Limitation of the axial forces or thrust on the rotor

b. Limitation of the rotational speed on the rotor and

c. Limitation of the yawing speed (rotation of the head around the tower axis). (Kragten, 1989).

2.10.11.1 Safety Devices

Breaking systems

i) Automatic (Springs): Here it is assumed that at very high wind speeds the pump will just vibrate at the datum and appear to be stationary (Figure 2.19).

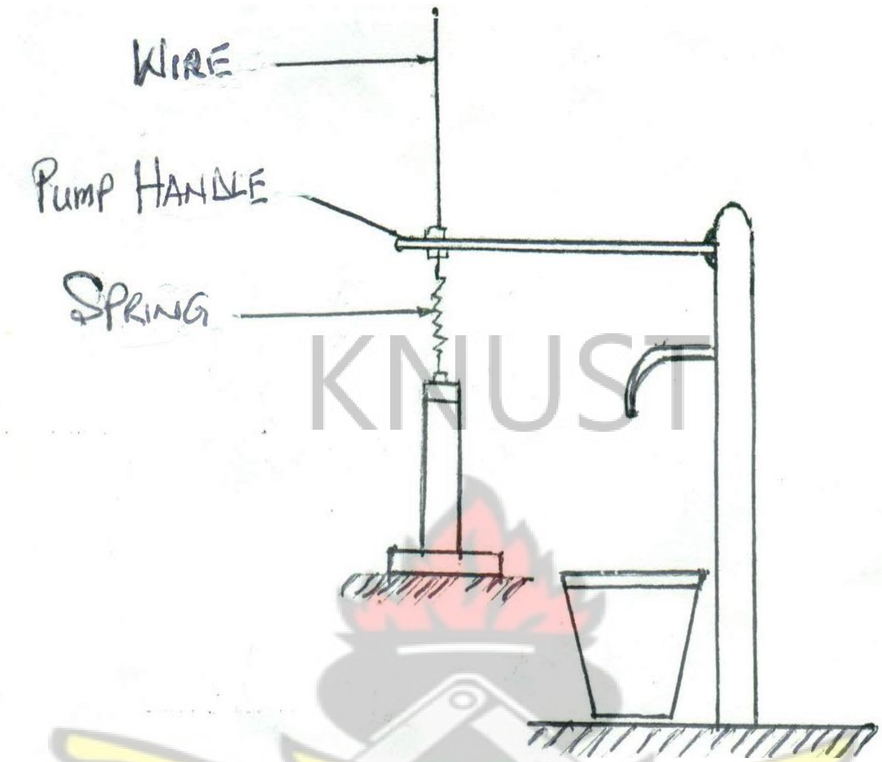


Figure 2.19 Hand pump fitted with spring device to automatically protect the pump

Source: Agbezudor, (1991)

(ii**) Semi-Automatic: (Shear Pin):**Here, the shearing of the shear pin causes the poles supporting the sails to fold (Figure 2.20).

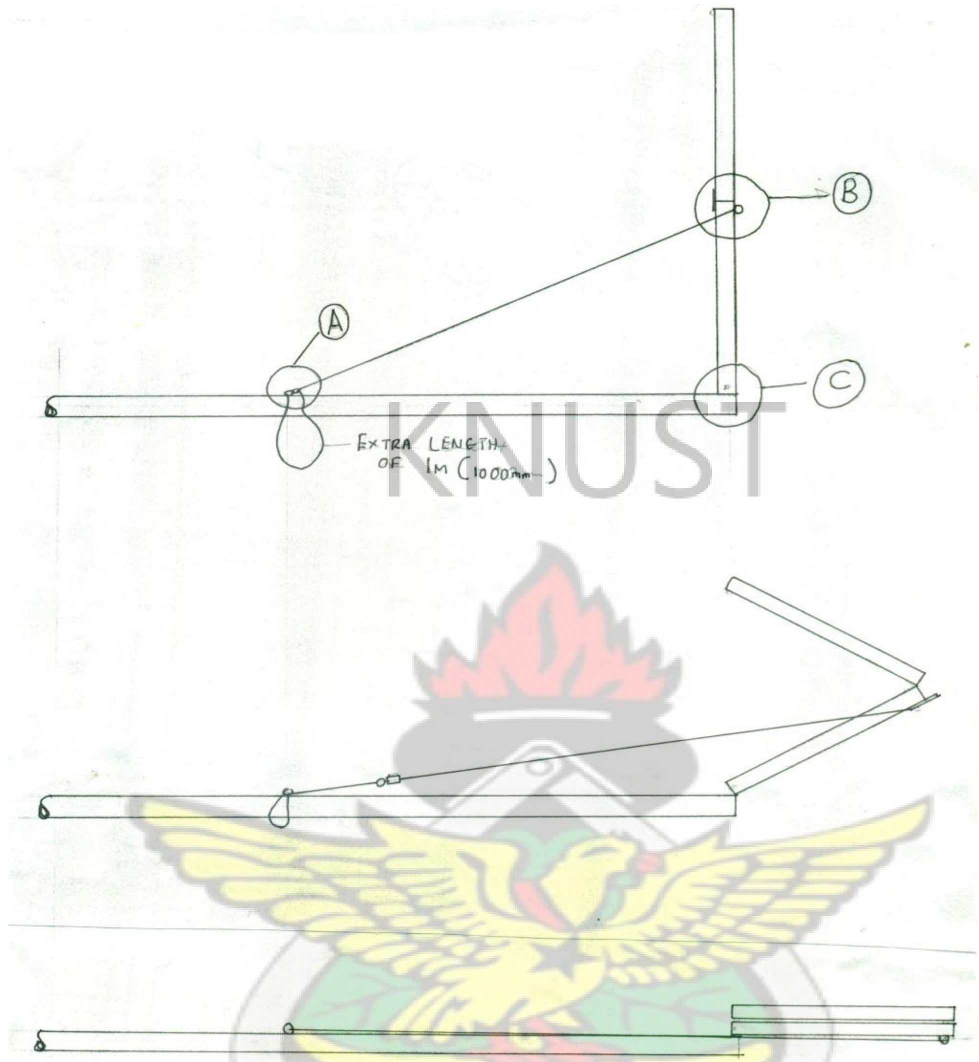


Figure 2.20 Semi-Automatic (Designed sail folding in time of storm).

Source: Agbezudor, (1991)

iii) The Breaking Device (Manual): The device consists of a bar on which an old break shoe is bolted. The bar is pivoted at the middle. A force is applied at the side opposite the break shoe which causes it to engage the hub on the rotor, stopping it by friction. The whole mechanism is a first class lever.

It consists of 60 mm X 10 mm metal bars being part of a long lever connection welded to the opposite sides of a hollow shaft. A square plate, 100 mm X 100 mm, is welded to the ends of one of the bars. The plate has four holes so that the break shoe can be bolted to it (Figure 2.21).

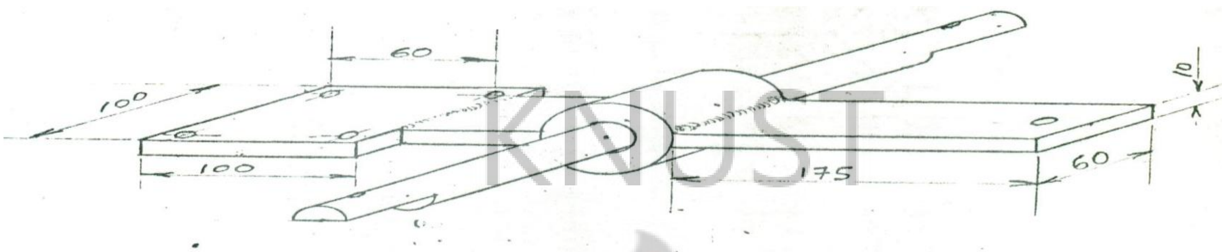


Figure 2.21 The manual breaking device

Source: Agbezudor & Amedorme (2013)

2.10.12 Strap holder

This is a rod of 10mm diameter rolled into an arc subtending an angle of 270°. Four square plates, 50mm X 50mm containing holes of diameter 13mm at their centres are welded to the arc at 90° from each other. This enables it to be secured firmly on four different parts on the supporting frame (figure2.22).

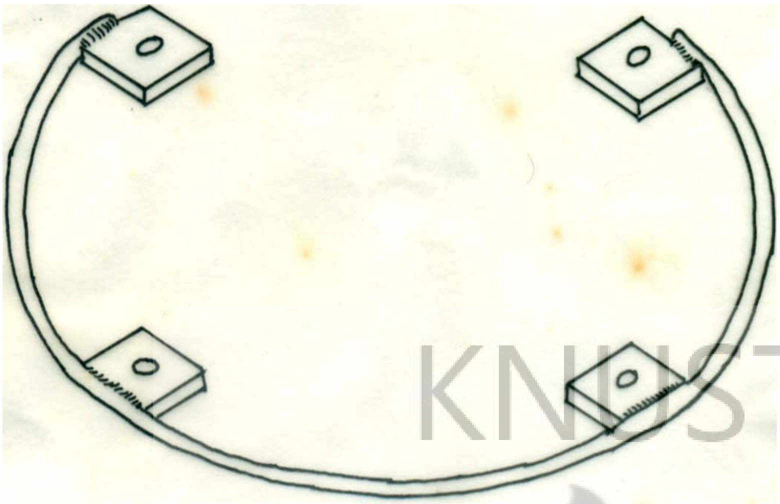


Figure 2.22 Strap holder

Source: Agbezudor & Amedorme (2013)

2.10.13 Sliding seat

It is intended that the rotor would be slid up on one side of the supporting frame by means of pulleys. To this side of the frame the platform does not extend, however the bell crank mechanism protrudes so a sliding seat is provided so that when the rotor is about to be mounted, it can be slid onto the central part of the supporting frame to prevent obstruction. The sliding seat consists of a flat metal bar of thickness 10 mm fixed to two U-bars by welding. The U-bars were shaped to fit into two pipes of diameter 60 mm.

2.10.14 Initial Test Results of the KNUST Wind pump

The initial result is as shown in figure 2.23.

