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ORIGINAL RESEARCH ARTICLE

DEVELOPMENT OF A WINDMILL FOR PUMPING WATER USING POSITIVE DISPLACEMENT PUMP

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ABSTRACT

The abundant renewable energy sources have not been harnessed for electricity and other uses to date. Wind speed is high in the Northern part of Nigeria and therefore require utilization so as to reduce the use of harmful non-renewable energy sources. In this work wind energy was used to drive a windmills that provide mechanical energy directly for a borehole with a positive displacement pump with a 2.5ft stroke. The design analysis of the wind mill was carried out numerically based on the wind data collected. The proposed design were fabricated using designed dimensions. The rotary motion of the shaft were converted to a linear motion using slider-crank mechanism. The designed horizontal axis windmill has 3 blades has three blades driving the shaft. Also the kinematic modelling of the mechanism was carried out. The assembled windmill was tested and was found to have an operated efficiency of 58.2%.

1.0 Introduction

Energy is considered as one of the most important resources of any country, especially if it will be used to supply water. It is noteworthy that high rate of industrial growth of any country is a function of the amount of energy available in that country and the extent it is utilized. Nigeria is an energy-resource rich country blessed with fossil resources such as crude oil, natural gas, coal and renewable energy resources like solar, wind and biogas. Windmill use wind speed to turn a blade designed in a particular shape to rotate a shaft. The torque in the shaft can be amplified for a particular user or the motion of the shaft may be converted to other forms of motion such as linear in this case as the windmill operates a positive displacement pump. The mean wind speed ranges in Northern and Southern Nigeria were found to lie between 4.0 - 7.5 m/s and 3.0 - 3.5 m/s, respectively at 10 m above the ground (Oluseyi 2010). Also, Idris, *et al.* (2012) has reported that fourteen (14) State in Northern Nigeria have high wind energy resources capable for generating over 50 MWh/year. This implies that rural areas and farms in Northern Nigeria can rely on wind power for water supply and their electricity supply.

Wind is generated due to various global phenomena such as 'air-temperature difference' associated with different rates of solar heating. Since the earth's surface is made up of land, desert, water, and forest areas, the surface absorbs the sun's radiation differently. Locally, a strong winds is created by sharp temperature difference between the land and the sea (Raja, *et al* 2006). The capacity to generate the required electricity in Nigeria is dropping with time due to numerous challenges such as equipment age, poor management, weather. Therefore, there is inadequate supply of electricity to all sectors of Nigeria. The present technology especially the energy sources (for pumping water uses petrol or diesel engine) are not sustainable principally due to environmental impact. The use of wind energy is more reliable in areas without tall structure to obstruct the flow of wind current and that can be potentially use for pumping water. Therefore, a windmill provides the best way of harnessing this wind power and using it to operate positive displacement pump. The potential application of the research work is in the commercial farms, which are located at rural areas were wind energy is hardly adulterated with pressure from traffic and other activities in urban area.

2.0 Materials and Method

2.1 Description of the Windmill for Pumping Water

Figure 1, shows the schematic of the wind mill under design, it is a mechanical structure utilizing wind power to produce a torque large enough to operate a positive displacement water pump via a slider-crank mechanism. The force of the wind against the blades causes a crank system (which consists of a crankshaft and counterweights) attached to the shaft to rotate. The positive displacement pump which is connected to the shaft via the crank mechanism reciprocates as the blades rotate, and thus creates suction, which transfer water from the water level to the earth surface. The amount of power that can be obtain from a windmill is proportional to the rotors swept area and available wind speed.

