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Development of Improved Dual-Purpose Fitness Bike for Electricity Generation

Arinola B. Ajayi[1*], Frank N. Okafor[2]

1. Dept. of Mechanical Engineering, Faculty of Engineering, University of Lagos, Lagos. Nigeria.
2. Dept. of Electrical and Electronics Engineering, Faculty of Engineering, University of Lagos, Lagos. Nigeria.

*Corresponding Author: Tel: +234-802 319 6439, E-mail: abajayi@unilag.edu.ng

Abstract

This research work is on development of dual purpose fitness bike for electricity. It is aimed at improving electricity generated during cycling exercise and reducing the dependence on fossil fuels and its attendant emissions of green house gases especially carbon dioxide, this can eventually lead to reduction in the risk of global warming. In recent times, attempts have been made to harvest energy generated from human powered fitness bicycles and convert it to electricity. The existing fitness bicycle designs were unable to generate feasible electricity that can compensate for the considered financial investment. Therefore, the existing fitness bicycle designs were analyzed and improvements needed in the area of energy conversion were noted and carried out. With this improved dual-purpose fitness bike, the electrical power output of an average adult at an average speed of 60 rpm of cycling is about 3, 500 watts in one hour, as against 150W – 250W reported in the literature. This is an equivalent of 1.3 MW of electricity in one year which equals about 307,442 litres of carbon dioxide emission cut back in one year. This is considered a substantial improvement of electricity generation over the electricity generated by retrofitted fitness bicycles design already in existence.

Keywords: Electricity generation; Fitness bicycle; Fossil fuels; Global warming; Green house gases.

Nomenclature

a number of conductors parallel paths in the alternator
$\mathbf{a}_t, \mathbf{a}_s, \mathbf{a}_f$ acceleration of thigh, shank and foot segments respectively
$\boldsymbol{F}$ Force
i stands for subscript t, s, and f, thigh, shank and foot segments respectively
I_a armature current, which is dependent on machine parameters
l_1, l_2, l_3 length of thigh, shank and foot segment respectively
l_4 crank arm length
l_5, l_6 horizontal and vertical distances respectively of the seat from the crank spindle
p number of poles in the alternator
P_E gross output power
T_E electromagnetic torque produced by the alternator
Tm mechanical torque produced by the fitness bike
$\boldsymbol{r_p}$ position vector of the pedal during cycling session
z number of conductors in the armature
$\theta_1, \dot{\theta}_1, \ddot{\theta}_1$ thigh angle, angular velocity and angular acceleration respectively
$\theta_2, \dot{\theta}_2, \ddot{\theta}_2$ shank angle, angular velocity and angular acceleration respectively
$\theta_3, \dot{\theta}_3, \ddot{\theta}_3$ foot angle, angular velocity and angular acceleration respectively
$\theta_4, \dot{\theta}_4, \ddot{\theta}_4$ crank arm angle, angular velocity and angular acceleration respectively
ω alternator armature angular velocity
Φ flux per pole
η efficiency of the system

1. Introduction

Human energy, such as energy generated during exercises, is a low density renewable energy which requires appropriate technology to harvest effectively [1]. Electrical energy that can be generated during cycling fitness session is not an exception. In order to overcome this limitation, an improved fitness bike is needed to be well designed to effectively harvest energy expended during cycling exercise and convert it to electricity that can justify the investment on it. Although, moving bicycles had always been fitted with dynamos (3W) to generate electricity needed at night by their riders, the limitations are (1) the electricity generated is small and (2) electricity generation stops the moment the bicycle riding stops. In the past, many researches had been carried out on cycling, while in recent times, due to escalating prices of crude oil and renewed concern for environmentally friendly alternative sources of energy, more researches are being carried out in this area to produce substantial amount of electricity worth the effort, investment and time input [2-8]. Also, attempts are being made to harvest electricity from human powered fitness bicycles in Fitness Clubs [9]. In a study carried out by Stuart Wilson [10] at Oxford University, an average person is capable of producing between 150 watts and 250 watts of power during cycling session. In the light of fore going, there is need to improve on the existing fitness bikes in other to deliver substantial amount of electricity worth the effort, investment and time input. The objective of this paper is to present the mathematical model (kinematics) of the pedaling motion, the improved fitness bike that can be used for electricity generation while exercising and electricity generated with it during pedaling session.