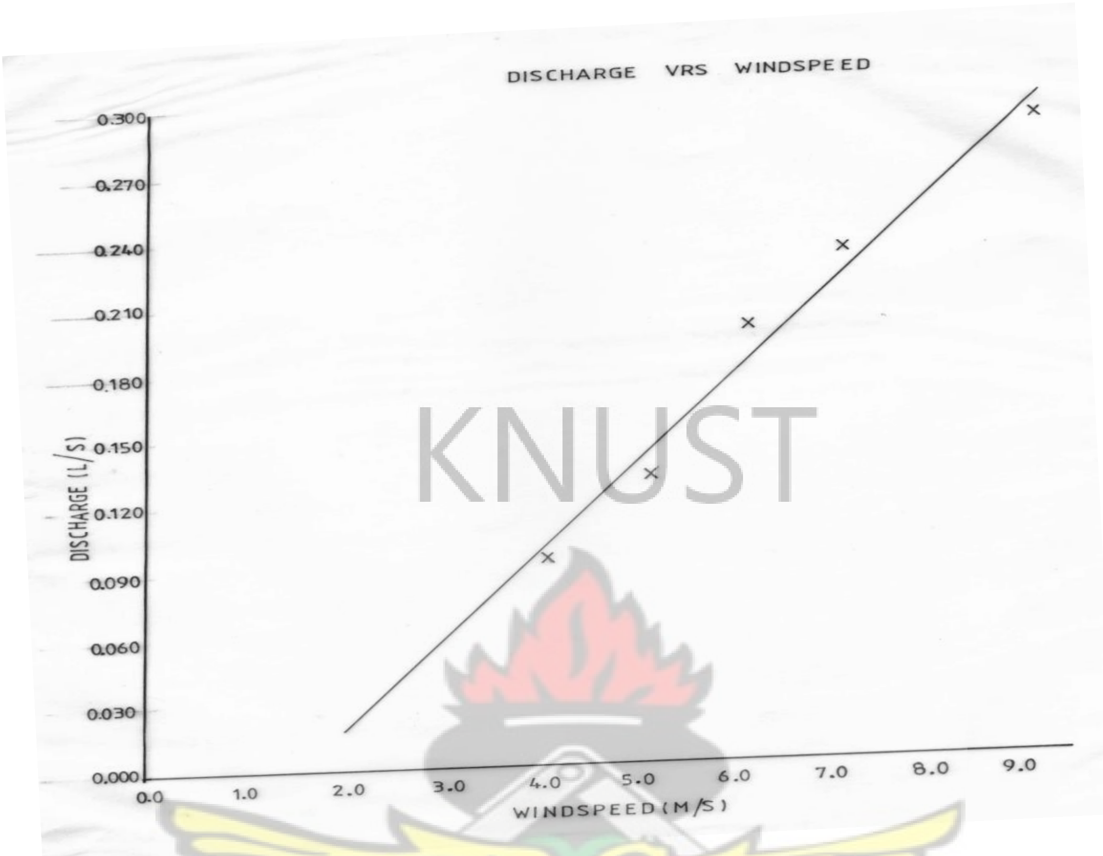


Figure 2.23 A graph showing Discharge against Wind speed

Source: Agbezudor (1991)

2.11 Power available in the wind

The power in the wind is proportional to the wind speed cubed; the general formula for power in the wind is: $\mathbf{P = 1/2pAV^3}$

where P is the power available in watts, p is the density of air (which is approximately 1.2kg/m3 at sea level), A is the cross-section (or swept area of a windmill rotor) of air flow of interest and V is the instantaneous free-stream wind velocity. If the velocity, V, is in m/s, the power in the wind at sea level is: $\mathbf{P = 0.6V^3}$ **watts/m^2 of rotor area**

Because of this cubic relationship, the power availability is extremely sensitive to wind speed; doubling the wind speed increases the power availability by a factor of eight; Table 2.1 indicates this variability (FAO, 1986).

Table 2.1 Power in the wind as a function of wind speed

Wind speed	m/s	2.5	5	7.5	10	15	20	30	40
	km/h	9	18	27	36	54	72	108	144
	Mph	6	11	17	22	34	45	67	90
Power density	kW/m^2	.01	.08	.27	.64	2.2	5.1	17	41
	hp/ft^2	.001	.009	.035	.076	.23	.65	2.1	5.2

Source: (FAO, 1986)

This indicates the very high variability of wind power, from around $10W/m^2$ in a light breeze up to $41,000W/m^2$ in a hurricane blowing at 144km/h. This extreme variability greatly influences virtually all aspects of system design. It makes it impossible to consider trying to use winds of less than about 2.5m/s since the power available is too diffuse, while it becomes essential to shed power and even shut a windmill down if the wind speed exceeds about 10-15m/s as excessive power then becomes available which would damage the average windmill if it operated under such conditions.

The power in the wind is a function of the air-density, so it declines with altitude as the air thins, as indicated in Table 2.2

Table 2.2 Variation of air density with altitude

Altitude (ft)	0	2 500	5 000	7 500	10 000
a.s.l. (m)	0	760	1 520	2 290	3 050
Density correction factor	1.00	0.91	0.83	0.76	0.69

Source: (FAO, 1986)

Because the power in the wind is so much more sensitive to velocity rather than to air density, the effect of altitude is relatively small. For example, the power density of a 5 m/s wind at sea level is about 75 watts/m^2; however, due to the cube law, it only needs a wind speed of 5.64 m/s at 3,000m a.s.l. to obtain exactly the same power of 75 watts/m^2. Therefore the drop in density can be compensated for by quite a marginal increase in wind velocity at high altitudes (FAO, 1986).

2.12 Energy available in the wind

Because the speed of the wind constantly fluctuates, its power also varies to a proportionately greater extent because of the cube law. The energy available is the summed total of the power over a given time period. The usual starting point to estimate the energy available in the wind at a specific location is some knowledge of the mean or average wind speed over some predefined time period; typically monthly means may be used. The most important point of general interest is that the actual energy available from the wind during a certain period is considerably more than the energy that would be produced if the wind blew at its mean speed without variation for the same period. Typically, the energy available will be about double the value obtained simply by multiplying the instantaneous power in the wind that would correspond to the mean wind speed blowing continuously, by the time interval. This is because the fluctuations in wind speed result in the average power being about double that which occurs instantaneously at the mean wind speed. The actual factor by which the average power exceeds the instantaneous power corresponding to the mean wind speed can vary from around 1.5 to 3 and depends on the local wind regime's actual variability; the greater the variability the greater this factor. However, for any specific wind regime, the energy available will still generally be proportional to the cubed of the mean wind speed (FAO, 1986).

2.13 Converting wind power to shaft power

There are two main mechanisms for converting the kinetic energy of the wind into mechanical work; both depend on slowing the wind and thereby extracting kinetic energy. The most crude and least efficient technique is to use drag. Drag is developed simply by obstructing the wind and creating turbulence - and the drag force acts in the same direction as the wind. Some of the earliest and crudest types of wind machine, known generically as "panamones", depend on exposing a flat area on one side of a rotor to the wind while shielding or reefing the sails on the other side. The resulting differential drag force turns the rotor.

The other method, used for all the more efficient types of windmill is to produce lift. Lift is produced when a sail or a flat surface is mounted at a small angle to the wind; this slightly deflects the wind and produces a large force perpendicular to the direction of the wind with a much smaller drag force. It is this principle by which a sailing ship can tack at speeds greater than the wind. Lift mainly deflects the wind and extracts kinetic energy with little turbulence, so it is therefore a more efficient method of extracting energy from the wind than drag.

It should be noted that the theoretical maximum fraction of the kinetic energy in the wind that could be utilized by a "perfect" wind turbine is approximately 60%. This is because it is impossible to stop the wind completely, which limits the percentage of kinetic energy that can be extracted (FAO, 1986).

2.14 Wind pump performance estimation

To size a wind pump for irrigation purposes will usually require an estimate to be made of the week by week or month by month average output. One method for making such an estimate is to combine data on the known performance of the wind pump at various hourly average wind speeds with data from a wind velocity distribution histogram (or numerical information on the number of hours in the month that the wind blows within pre-defined speed "bins"). This is illustrated by Table 2.3, which gives the expected output of a wind pump in various wind speeds, and the statistical average number of hours that the wind blows within each speed range, (or speed "bin" is the favoured jargon). Hence, the total output for each speed bin is obtained by multiplying the output per hour at that speed and the number of hours at which that speed is likely to recur. By adding together the output for each speed bin, we arrive at the total annual output. The importance of doing this monthly is that quite often, the least windy month will have a mean wind speed of only around 60 to 70% of the annual mean wind speed. So the available wind energy in the least windy month can be as little as 20% of what can be expected for a mean wind speed equal to the annual average wind speed. Therefore if annual averages are used, a considerable margin of safety is necessary to allow for "least windy month" conditions, (assuming irrigation water is needed in the least windy month or in a month with a mean wind speed below the annual average) (FAO, 1986).

Table 2.3 Calculation of wind pump output using "binned" wind speed data

Annual output of water for a given wind regime				
Wind speed		**Annual duration hours**	**Output rate m^3/hr**	**Total output m^3**
m.p.h.	**m.p.h.**			
7	3.15	600	0.3	180
8	3.6	500	1.4	700
9	4.05	500	2.3	1,150
10	4.5	400	3	1,200
11	4.95	500	3.7	1,850
12	5.40	450	4.2	1,890
13	5.85	450	4.7	2,115
14	6.30	300	5.2	1,560
15	6.75	300	5.7	1,710
15 plus		1,700	6	10,200
				Annual
		Total 5,700 hr		Total 22,555 m^3

Source: FAO, (1986)

2.15 Cost of a windmill

Like other renewable energy technologies, wind is capital intensive, but has no fuel costs. The key parameters governing wind power economics are the:

- Investment costs (including those associated with project financing);
- Operation and maintenance costs (fixed and variable);
- Capacity factor (based on wind speeds and turbine availability factor);
- Economic lifetime; and
- Cost of capital (IRENA, 2012).

2.16 Summary: Applicable features for a local design

Considering the low wind regime in Ghana and the technological knowhow of majority of the farmers who will benefit from the new design, it is important for the new design to have special features to meet the present need.

The aerodynamic design must:

- be simple and effective, utilizing low wind velocities (which occurs far more often than higher velocities) to deliver a high starting torque
- have a simple technology which every layman can understand
- have its entire know-how within the country and everything locally made with raw materials and spare parts readily available, reliable and cheap
- be independent of any other technology available at the site. The operational and maintenance costs during its complete service life minimized
- not have well-equipped workshop with qualified personnel or specialists.

CHAPTER THREE

DESIGN OF WINDMILL

This chapter looks at the design of the wind mill project. Details of the design parameters are given and discussed.

3.1 Introduction

For the windmill to have the right specification for easy construction and stand the test of time it must be well designed using the appropriate equations and relations.

The rotor assembly which was made up of a straight treated bamboo 3 m in length had one end of the bamboo secured to the flywheel cum hub by special locking mechanism and the other end fixed to another bamboo which made the circumference of the rotor assembly. Eight bamboos were fastened on the flywheel and radiated outside to form a triangle. The angle subtended at the centre by each bamboo was 45^0. To minimise friction the rotor shaft (power shaft) was supported with two bearings, a roller and a taper bearings. Tower structure 4 m high tower was made from galvanized pipe and the sails or cones were also designed and constructed with the specification of vertical height 1.4 m, the base 1 m and the slant height of 1.5m. A total of sixteen (16) sails or cones were used.

The Designed Assembled Windmill and the Designed Wind Rotor with Sixteen Sails are shown in figure 3.1 and figure 3.2 respectively.