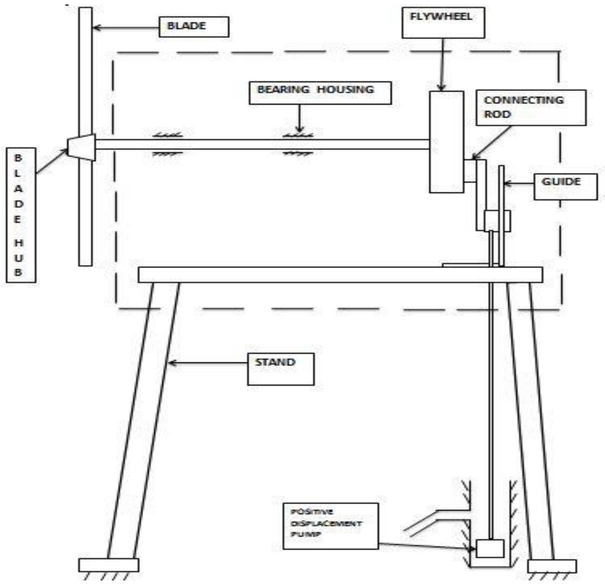


Figure 1: Schematic Diagram of the Windmill Water Pump.

2.2 Materials Used

The components selected for the fabrication of the windmill are;

Table 1: List of the Components of Windmill & the Material Selected.

S/No	Component	Specification/ Material
1	Blade	R1.2m , 1mm thickness/ Al-sheet
2	Blade hub	Ø170mm /Al-alloy (casted)
3	Shaft	19mm diameter stainless steel pipe
4	Flywheel	Ø300 x 10mm, Mild Steel
5	Links	4mm thickness/Al –alloy plate
6	Plunger	Ø20mm Stainless steel pipe
7	Top frame	1" x 1" Rectangular Pipe/Mild-steel
8	Tower Structure	2" x 2" Equal Angle/Mild-steel
9	Displacement pump	Al-Alloy

2.3 Methods

The procedure used for the development of this windmill for pumping water using a positive displacement pump are the design analysis and synthesis, kinematic modeling and fabrication stages.

2.3.1 Design Analysis and Calculations

A. Design Requirement

The design requirement for windmill for pumping water include:

i. The mean wind speed of 4.3m/s
ii. Min. pumping power displacement.
iii. Pump head of 2-2.5ft (positive displacement pump).
iv. Min. Pump thrust >91N).
v. Diameter of the Pump, (25.4mm).

B. Blade design

According to data obtained from WASCAL-FUT Minna, Minna has air maximum wind speed of 8.3m/s and minimum of 0.3m/s. the average of the maximum and minimum forms the basis of the design. Blade utilizes wind power to generate a rotating motion. The shape of the blade adopted is shown in Figure 2.

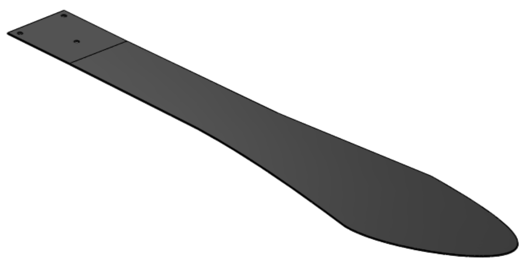


Figure 2: Isometric view of the blade

Mass of the blade, Mb = 0.169 kg (obtained from the CAD software).
Density (ρb) - 2700 kg/m³
Thickness of blade - 1 mm

The shape of the blade is in the form of a trapezium, and the area of a trapezium is given by;

$$A_b = \frac{1}{2}(A + B)\,X\,l = \frac{1}{2}(0.06 + 0.12)\,X\,0.8 = 0.072m^2 \quad (1)$$

The pump area were computed from equation 2;

$$A_p = \frac{\pi}{4}{D_p}^2 \quad (2)$$

Where; A_p = area of the pump (m^2).
D_p = diameter of pump (25.4 m).

$$A_p = \frac{\pi}{4}\,X\,0.0254^2\;5.067\,X\,10^{-4}\,m^2$$

Therefore, the volumetric flow rate was calculated using equation 3;

$$Q = A_p v = 5.067\,X\,10^{-4}\,X\,4.3 = 2.179\,X\,10^{-3}m^3/s \quad (3)$$

Where; v = mean wind speed (m/s)