2.0 Methodology

2.1 Mathematical Model of the Pedaling Motion

The schematic of the leg, the bicycle diamond frame with crank arm, the coupling and the alternator is shown in Fig. 1. The leg-crank arm-bicycle frame is modeled as a five-bar planar linkage system with four numbers of active links and one inactive link. The system is assumed to be revolute rigid bodies in planar motion with frictionless pinned joints. This is a two degree of freedom problem. The configuration of the model will depend on two coordinates θ_3, and θ_4. From Fig.1 below, we can write the position vector of the pedal represented by its spindle in two ways, (1) using the leg segments, and (2) using the bicycle frame with the crank arm of the pedal. This gives rise to Eq.1a and Eq.1b.

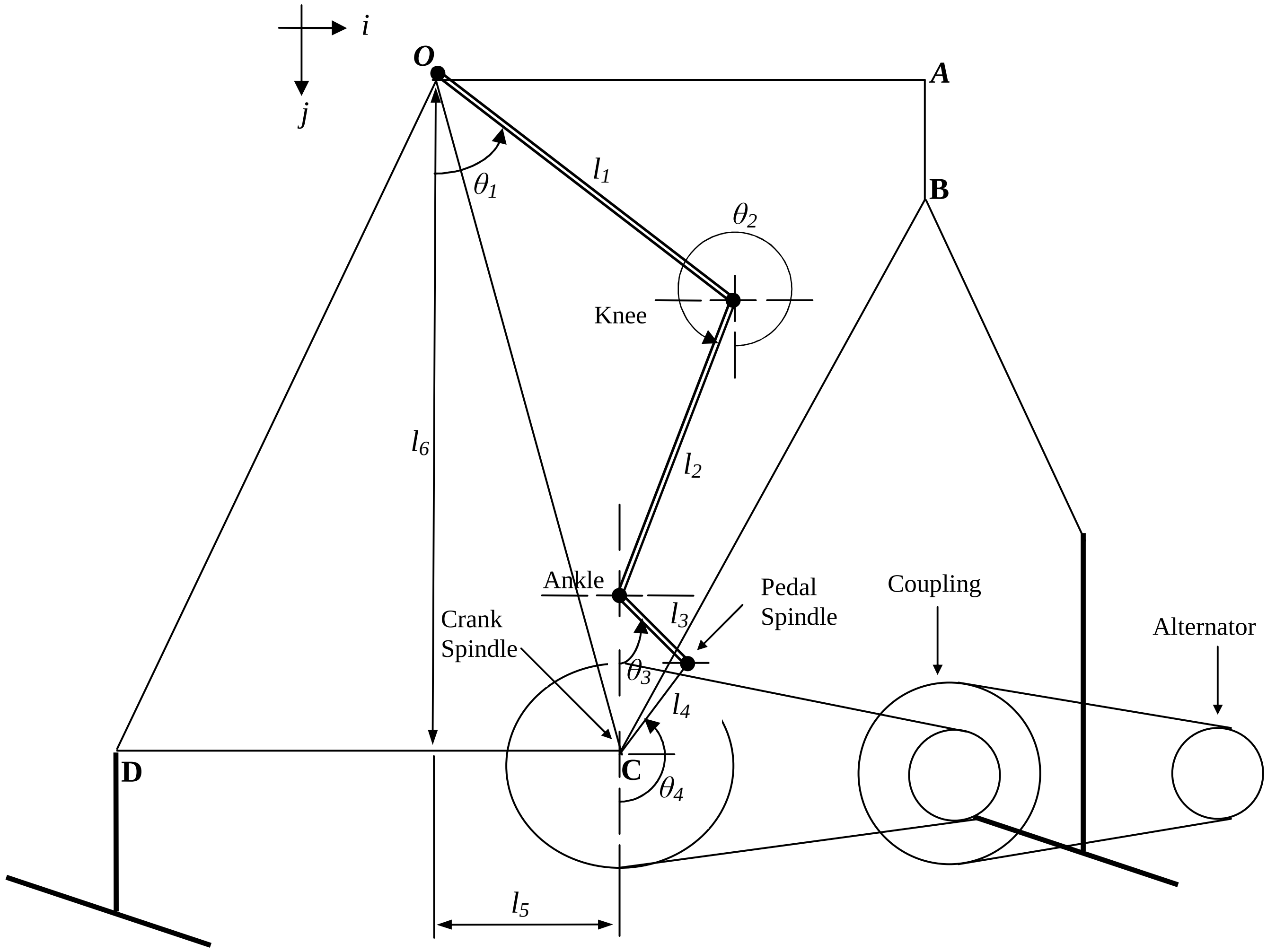

Fig 1: Schematic of the leg, bicycle diamond frame, coupling and alternator

$$\mathbf{r}_p = (l_1 \sin\theta_1 + l_2 \sin\theta_2 + l_3 \sin\theta_3)i - (l_1 \cos\theta_1 + l_2 \cos\theta_2 + l_3 \cos\theta_3)j \tag{1a}$$