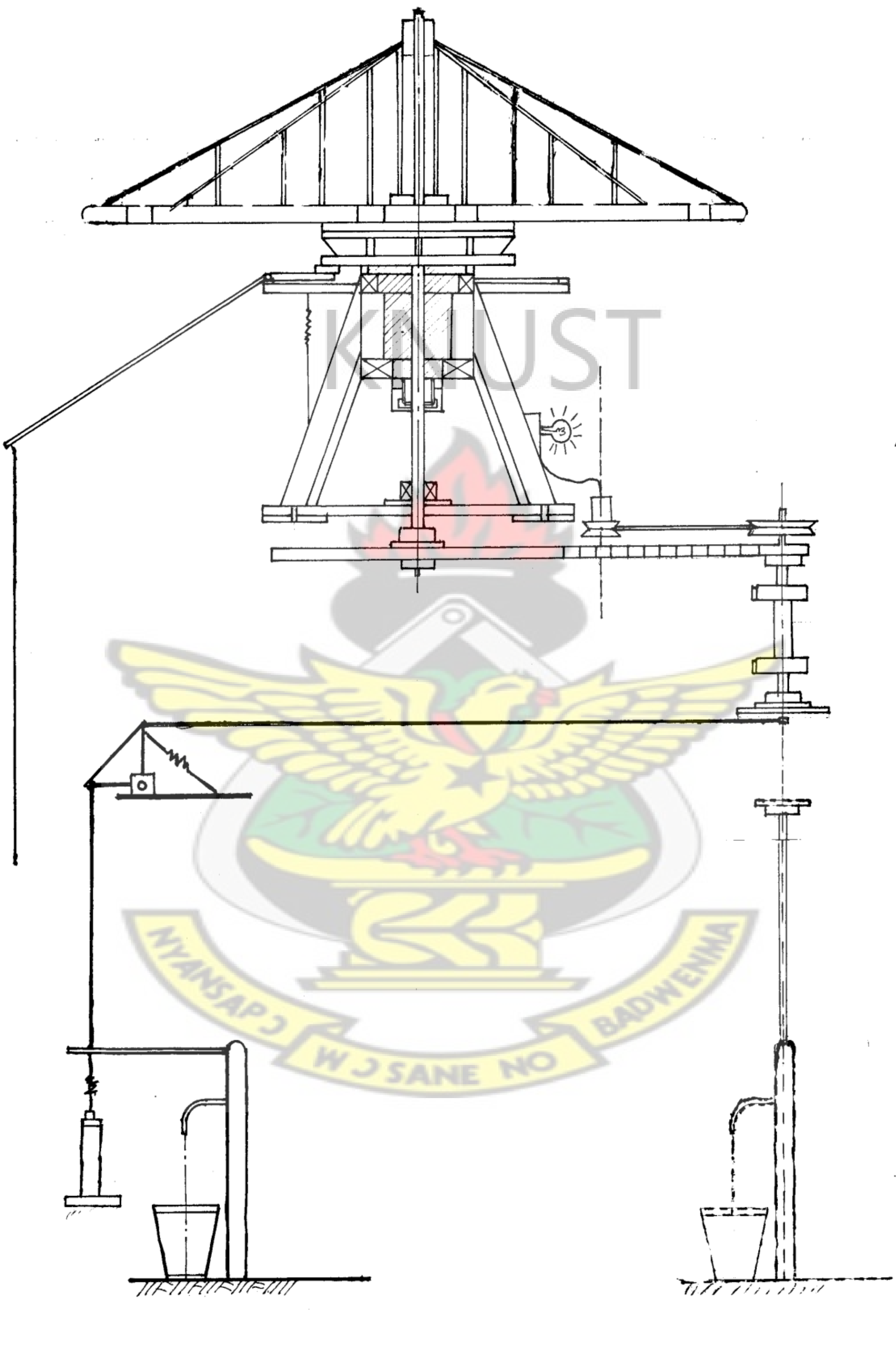


Figure 3.1 The designed assembled windmill

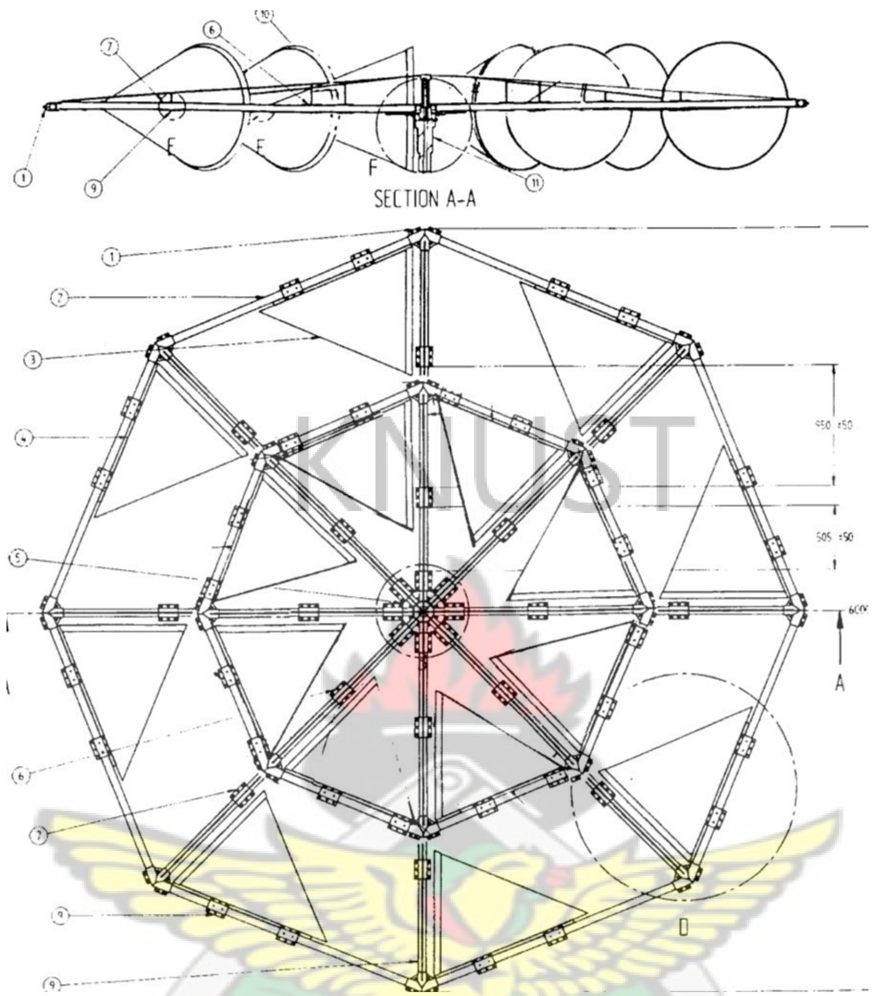


Figure 3.2 The designed wind rotor (sixteen sails)

3.2 The Design Calculation for wind pump

The concept as proposed in this study is a diametral flow vertical axis wind turbine. Being a drag machine, it has a tip speed ratio less than 1.0 and it operates based on a similar principle as the cup anemometer (Practical Action, 2012).

The drag coefficient model assumes the longitudinal aerodynamic torque to be expressed in terms of two drag coefficients (Pederson, 2003). On one side where the sail moves with the wind, there is a constant high drag coefficient C_{DH}, and on the other side that moves against the wind, there is a constant low drag coefficient C_{DL}.

The resulting aerodynamic torque is given as

$$Q_A = R(D_H - D_L) \quad [1]$$
$$= R\left\{\frac{1}{2}\rho AC_{DH}(U - R\omega)^2 - \frac{1}{2}\rho AC_{DL}(U + R\omega)^2\right\}$$

$$= \frac{1}{2}\rho AR\{C_{DH}(U - R\omega)^2 - C_{DL}(U + R\omega)^2\} \quad [2]$$

where U is the free stream velocity in metres per second ($^m/_s$)

R is the radius of rotation in metres (m)

A is the swept area of one sail (ie. the base area of the conical sail) in square metres (m^2)

ρ is the density of air in kilogram per cubic metre (kg/m^3)

ω is the angular velocity of the rotor radians per second (rads/s)

The tip speed ratio is defined as $\lambda = {^{R\omega}}/_U$

Substituting in equation [2] yields

$$Q_A = \frac{1}{2}R\rho AU^2\{C_{DH}(1 - \lambda)^2 - C_{DL}(1 + \lambda)^2\} \quad [3]$$

The corresponding aerodynamic power would be given by

$$P_A = Q_A \omega$$

$$= \frac{1}{2} \lambda \rho A U^3 \{C_{DH}(1-\lambda)^2 - C_{DL}(1+\lambda)^2\} [4]$$

In the operation of the wind turbine, power is expended on frictional resistance in the bearings as well as the inertia of the rotating components. Thus, the available mechanical power output is the net value after these dissipations have been deducted which is given by

$$P_m = [Q_A - \frac{1}{2} I \omega^2 - Q_f] \omega$$

where Q_f is the frictional torque in newton metre (Nm)

I is the moment of inertia of the rotor in kilogram square metre (kgm^2)

Experimentally, the drag coefficients have been shown to depend on the geometry of the cone. In particular, the drag will vary depending on how steep the angle of the cone is. The angle of interest is called the half-vertex angle, ε, measured from the centreline of the cone to one of its walls (Hoerner, 1965). According to figure 3.1, the drag coefficient increases as the angle increases.

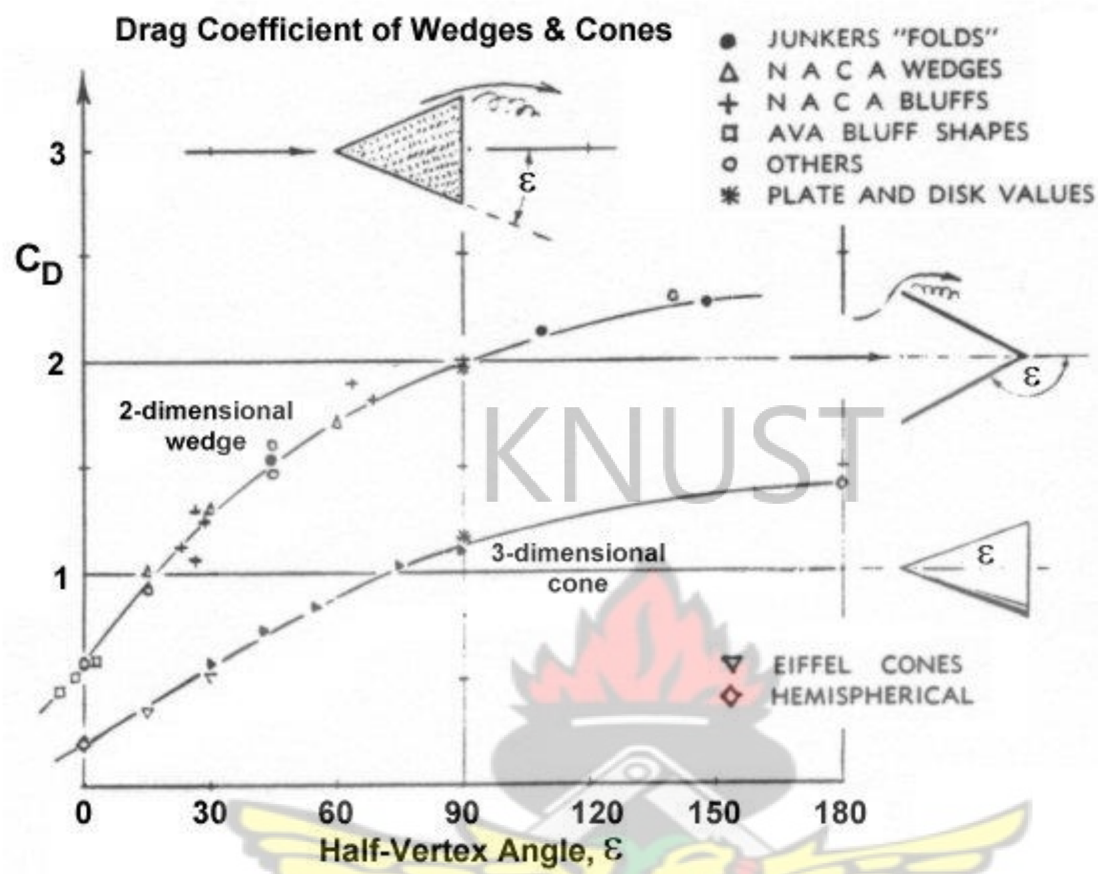


Figure 3.3 Drag coefficient of wedges and cones versus half-vertex angle

Source: Hoerner, (1965)

Based on the above graph provided by Hoerner (1965), the drag coefficient is observed to have a linear variation with the half vertex angle from 0^o to 90^o. This variation is approximated by the equation $C_D = 0.0112\varepsilon + 0.162$ [4]

Where ε is the half-vertex angle, (measured from the centreline of the cone to one of its walls)

For the proposed design, the requisite parameters are as follows;

$R = 2.41m, d = 0.90m, l = 1.09m, A = 0.6363m^2, \varepsilon = 22.43^o$

Thus the low drag coefficient encountered by the sail as it moves against the wind is C_{DL}=0.4132 according to the relation in equation [4].