The blade swept area (A_s) given in equation 4, was obtained by equating the actual power (source) to the Hydraulic power (source).

$$A_s = \frac{\rho_w gHQ}{0.5 \text{ X } \rho \text{ X } v^3} \quad (4)$$

$$A_s = \frac{1000 \text{ X } 9.81 \text{ X } 0.762 \text{ X } 1.14 \text{ X } 10^{-3}}{0.5 \text{ X } 1.23 \text{ X } 2.25^3} = 1.2\text{m}^2$$

where: P_w = wind power (W)
C_p = coefficient of power (W)
H = pumping head (m)
v = mean wind speed (m/s)
C_p = power coefficient
ρ = density of air (kg/m^3)
ρ_w = density of water (kg/m^3)
Q = volumetric flow rate (m^3/s)

For a Horizontal Axis Wind Turbine (HAWT), the swept area is circular, (i.e. the area cover as the blade rotates). Thus, from the equation 2, the area of a circle was used to calculate the radius of the rotor, which is 0.6 m. and therefore the angular speed (ω) of the blade was obtained from the wind speed data (average wind speed from wind data 4.3 m/s) as given by equation (5).

$$\omega = \frac{v}{R} = \frac{4.3}{0.6} = 7.167 \text{ rad/s} \quad (5)$$

Hence; the wind power were calculated using equation 6;

$$P_w = \frac{1}{2}\rho A_s v^3 = \frac{1}{2} \text{ X } 1.23 \text{ X } 1.2 \text{ X } 4.3^3 = 117.53 \text{ watts} \quad (6)$$

Hence, the theoretical torque (T_t) is given by;

$$T_t = \frac{P_w}{\omega} = \frac{117.53}{7.167} = 16.37 \text{ Nm} \quad (7)$$

2.3.1.3 Tip Speed Ratio

The tip speed ratio is defined as the relationship between rotor blade velocity and relative wind velocity. The dimensions are calculated using equation 8 (Ronak, et al. 2015);

$$\lambda = \frac{\omega R}{v} = \frac{7.167 \text{ x } 0.6}{4.3} = 1 \quad (8)$$

2.3.1.4 The coefficient of starting torque

The coefficient of starting torque is given as;

$$C_{T_{start}} = \frac{1}{2\lambda^2} = 0.5 \quad (9)$$

Where; $C_{T_{start}}$ = coefficient of starting torque
λ = design tip speed ratio

Coefficient of power or the efficiency of the windmill is calculated from

$$C_p = C_T . \lambda = 0.5 \quad (10)$$

Hence, the efficiency of the windmill is 50 %.

2.3.1.5 Calculation of blade setting angle (φ)

According to (McCosker 2012) a wind turbine blade is divided into seven (7) equal segments with a step of 0.23 m. The blade setting angle can be obtained;

$\varphi = \frac{2}{3}\tan^{-1}\frac{1}{\lambda_r}$ (11)

where, $\lambda_r = \frac{\lambda_d \mathrm{X}\, r}{R}$ (12)

where:
φ = blade setting angle (degree)
λ_r =mean of the local tip speed ratio
λ_d = design tip speed ratio
r = radius at each stations of the blade (m)
R = rotor radius (m)

2.3.1.6 Shaft Design

The windmill shaft shown in Figure 4, connects the rotating blades and the pump drive mechanism and it is subjected to combined bending (due to the weight of the blade, hub e.t.c) and twisting moments (due to wind load). According to (Khurmi and Gupta 2008), the equivalent twisting moment for this kind of loaded is given by equation 13 and 14;

$T_e = \sqrt{(K_m \times M)^2 + (K_t \times T)^2}$ (13)

And; $T_e = \frac{\pi}{16} \mathrm{X}\, \tau \, \mathrm{x}\, d^3$ (14)

Where;
K_m = combined shock and fatigue factor for bending
K_t = combined shock and fatigue factor for twisting
τ = maximum shear strength of mild steel (N/m^2)
d = shaft diameter (mm)
M = maximum bending moment (Nm)
T = torque developed (Nm).