$$\mathbf{r}_p = (l_6 \sin\pi + l_5 \sin\frac{\pi}{2} + l_4 \sin\theta_4)i - (l_6 \cos\pi + l_5 \cos\frac{\pi}{2} - l_4 \cos\theta_4)j \tag{1b}$$

Differentiating Eq.1a and Eq.1b above twice and simplifying will give the expression for the acceleration of the leg segments, and given as Eq.2a, Eq.2b, and Eq.2c.

$$\ddot{\theta}_1 = \frac{\left\{\begin{array}{l}\left\{\begin{array}{l} l_2\dot{\theta}_2^2 \cos\theta_2 + l_1(\dot{\theta}_1^1 \cos\theta_1) + l_3\ddot{\theta}_3 \sin\theta_3 \\ + l_3\dot{\theta}_3^2 \cos\theta_3 - l_4\ddot{\theta}_4 \sin\theta_4 - l_4\dot{\theta}_4^2 \cos\theta_4 \end{array}\right\} l_2(\cos\theta_2) \\ -\left\{\begin{array}{l} l_1\dot{\theta}_1^2 \sin\theta_1 - l_2\dot{\theta}_2^2 \sin\theta_2 + l_3\dot{\theta}_3^2 \sin\theta_3 \\ - l_3\ddot{\theta}_3 \cos\theta_3 - l_4\dot{\theta}_4^2 \sin\theta_4 + l_4\ddot{\theta}_4 \cos\theta_4 \end{array}\right\} l_2(-\sin\theta_2)\end{array}\right\}}{(-l_1 \sin\theta_1)(-l_2 \cos\theta_2) - l_1(\cos\theta_1) l_2(-\sin\theta_2)} \tag{2a}$$