On the other side where it moves with the wind, the angle under consideration becomes the obtuse supplement of the value used in calculation C_{DL} (ie. $\varepsilon_2 = 180 - \varepsilon_1$).

Thus, $\varepsilon_2 = 180° - 22.43° = 157.57°$.

The corresponding drag coefficient as read from the graph in figure 3.3, is $C_{DH} = 1.40$

Where ε_1 half-vertex angle of the convex side of the cone and

ε_2 half-vertex angle of the concave side of the cone.

Table 3.1 shows the parameters used and obtained from the designed calculations.

PARAMETERS	SYMBOL	VALUES	UNITS
Air density	ρ	1.25	kg/m3
Swept Area	A	0.6363	m2
free stream velocity	U	6	m/s
tip speed ratio	λ	0.18	
Radius of rotation	R	2.41	m
High drag coefficient	C_{DH}	1.4	
low drag coefficient	C_{DL}	0.4132	
angular speed of rotor assembly	ω	0.448133	rad/s
Inertia of rotor assembly	I_c	439.4	kgm2
Aerodynamic power	P_{AT}	90.92334	Watts
Power dissipated by rotating components	$I_c\omega^2$	44.12081	Watts
Available shaft power	P_{sh}	46.80253	Watts

Table 3.1 Design parameters for the windmill

CHAPTER FOUR

CONSTRUCTION OF WINDMILL

This chapter looks at the construction of the wind pump project. The details of the design drawing and materials used, the methods employed in achieving the desired results and the actual construction are discussed in this chapter. Photographs and illustrations are given where necessary to highlight important stages in the construction of the windmill.

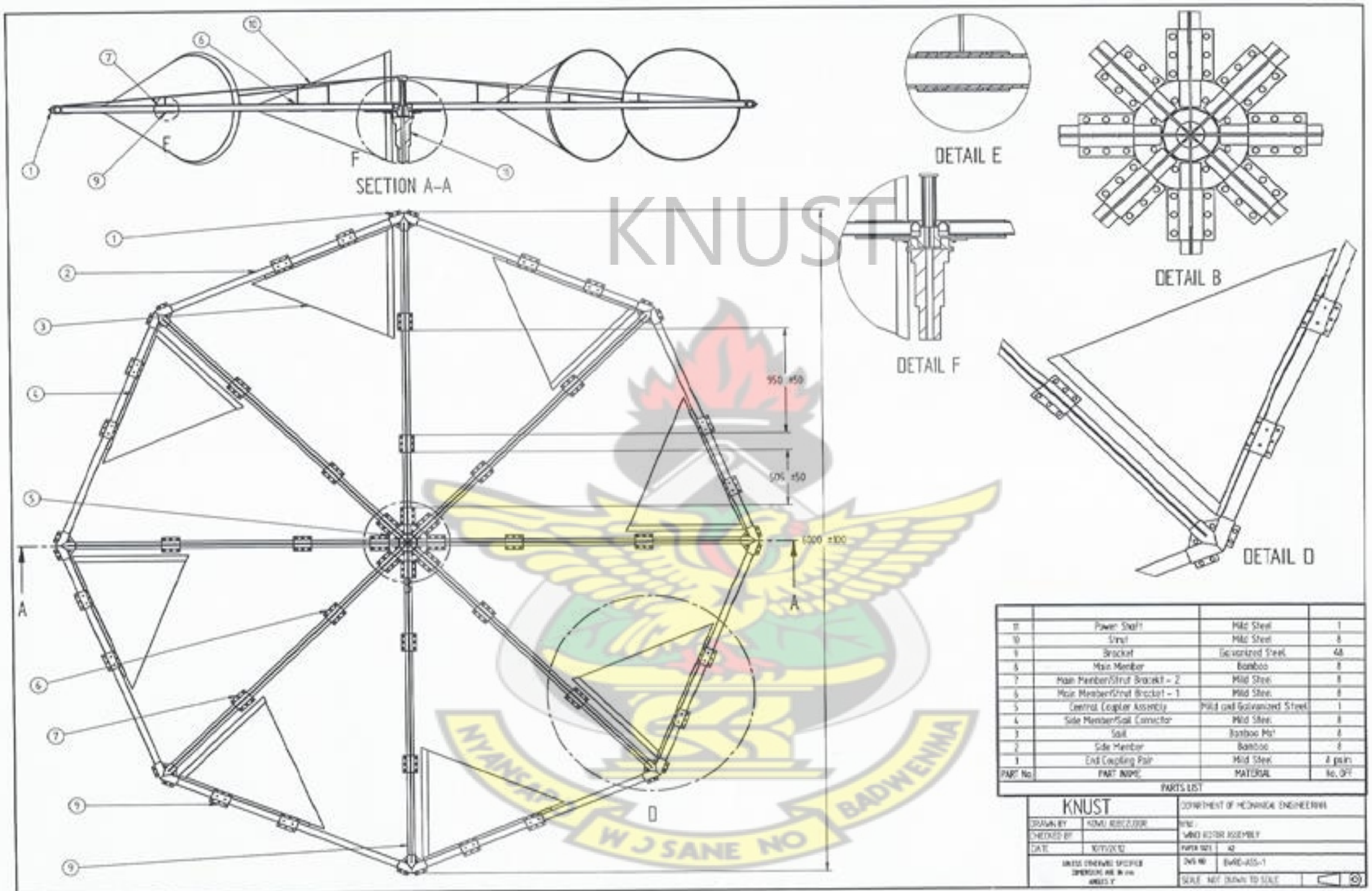
4.1 Introduction

To establish technical feasibility and economic viability of the proposed design of the windmill, the windmill must be constructed using the design parameters. Detailed design and assembly drawings and other technical specifications on the wind mill are done and followed for easy construction. Other information on bamboo treatment set up, design features such as rotor assembly, sails and blades, mechanical power transmission, tower or stand structure and tail assembly are also provided along with suitable illustrations and photographs.

4.2 Working drawings

The figures 4.1-4.10 show the detail assembly drawing, elevations, sectional views and various parts lists of the proposed windmill.

The driven shaft is of diameter 35 mm. One end takes a tapper bearing and a flange (as part of the transmission hub and also acts as a point of attachment to a rotary pump) and the other end takes the smaller sprocket and a pulley for possible generation of electricity.



PART No	PART NAME	MATERIAL	No. OFF
11	Power Shaft	Mild Steel	1
10	Strut	Mild Steel	8
9	Bracket	Galvanized Steel	48
8	Main Member	Bamboo	8
7	Main Member/Strut Bracket - 2	Mild Steel	8
6	Main Member/Strut Bracket - 1	Mild Steel	8
5	Central Coupler Assembly	Mild and Galvanized Steel	1
4	Side Member/Sail Connector	Mild Steel	8
3	Sail	Bamboo Mat	8
2	Side Member	Bamboo	8
1	End Coupling Pair	Mild Steel	8 pairs

PARTS LIST

Figure 4.1.1 Wind rotor assembly (eight sails)

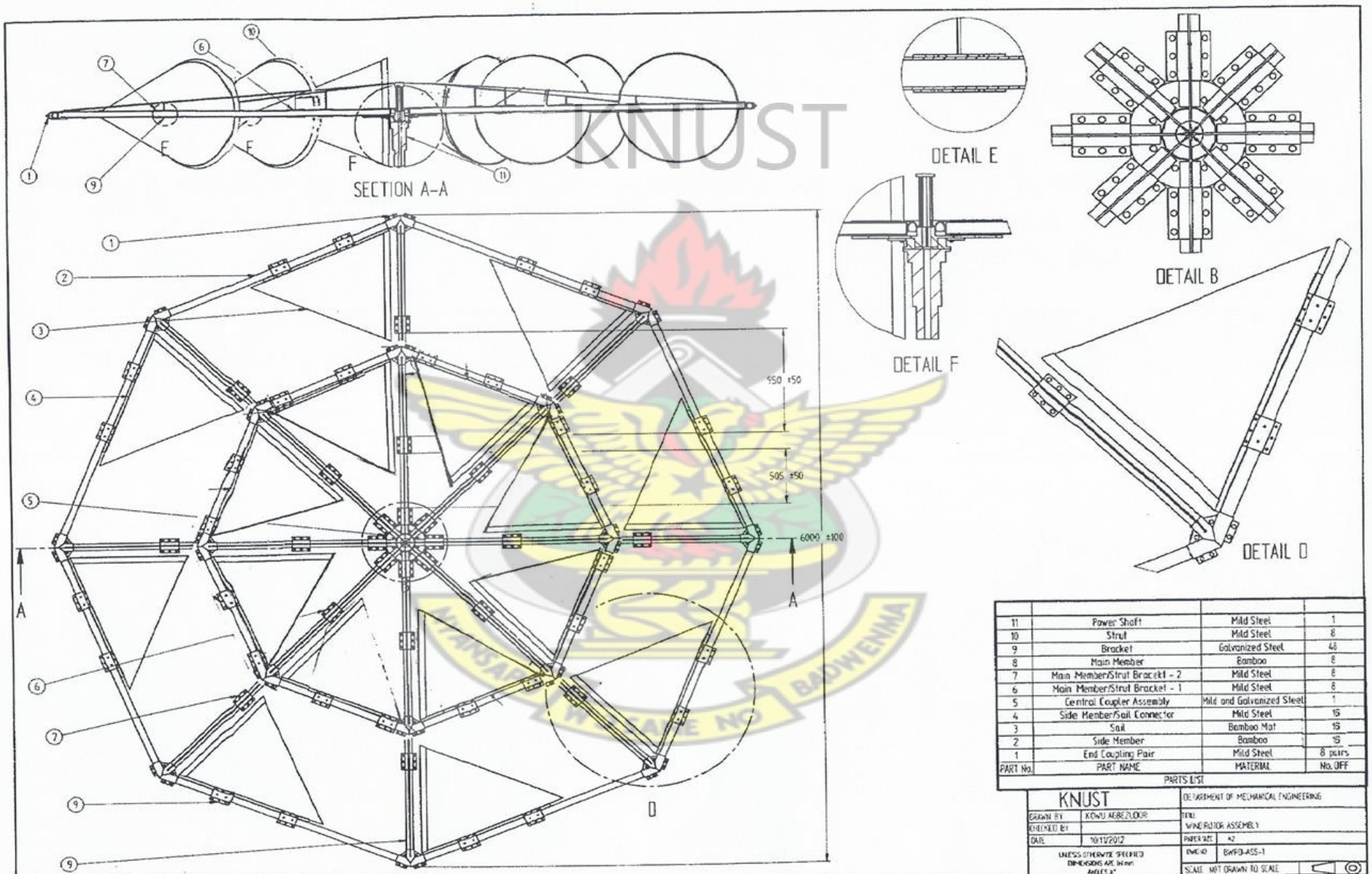


Figure 4.1.2 Wind rotor assembly (sixteen sails)