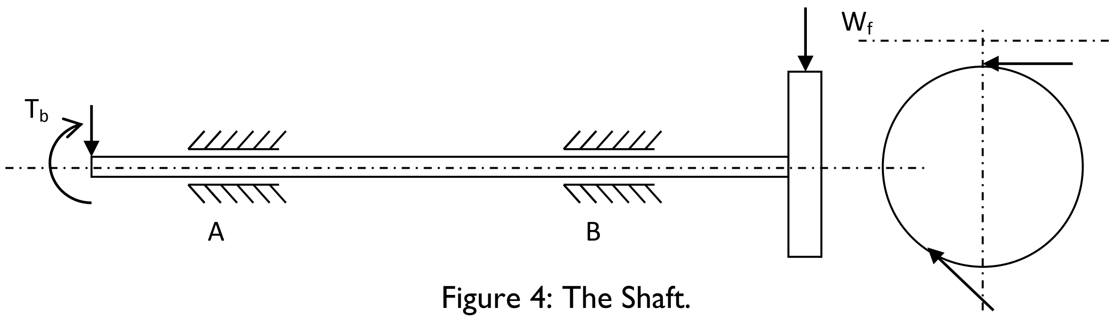


Figure 4: The Shaft.

Considering the equilibrium of the shaft, the Max. Bending moments (M) is 20.1Nm. Therefore the equivalent twisting moment from equation 14 is;

$$T_e = \sqrt{(K_m \times M)^2 + (K_t \times T)^2} = \sqrt{(1.5 \times 20.1)^2 + (1.0 \times 31.53)^2} = 43.63\mathrm{Nm}$$

And the diameter of the shaft from equation 14 is;

$d = 0.0164\ \mathrm{m} = 16.4\ \mathrm{mm}\ (\approx 20\ \mathrm{mm\ or}\ 25.4\ \mathrm{mm}).$

2.3.1.7 Force Acting on the Plunger.

Recall from eqn. (7) that the torque rotating the shaft T_t = 16.37 Nm is the torque required to turn the flywheel. Hence, the force acting on the flywheel (radius of the flywheel chosen as 0.15 due to space constraint).

$$F = \frac{T_w}{r} = \frac{16.37}{0.15} = 109.2 \text{ N}. \qquad (15)$$

Torque required to turn link 1;

$$T_{l1} = F_w \times (r + x) = 109.2 \times (0.15 + 0.097) = 27 \text{ Nm} \qquad (16)$$

Force acting on link 1

$$F_{l1} = \frac{T_{l1}}{a} = \frac{27}{0.255} = 105.74\, N \qquad (17)$$

Resolving the Fl1 along x-axis gives the force acting on link 2,

$F_x = F_{l1}\cos\theta = 105.74 \text{ x} \cos(45) = 74.76 \text{ N}$

2.3.1.8 Determination of the Plunger Diameter

For long slender columns where the slenderness ratio (L/k) is greater than a certain value, buckling of the column is predicted if the calculated axial stress (σ_{axial}) is greater than the critical stress (σ_{cr}) given in equation (18), called the Euler Buckling formula. (Egbe, et al. 2016)

$$\sigma_{cr} = \frac{C_{ends}\pi^2 EI}{l^2} \qquad (18)$$

The plunger is fixed at both ends, hence C_{ends}= 4, (Alkali, et al. 2016).

$$\frac{4 \times \pi^2 \times 2 \times 80 \text{ x } 10^8 \times I}{3.35^2} = 74.76$$

$\therefore I = 1.328 \text{ x } 10^{-9}$

The minimum safe diameter of the plunger is;

$$r = \left(\frac{I \times 4}{\pi}\right)^{\frac{1}{4}} = \left(\frac{4 \times 5.02 \times 1328 \text{ x} 10^{-9}}{3.142}\right)^{0.25} = 0.006412\, m\ (i.e\ 6\, mm\ \approx 10\, mm\ will\ be\ safe)$$

The minimum plunger diameter is 10 mm solid pipe.