$$\ddot{\theta}_2 = \frac{\left\{\begin{array}{l} l_1(-\sin\theta_1)\left\{\begin{array}{l} l_1\dot{\theta}_1^2 \sin\theta_1 - l_2\dot{\theta}_2^2 \sin\theta_2 + l_3\dot{\theta}_3^2 \sin\theta_3 \\ - l_3\ddot{\theta}_3 \cos\theta_3 - l_4\dot{\theta}_4^2 \sin\theta_4 + l_4\ddot{\theta}_4 \cos\theta_4 \end{array}\right\} \\ - l_1(\cos\theta_1)\left\{\begin{array}{l} l_2\dot{\theta}_2^2 \cos\theta_2 + l_1(\dot{\theta}_1^2 \cos\theta_1) + l_3\ddot{\theta}_3 \sin\theta_3 \\ + l_3\dot{\theta}_3^2 \cos\theta_3 - l_4\ddot{\theta}_4 \sin\theta_4 - l_4\dot{\theta}_4^2 \cos\theta_4 \end{array}\right\}\end{array}\right\}}{(-l_1 \sin\theta_1)(-l_2 \cos\theta_2) - l_1(\cos\theta_1) l_2(-\sin\theta_2)} \tag{2b}$$

$$\ddot{\theta}_3 = \frac{\left\{\begin{array}{l} l_3\sqrt{\left(1 - \left(\frac{l_4}{l_3}\sin\theta_4\right)^2\right)}\left(l_4\left[\dot{\theta}_4 \sin\theta_4\right]\right) \\ + \left(\left(l_4\dot{\theta}_4 \cos\theta_4\right)^2\left[1 - \left(\frac{l_4}{l_3}\sin\theta_4\right)^2\right]^{-1/2}\right)\end{array}\right\}}{l_3^2\left(1 - \left(\frac{l_4}{l_3}\sin\theta_4\right)^2\right)} \tag{2c}$$

The force developed by the lower limb segments is given in Eq.3. below

$$\mathbf{F} = m_t\mathbf{a}_t + m_s\mathbf{a}_s + m_f\mathbf{a}_f = \sum_{i=1}^{i=3} m_i\mathbf{a}_i \tag{3a}$$

$$\mathbf{F} = m_t\ddot{\theta}_1 + m_s\ddot{\theta}_2 + m_f\ddot{\theta}_3 \tag{3b}$$

The mechanical torque Tm, developed at the pedal spindle

$$T_m = \mathbf{F}(l_4 \sin\theta_4) \tag{4a}$$

$$T_m = l_4 \sin\theta(m_t\ddot{\theta}_1 + m_s\ddot{\theta}_2 + m_f\ddot{\theta}_3) \tag{4b}$$

2.2 The Development of the Dual –purpose Fitness Bike

The dual-purpose fitness bike can be constructed by modifying an adult bicycle by removing the front and the back tyres and replacing them with specially designed stands to fit into the frame constructed for the purpose. The crank wheel of the bike is connected to the alternator through a coupling system. The coupling system is a reducing/increasing gearing system that has one velocity ratio of 25. The whole assembly is placed on a frame constructed from a 2” by 1” pipe to form a rigid base. The alternator is connected to the load through inverter/charger system which connects to the battery bank for the storage of electrical power.

2.3 Electricity Generated during Cycling Session

Mechanical power generated by the Fitness Bike is transferred to the alternator to generate electricity through the coupling system as shown in Fig. 2.

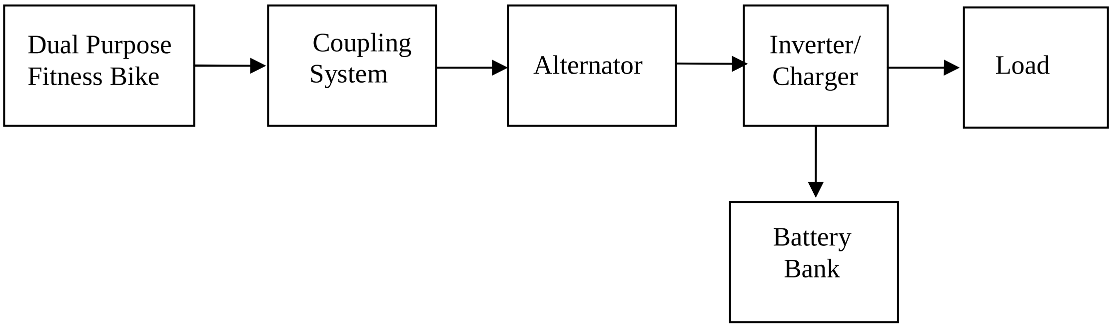

Fig 2: Block diagram of Dual-purpose fitness bike for electricity generation.