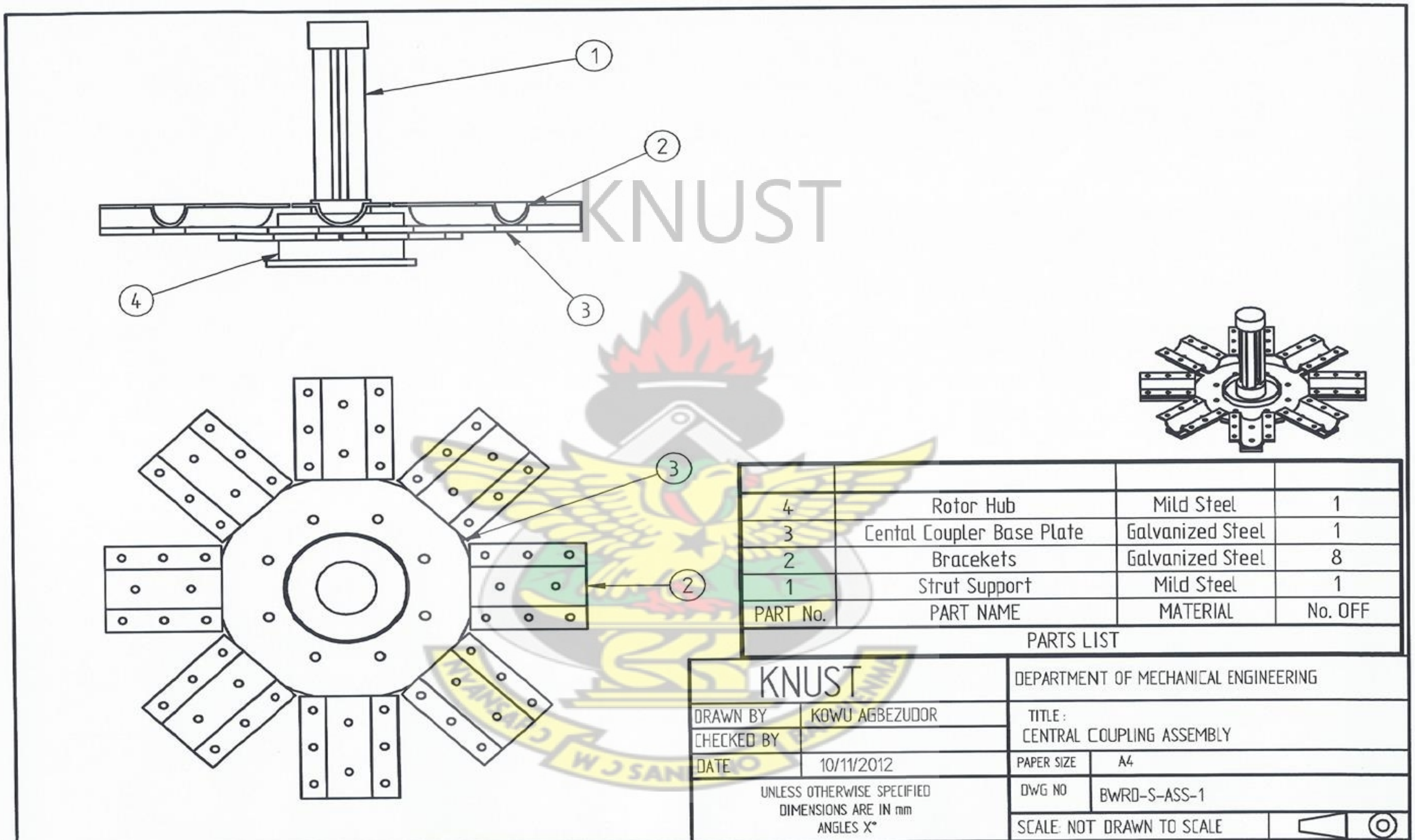


Figure 4.2 Central coupling assembly

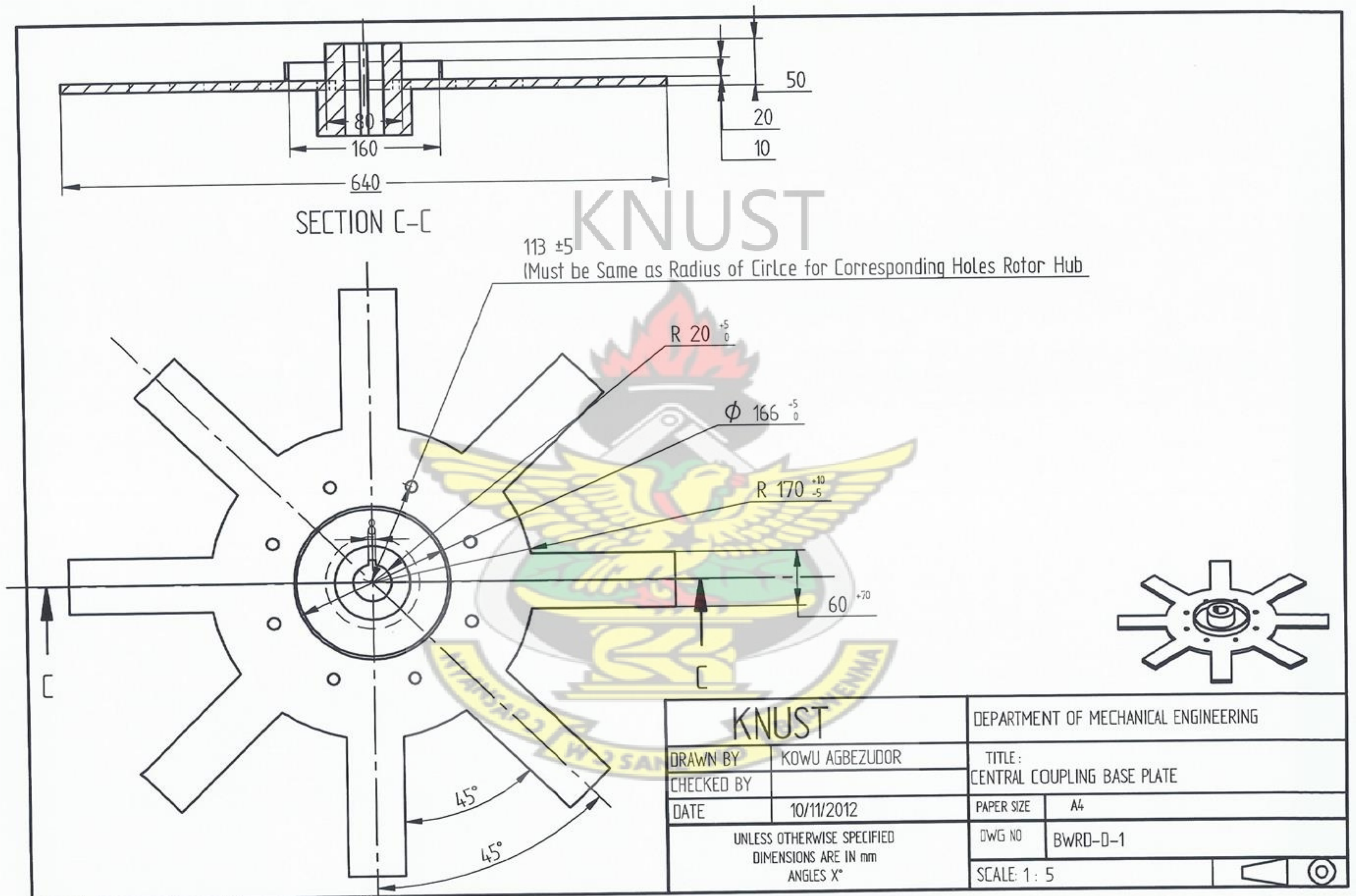


Figure 4.3 Central coupling base plate

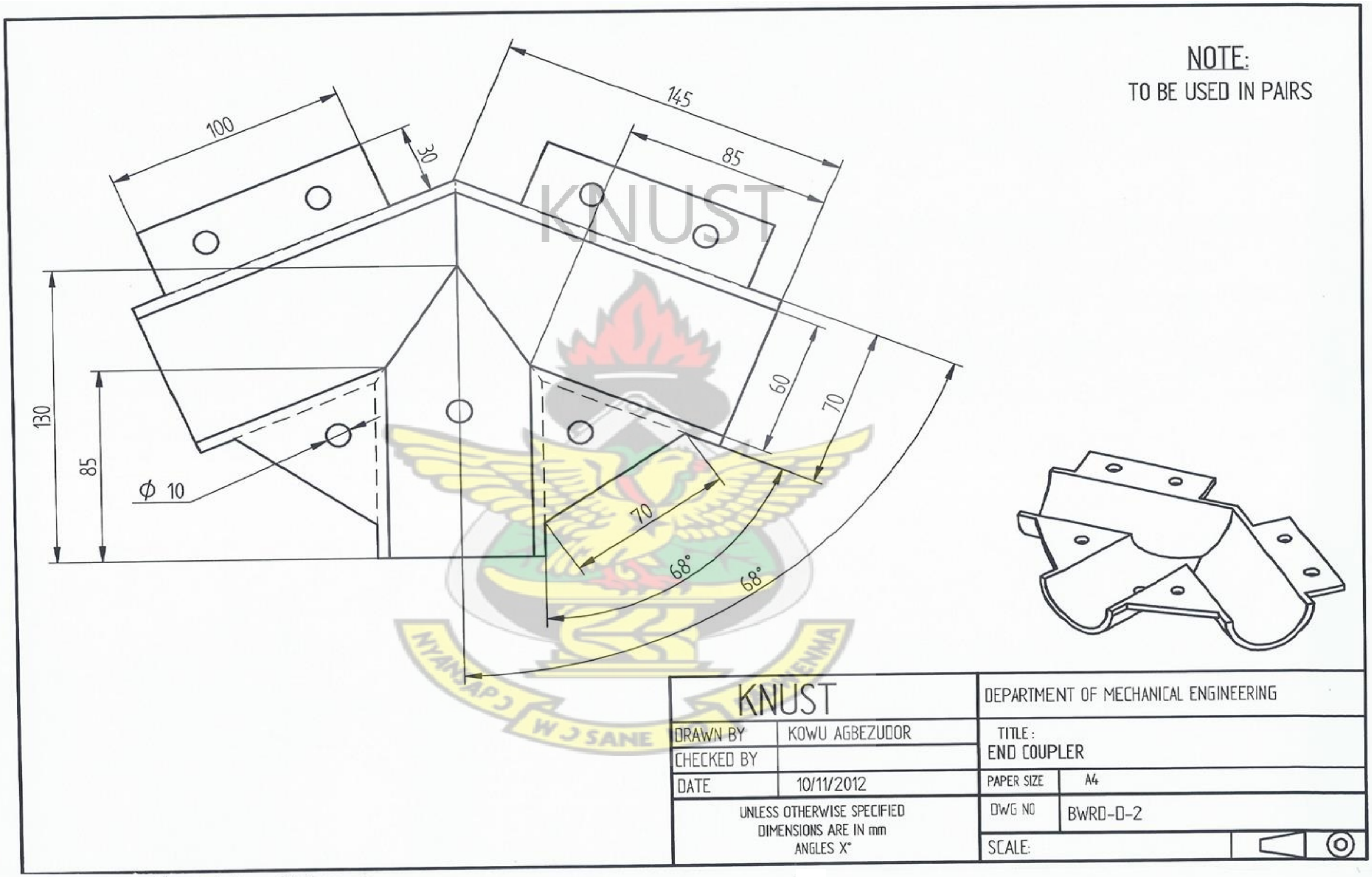


Figure 4.4 End coupler

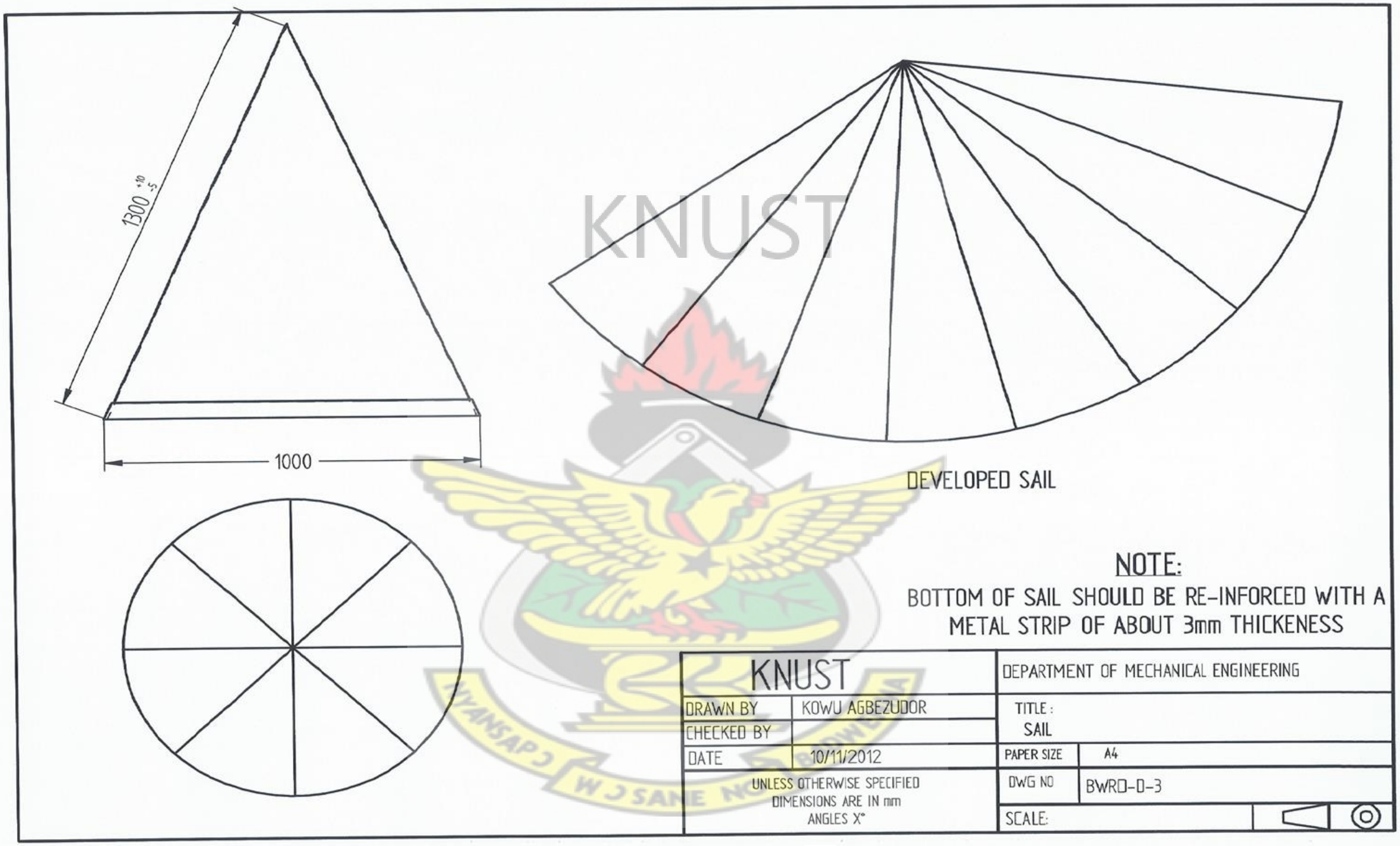


Figure 4.5 Detail drawing of sail

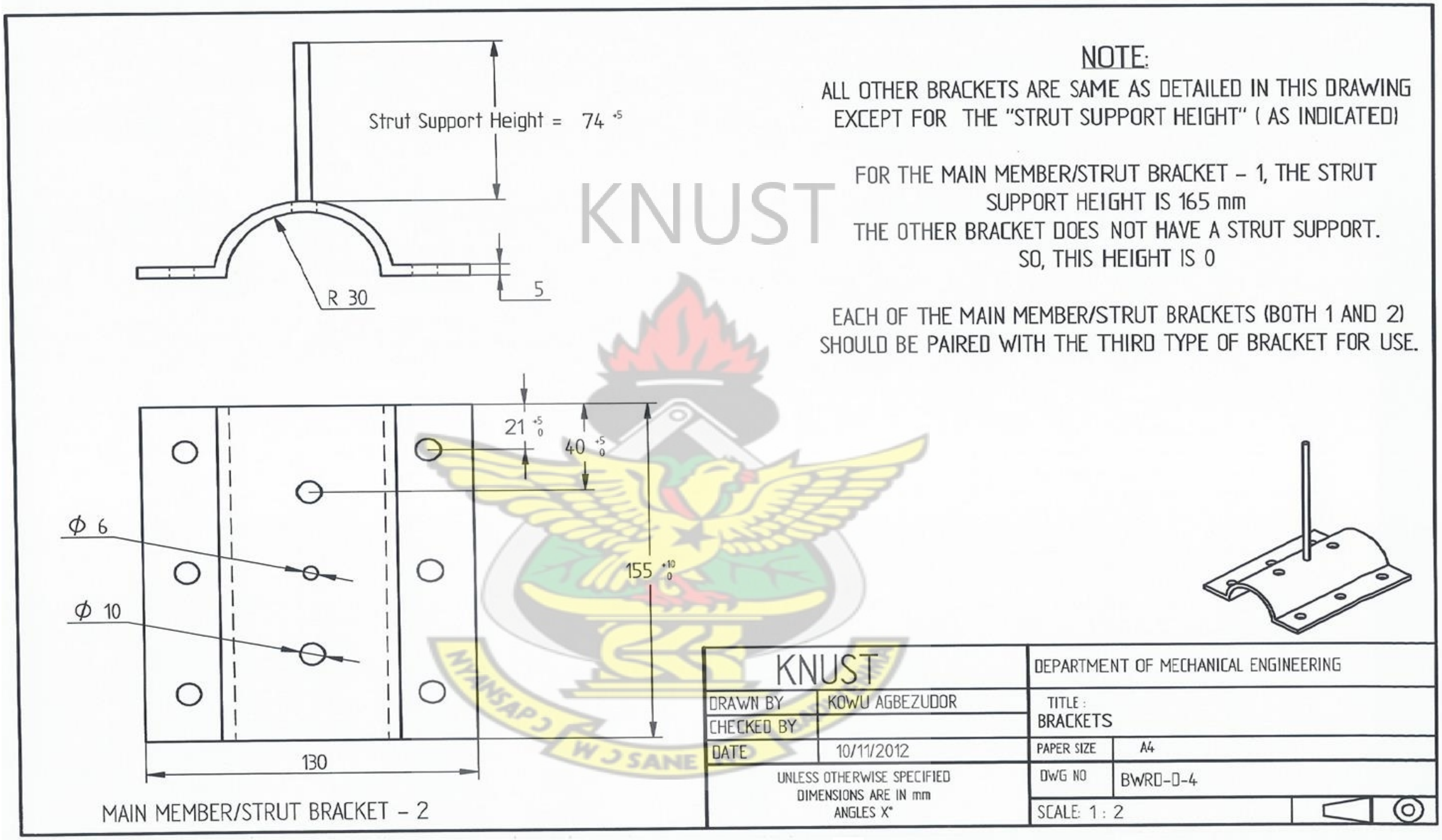


Figure 4.6 Brackets