2.4 Kinematics of the Mechanism

The mechanism used to transform the rotary motion from the shaft to the linear reciprocating motion for the pumping energy is shown in Figure 5, it is a modified slider crank mechanism with the plunger connected to it.

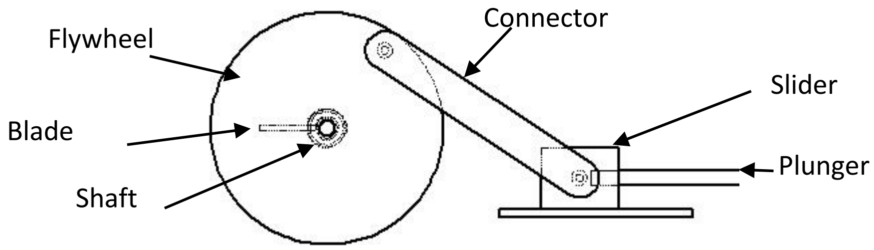


Figure 5: Modified Slider-Crank Mechanism.

The kinematics characteristics of the mechanism are presented in equation 19-23. These equations were derived from the closed loop equation for the mechanism in figure 5 are presented in equation 19 and this were used to obtain the position, velocities and acceleration of the mechanism. The close loop equation was expanded and separated into real and imaginary parts for the determination of the unknown quantities such as angular velocity and angular acceleration of the connector (L_2) and linear velocity and acceleration of the slider (L_4).

$$R_2 + R_3 - R_4 = 0 \tag{19}$$

The angular position of the connector (L_3) is given in equation 20 and 21.

$$\theta_3 = sin^{-1}\left(\frac{L_2}{L_3} sin\theta_2\right) \tag{20}$$

Also the position of the slider (L_4);

$$L_4 = L_2 cos\theta_2 + L_3 cos\theta_3 \tag{21}$$

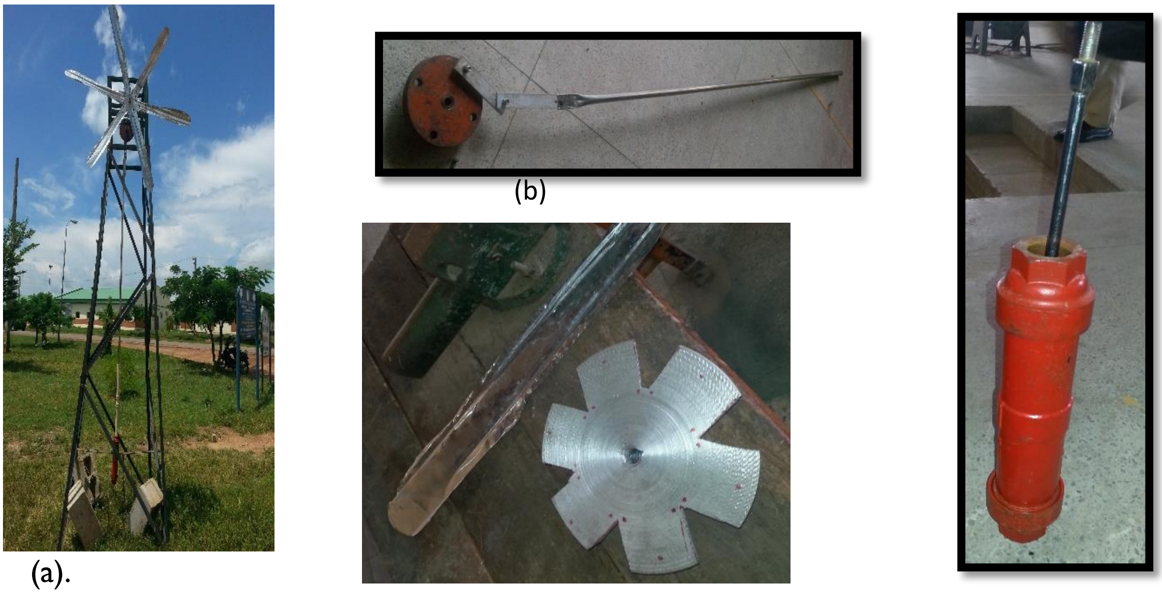
The velocities equation and acceleration equation of the connector and the slider are given by equations 22-23.