Mechanical Power, P_m, developed at the crank spindle is

$$P_m = T_m \dot{\theta}_4 \quad (5)$$

Electrical power, P_E, generated by the alternator is given by:

$$P_E = EI_a \quad (6)$$

where $E = \frac{pz}{2\pi a}\Phi\omega$

It follows therefore that

$$P_E = \frac{pz}{2\pi a}\Phi\omega I_a = T_E\omega \quad (7)$$

$$T_E = \frac{P_E}{\omega} = \frac{pz}{2\pi a}\Phi I_a = GI_a \quad (8)$$

Where $G = \frac{pz}{2\pi a}\Phi$

From Eq.8, it is observed that,

i) For a particular machine with a set of alternator parameters, if the number of poles *p*, number of conductors in the armature, *z*, and the number of parallel paths, *a* are kept constant, electromagnetic torque, T_E, is proportional to armature current, I_a,

ii) Therefore, to increase the electromagnetic torque, T_E, its is either need the number of poles *p* are increased, and/or the number of conductors in the armature, *z*, are increased and/or the number of parallel paths, *a*, are decreased.

In order to relate the mechanical power input to the electrical power output of the system, the efficiency, η, of the system shown in Fig. 1 is considered. The efficiency is the ratio of mechanical advantage (M.A.) of the system which is defined as the ratio of load to effort [11a] and velocity ratio which is the ratio between the velocities of the driver and the follower (driven) [11b].

$$\therefore \eta = \frac{M.A}{V.R.} \times 100\% \quad (9)$$

where

$$M.A. = \frac{Load}{Effort} = \frac{Electromagnetic\ Torque}{Mechanical\ Torque} = \frac{T_E}{T_M} \quad (10)$$

and

$$V.R = \frac{\text{distance moved by effort}}{\text{distance moved by the load in same time}} = \frac{\dot{\theta}_4}{\omega} \quad (11)$$

$$\therefore\ M.A = \frac{Load}{Effort} = \eta \times V.R \quad (12)$$

$$Load, T_E = Effort, T_m \times V.R \times \eta = T_m \times V.R \times \eta \quad (13)$$

From Eq.13, it can be said that

i) Load output, T_E, is directly proportional to the effort, T_m, if velocity ratio, V.R., and efficiency, η, are kept constant.

ii) Load output, T_E, is directly proportional to velocity ratio, V.R., if the effort, T_m, and efficiency, η, are kept constant.

Equating Eq.8 and Eq.13 and simplifying, we have,

$$I_a = \left[\frac{\eta \times V.R.}{G} \right] T_m \tag{14}$$

From Eq.14 it can be concluded that,

i) Mechanical torque input, T_m, is directly proportional to armature current output, I_a, for a particular experimental configuration.

ii) For a particular alternator, increasing velocity ratio and or transmission efficiency will increase the output armature current.

3.0 Results and Discussions

Table 1 below shows the value used for the parameter studies. Fig. 3 below is the plot of mechanical torque against crank arm rotation and the average torque developed is 85.44 Nm. The output power measure during this session is about 3, 500W pedaling at an average of 60 rotations per minute. The curve below in Fig. 3 is sinusoidal with no negative torque.