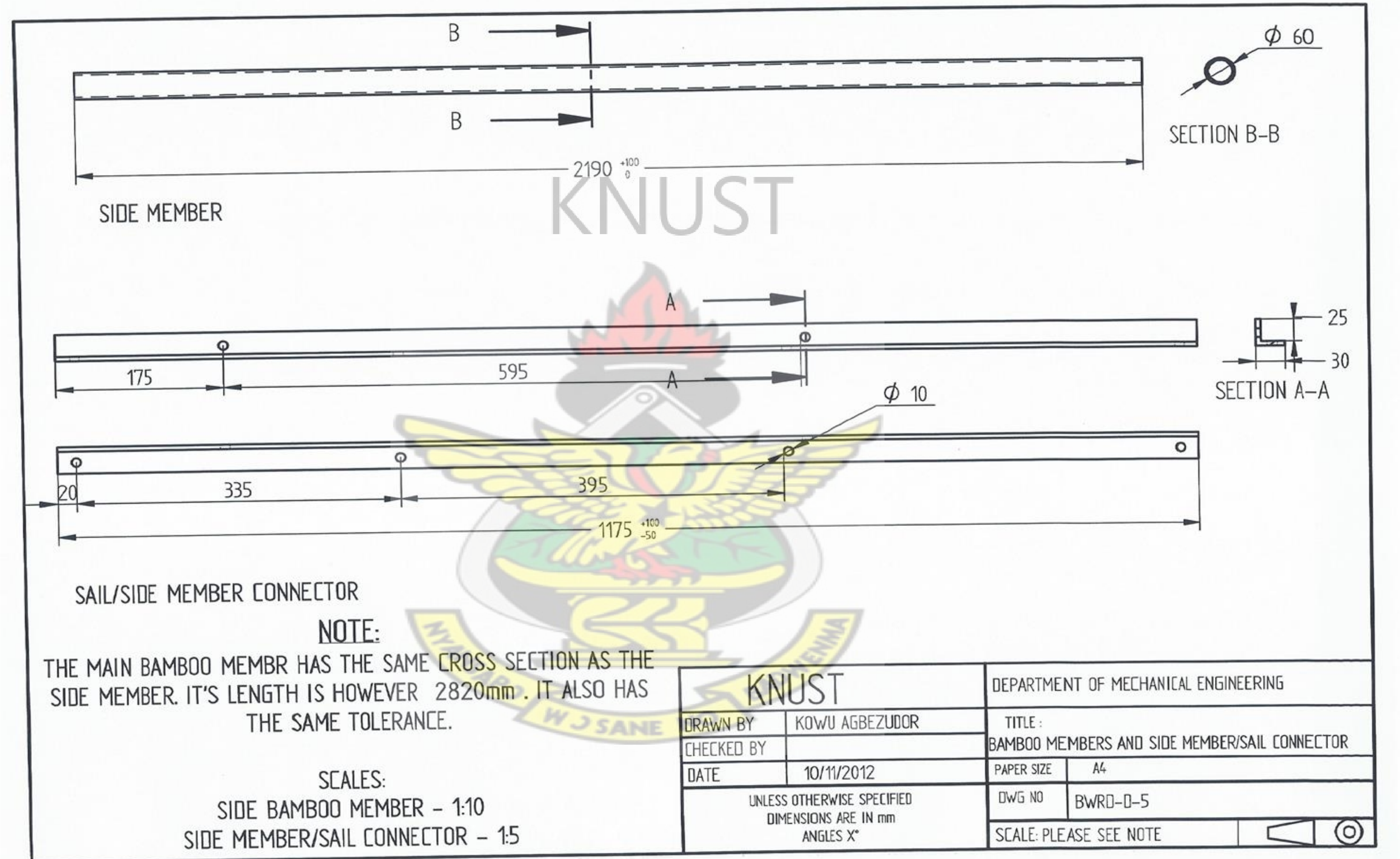


Figure 4.7 Bamboo members and side member sail connector

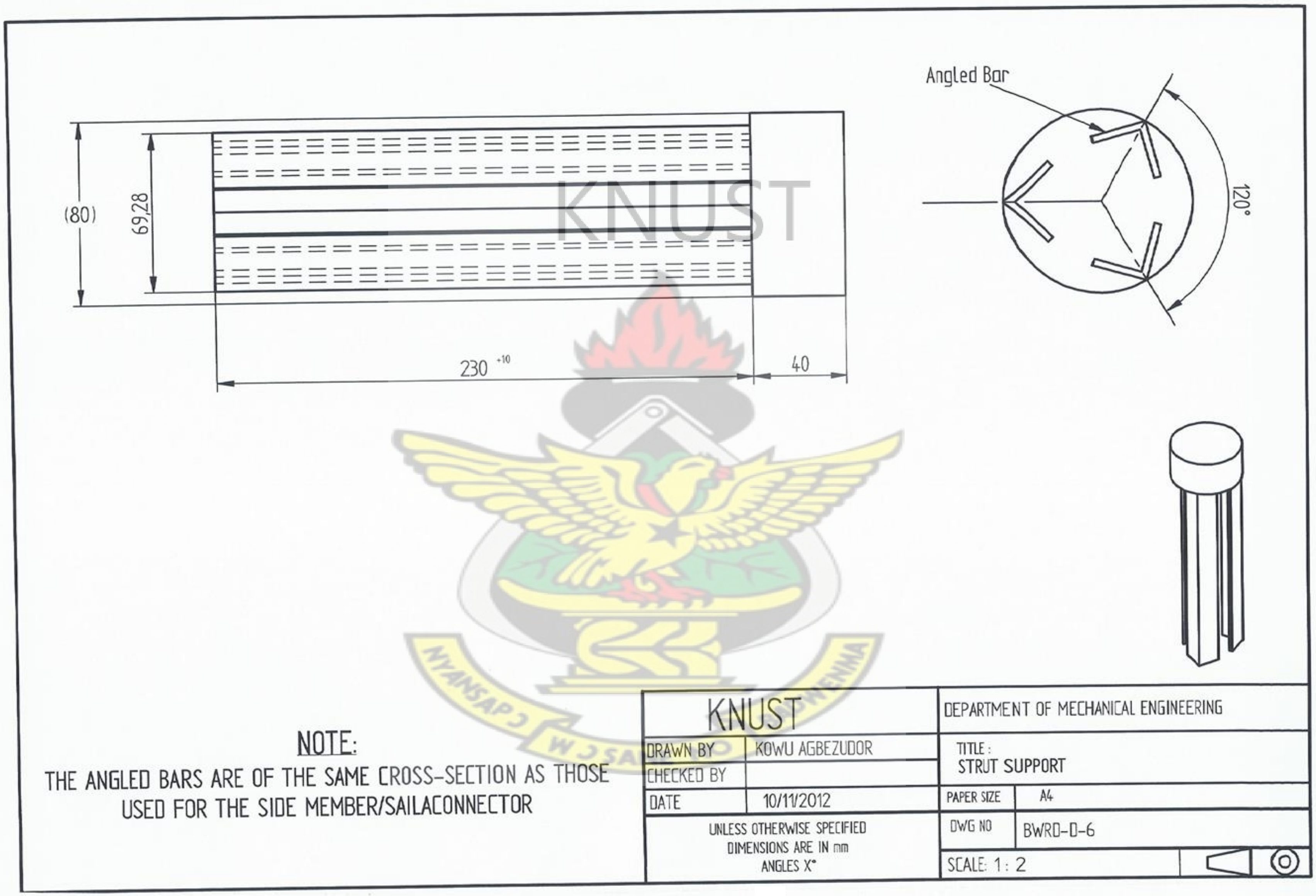


Figure 4.8 Strut support

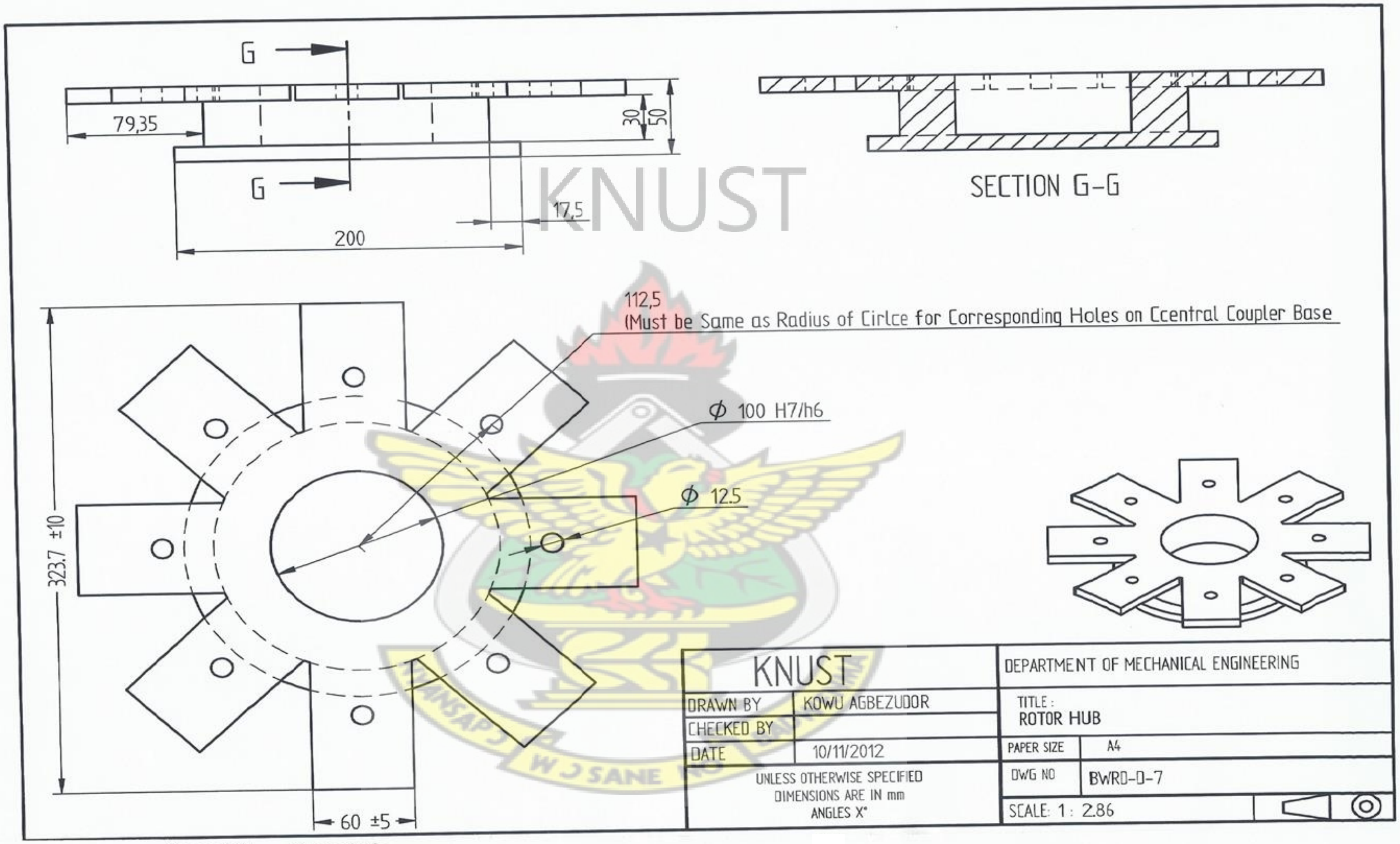


Figure 4.9 Rotor hub

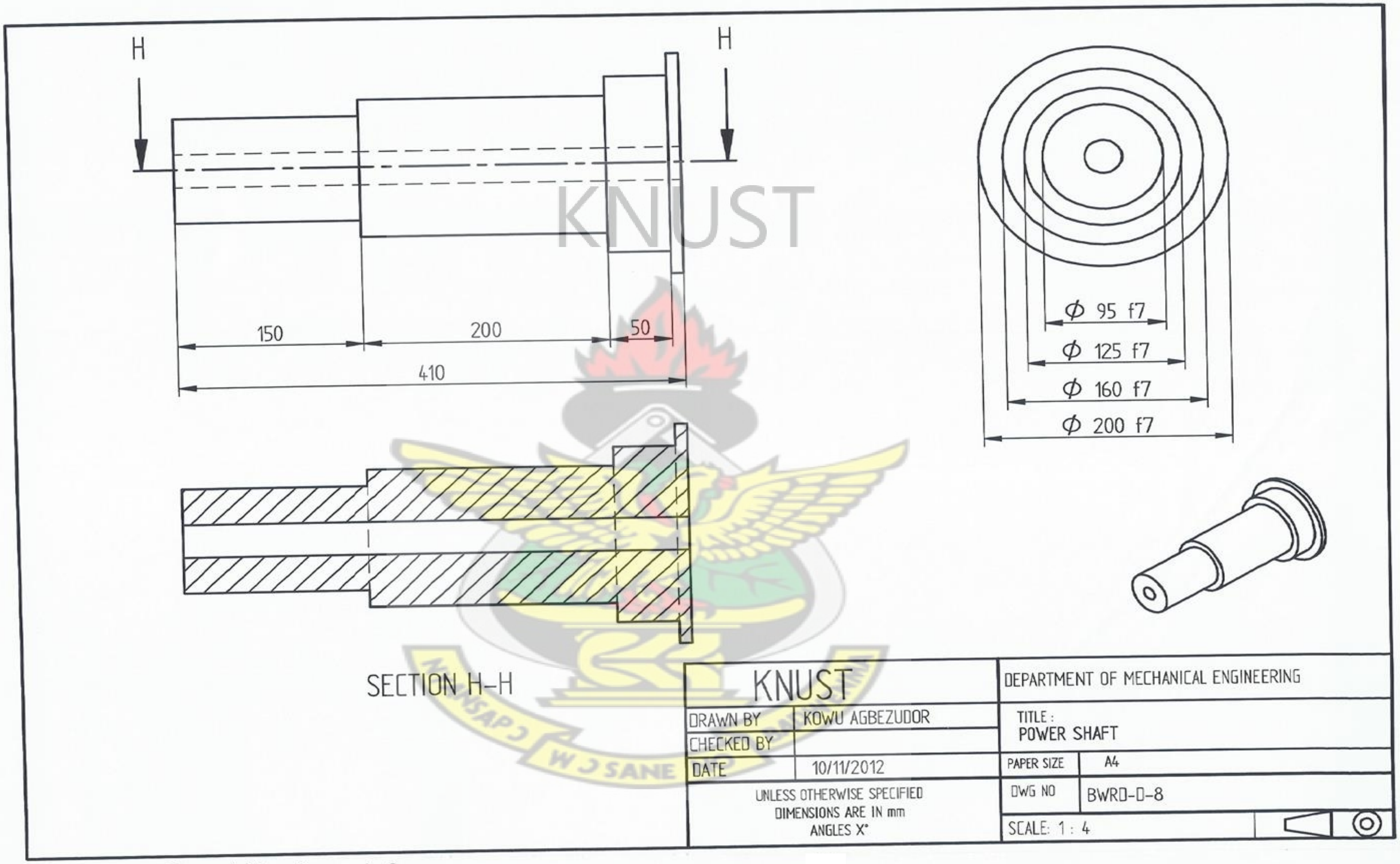


Figure 4.10 Power shaft

4.3 Description of Bamboo treatment set up

For the blades or the rotor of the wind turbine or windmill to be lighter in weight and last longer, the bamboo is treated with a special chemical called Dursban. To ensure that the treatment of the bamboo is fast and complete to prevent insect infestation, holes are bored in the fresh bamboo, figure 4.11, placed and kept immersed in the treatment bath, figure 4.12, for thirty (30) days.