$$\begin{bmatrix} -L_3 sin\theta_3 & -1 \\ L_3 cos\theta_3 & 0 \end{bmatrix} \begin{bmatrix} \omega_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} L_2 sin\theta_2 \omega_2 \\ -L_2 cos\theta_2 \omega_2 \end{bmatrix} \tag{22}$$

$$\begin{bmatrix} -L_3 sin\theta_3 & -1 \\ L_3 cos\theta_3 & 0 \end{bmatrix} \begin{bmatrix} \alpha_3 \\ a_4 \end{bmatrix} = \begin{bmatrix} L_2(sin\theta_2 \alpha_2 + cos\theta_2 \omega_2^2) + L_3 cos\theta_3 \omega_3^2 \\ -L_2(cos\theta_2 \alpha_2 + sin\theta_2 \omega_2^2) + L_3 sin\theta_3 \omega_3^2 \end{bmatrix} \tag{23}$$

2.5 Fabrication and Assembly

The designed components were produced and assembled as shown in Figure 6. The blades were produced from a 1 mm Al-alloy sheet, the hub was casted and machined to dimensions.



(a). (b) (c) (d)

Figure 6: Fabricated Components, (a) Assembled Windmill (b) Flywheel and Links Mechanism. (c) Blade and Hub, (d) Positive Displacement Pump.

3.0 Results and Discussion

3.1 Mechanical Design

The summary of the mechanical design results of the components are presented in Table 2. This includes minimum safe dimensions as that were used in the fabrication of the windmill water pump.

Table 2: Dimensions of the Blade Design

Description of Parameter	Calculated Values	Unit
1. Blade		
Base length	60	mm
Top length	120	mm
Height of blade	800	mm
Minimum Thickness	1	mm
Area of blade	1.2	m^2
Diameter of blade	1.2	m^2
Tip speed	1	
2.Shaft		
Diameter of shaft	15	mm
Maximum bending Moment	20.1	Nm
Maximum Torsional moment	31.23	Nm
Length of Shaft	500	mm
3. Flywheel		
Diameter	300	mm
Thickness	15	mm
Mass of Disc	2.88	kg
Torque required to rotate disc	210.2	Nm
4. Connector		
Mass	0.06	kg
Force	203.61	N
Area	0.03	m^2

The windmill for pumping water was constructed using the design results in Table 2. The result for the blade angle setting is presented in Table 3.

Table 3: Blade setting angle

S/N	r (m)	λd	R (m)	λr	φ
1	0.23	1.66	0.6	0.6363	38.36
2	0.46	1.66	0.6	1.2727	25.44
3	0.69	1.66	0.6	1.909	18.43
4	0.92	1.66	0.6	2.5453	14.30
5	1.15	1.66	0.6	3.1817	11.63
6	1.38	1.66	0.6	3.818	9.78
7	1.6	1.66	0.6	4.4267	8.79

The variation of blade angle with blade length is presented in Figure 7. It can be seen from the Figure that the blade angle decreased with increase in blade length.