Table 1: Values for Parametric studies

S/N	DESCRIPTION	SYMBOLS	VALUES USED
1	Length of thigh segment	l_1	0.393m
2	Length of shank segment	l_2	0.433m
3	Length of foot segment	l_3	0.203m
4	Length of crank arm	l_4	0.170m
5	Horizontal distance between hip and crank axis	l_5	0.212m
6	Vertical distance between hip and crank axis	l_6	0.693m
7	Estimated mass of thigh segment	m_1	7.36kg
8	Estimated mass of shank segment	m_2	3.27kg
9	Estimated mass of foot segment	m_3	1.05kg
10	Alternator		5,000W
11	Input speed		60rpm
12	Output speed		1500rpm

Fig. 3 shows that the power generated by the left leg is greater than the right leg. The power is almost zero at 0^0 and 180^0 while peaked at 90^0 and 270^0. The power generated by the two legs is additive and 180^0 out of phase.

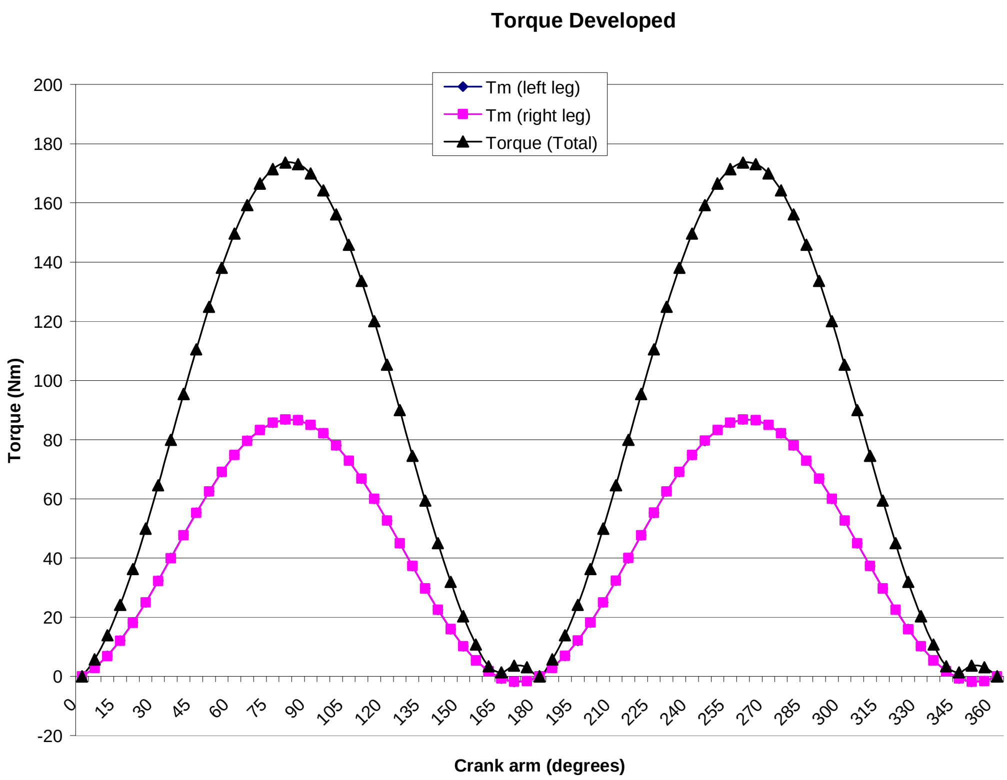

Fig 3: Mechanical Torque Developed by both legs

4.0 Conclusions

In this paper, the mathematical model of the pedaling motion, the improved dual-purpose fitness bike and electrical energy generated during cycling session has been presented. It was discovered that electricity generated during cycling session can be improved upon by changing the alternator parameters. And the output electricity generated with this fitness bike is about 1000% improvement over the existing ones. This amount of electrical energy produced thus is an equivalent of 1.3 MW of electricity in one year which equals about 307,442 litres of carbon dioxide emission cut back in one year. This is considered a substantial improvement of electricity generation over the electricity generated by the retrofitted fitness bicycles design already in existence with design production power output of between 150 watts and 250 watts for a single fitness bike. The quantum of electricity generation can always be improved upon over time thus justifying the investment of money and time on this type of exercise bikes.

4.0 Acknowledgement

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