Figure 4.11 Untreated Bamboo, Fresh Bamboo & Boring hole in Bamboo before treatment

Figure 4.12 The treatment basin & Tool for keeping bamboo immersed in a treatment bath

Three drums with each having a capacity of 500 litres and length of 90 cm are welded together to have a total capacity of 1500 litres and a total length of 270 cm. The ends of the drums are sealed to prevent the chemical leaving the drums.

For the bamboo to be placed inside the drum, an opening of a dimension 20 cm by 50 cm is made at the side of the drum. This opening gives access for the chemical to be poured inside the drum and also the point where the bamboo is monitored during the course of treatment. The process of making this hole on the drum is through marking out and cutting. The marking out is done by steel rule and a scriber after which hacksaw is used to cut the marked portion.

Since the drum will lie horizontal during treatment, it needs to be supported on stands which must withstand the weight of the drum if it is filled to the brim together with the bamboos. Since the overall capacity and length of the drum are quite high, three supports are made and they are positioned at a distance 45 cm, 135 cm and 225 cm of the drum. The height of the stand is 60 cm above the ground level. This is high enough to enable the content of the drum to be viewed. An arc of length 30 cm is welded on the top of the stand so that the drum can be stable while lying on the stand, figure 4.12. The material used is medium carbon steel and a hacksaw is used to cut the steel into pieces after the required dimensions have been specified. An arc welding is used to join the pieces together to form the stand.

4.4 Tower structure

A 4 m high tower made from galvanized pipe support the rotor and sail or cone assembly. It is reinforced with iron bars at joints to make it robust enough to withstand wind storms. The pipes are painted with special paint to prevent rust and corrosion and also as a protection against adverse weather conditions including soil effects.

4.5 Rotor assembly

This comprises of a straight treated bamboo 3 m in length. One end of the bamboo is secured to the flywheel cum hub by special locking mechanism. The other end is fixed to another bamboo which makes the circumference of the rotor assembly. Eight bamboos are fastened on the flywheel and radiate outside to form triangle. The angle subtended at the centre by each bamboo is 45^o. The thickness of the bamboo is 1 inch. To reinforce the bamboo, eight 1/4 inch iron rods are used as shown in figures 4.13-16.

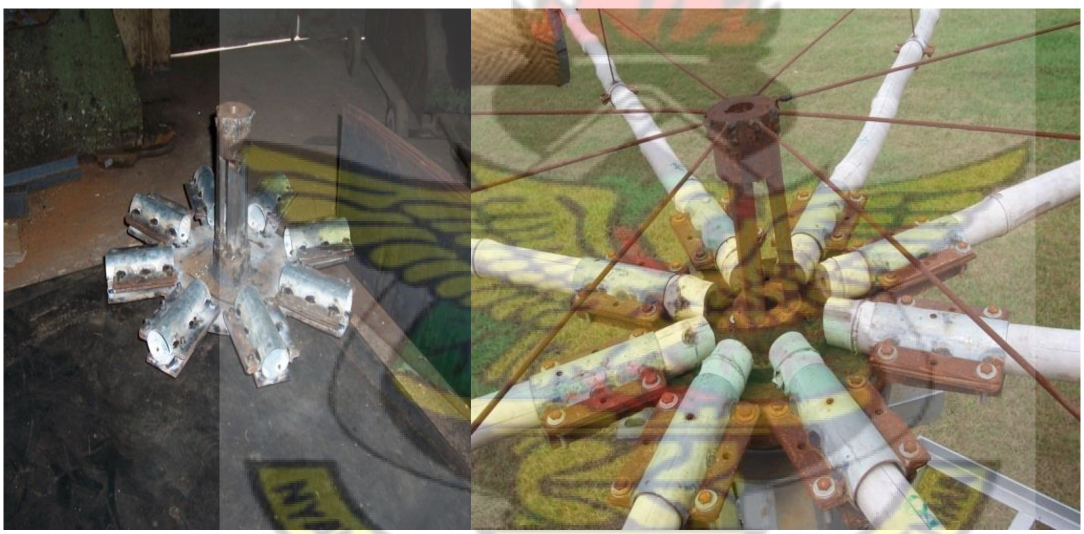


Figure 4.13 Central coupler & Central coupler with Bamboo at the centre

Figure 4.14 Rotor assembly (no sails) Figure 4.15 Rotor mounted three metres above ground

Figure 4.16 One end coupler & End coupler fitted with Bamboo

4.6 Formation of the sails or cones

The bamboo mat came in sizes of one square metre. Several of these are woven together to form a rectangular mat from which the sails/ cones are formed as shown in figures 4.17 and figures 4.18.

Figure 4.17 One square foot woven Bamboo mat & Woven Bamboo mat

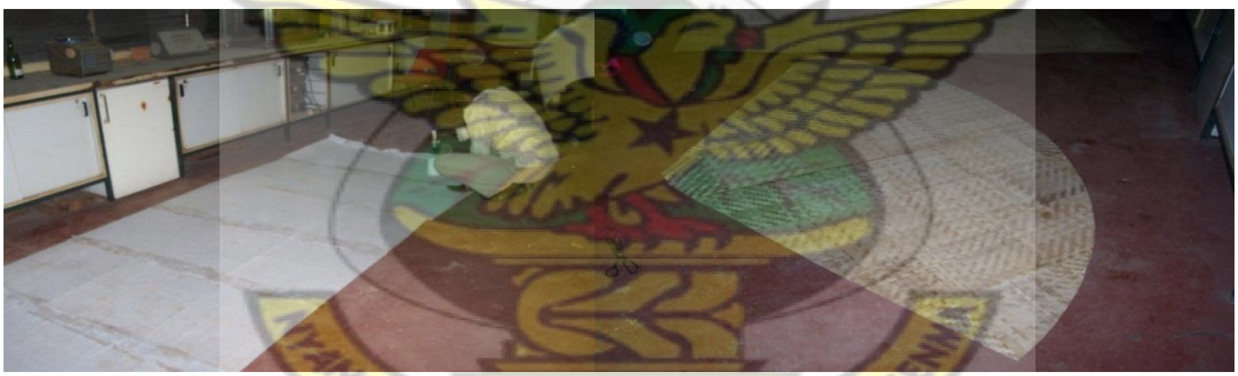


Figure 4.18 Technician attaching stiff material on a Bamboo mat & A developed Bamboo sail

4.7 Rotor mounted with sails

The sails which are sixteen in number are conical in shape and are made of high-quality mat. The vertical height is 1.4 m, a base 1 m and a slant height of 1.5 m. The tail and leading edges are fixed to the bamboos special formed side couplers making the circumference of the rotor as shown in figures 4.19-20. The various stages of the construction are shown in figures 4.21-23.

Figure 4.19 Side couplers   &   Side couplers holding Bamboo and sails

Figure 4.20 Mounting sails on rotor

Figure 4.21 Rotor with two sails & Rotor with four sails

Figure 4.22 Rotor with six sails & Rotor with eight sails

Figure 4.23 Rotor with sixteen sails

4.8 Safety measures

The following safety measures were taken into consideration during the construction and the operation of windmill.

1. Good lighting conditions, working space and efficient working machines were needed at the workshop.
2. Helmets were worn while working on the mill (considering the size, mounting techniques and materials employed).
3. While working on top of the mill, it was necessary get strapped to the support to prevent accidental fall.
4. Workers were well-dressed with shoes, gloves, helmets, goggles, etc.
5. Only few people were made fully responsible for the use and maintenance of the mill. This ensures proper and regular maintenance.
6. If breaking the mill was necessary, it was done gently and not suddenly as sudden breakage might damage it.
7. Before putting the mill into operation each time, all parts were lubricated with oil and grease. The principle was, "lubricate often with a little grease rather than seldom with a lot".
8. All bolted connections were checked periodically.
9. Neglect of or attack on wood and metal was prevented by impregnating with compounds, (tar products or pain).

10. Holes were always drilled for bolted connections.

11. Fair-size washers were always used under the heads of the bolts and nuts when joining parts, especially, to prevent damage to the woody parts.

12. Provide a fair set of hand tools. Good tools are half the job (nothing is more annoying than working with blunt and defective tools).

13. People were kept away from beneath the mill when work was carried out on it (falling parts or tools could have injured people underneath). A tool box was attached to the tower to help put away tools (Van de Van, 1977).

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research sought to design a vertical axis wind turbine rotor using bamboo together with metal and construct the designed wind turbine rotor.

The designed Sixteen Sail vertical axis wind turbine rotor with a net mechanical power available of 46.803 W has been constructed. This bamboo-mat Sixteen Sail Windmill was locally made using the local materials, skills and tools. The durability and reliability of the windmill was ensured by using quality and chemical-resistant materials.

The aerodynamic design and dimensions of the Sixteen Sail Windmill rotor makes it possible for the wind which should have been expelled on one half of the rotor to be redirected into the open sails behind resulting in a higher torque.

The construction was done in an area of very low wind regime and the general performance of the Sixteen Sail Windmill rotor was found to be satisfactory. At relatively moderate speed of 6 m/s the pump will be able to produce at least 13 liters/sec for 300 people for a locality like Mankuaze, in the Central Region of Ghana, which is a typical agricultural farming / rural setting. This output will correspond to a daily domestic water requirements for about 300 people on the average.

The Sixteen Sail Windmill rotor system is suitable for small scale wind energy conversion in regions with better wind regimes. The beauty of the Sixteen Sail Windmill rotor is that it can also be coupled to a hybrid system to alternate between its usage for electricity generation or water pumping. This is very important, because it further enhances the energy resources of the rural-based communities.

The ease of construction and design modification of the Sixteen Sail Windmill rotor meant that the system is well suited for technological transfer to rural-based community groups or organisations working in developing countries, and at the end of the learning period, the rural people would have sufficient skills to enable them to continue with the maintenance and further innovation on the design.

The whole project was estimated to cost about US$ 3,000. Though the new design was expected to be cheap (less than US$ 1,000), the mode of acquisition of the materials and the fact that this was a new technology made it rather expensive. Materials were not purchased in bulk, transport was not readily available and sourcing of the bamboo mat made it look expensive.

It is expected that the total cost of construction for subsequent windmills will reduce significantly to about US$ 1,000 each.

Although it is capital intensive, this technologies will be one of the most cost-effective renewable energy wind pumps in terms of the cost per water pumped in very low wind regimes.

5.2 Recommendations

The following recommendations have been arrived at to enable further research works to be carried out:

It is recommended that testing must be carried out for further research works to be done on the windmill. This is required to check any defects in the static structural strength design calculation and to reveal any unusual effects which may lead to unexpected failure.

Financial support in purchasing materials for the project was a very big challenge. Due to the fact that materials were not bought in bulk to reduce cost, the project became too expensive.

Therefore financial support must be given to wind energy research by KNUST to enable the research works on windmill be completed as scheduled.

The project has revealed several applications of Bamboo in windmill, especially in the construction of the rotor assembly. Therefore bamboo cultivation in Ghana must be considered as a priority for more economic benefits.

Wind power generation is a potential source of cheap power provision, especially in remote and rural areas. The government should consider this option and train more technicians in the field of wind power generation for use in irrigation and mechanised bore hole water.

The windmill is surrounded by obstacles such as trees and buildings. It is recommended that the windmill be moved to a location where obstructions are less so that suitable and meaningful study can be conducted on the windmill.

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