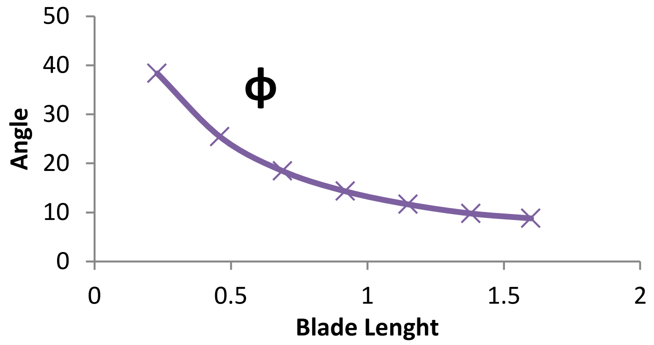


Figure 7: Blade Setting Angle

3.2 Kinematic Modelling

The kinematic model equations of the slider-crank mechanism (presented in equations 23 – 29) were graphically presented in Figure 8. From Figure 8, the blade rotates steadily completes half revolution on less than 0.5 sec, also the wind drives the blade to attain an angular speed of about 50 rad/sec (2.5m/s) and an acceleration of 25 m/s^2 in less than 0.3 sec. the wind velocity of 4.3 m/s give a maximum plunger velocity of 2.5 m/s (58.2% mechanism efficiency).

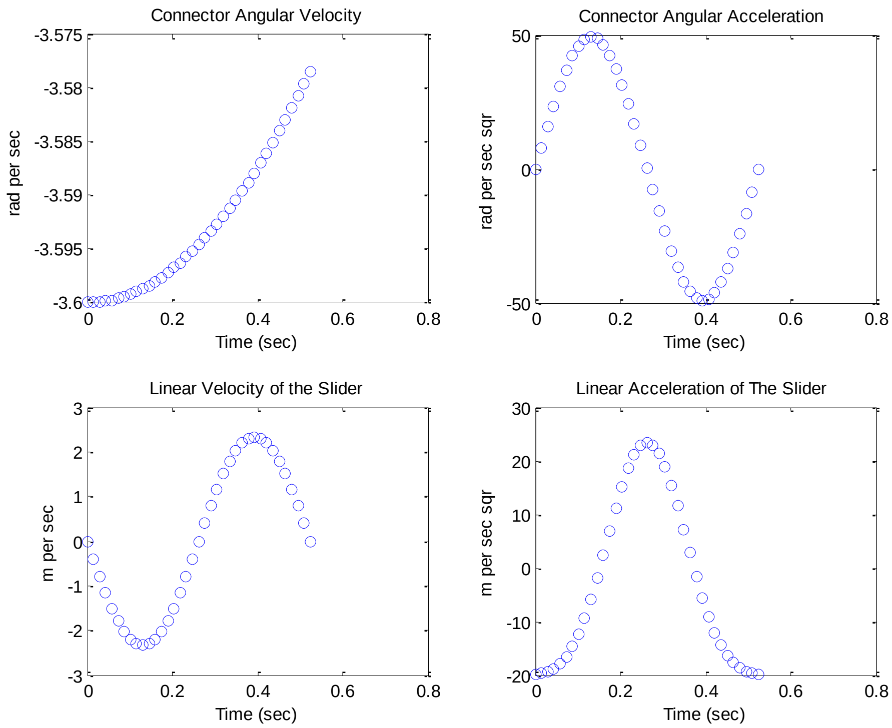


Figure 8: Kinematic Analysis.

4.0 Conclusion

This study designed a windmill that can operate a positive displacement pump for pumping water from a borehole. A modified slider-crank mechanism was used to convert the rotary motion from the wind into a linear motion required to operate a positive displacement pump. The analysis and synthesis of the forces acting in the components of the windmill were carried out. Also, the kinematic analysis of the mechanism was performed in order to estimate the maximum speed and acceleration of the slider mechanism during operation. This research will be more beneficiary in the rural areas where strong wind speed is available to operate the mechanism. This design can be used to replace the hand operated pump water borehole widely used presently in the rural area for water supply.

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