Design and Analysis of a Solar Operated Lawn Mower

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***Abstract*—The majority of lawn mowers available in the market are either fuel or electrically operated. Both sources of energy demand high operational and maintenance costs, and they are not environmentally friendly. This paper proposes the design and fabrication of a simple solar operated lawn mower. Its blade cutting operation is based on the scotch yoke mechanism. All other components are also presented. In addition, the necessary calculations of converting solar energy into electrical energy are done, as well as the calculations on the battery capacity and time needed to charge. The 3D CAD prototype is created, and the structural analysis to check stresses and deflections at critical locations on frame and blades of the lawn mower is performed by using SolidWorks© software. Structural analysis results show that the maximum stress on the frame is 0.34 MPa, and on the blades it is 0.82 MPa, both which are less than the yielding stress. Furthermore, the deflection at critical location on frame is 0.108mm and on blades it is 1.33 mm respectively. Those results have been compared to analytical calculations and good agreement was found. As a conclusion, this design demonstrates that a simple, efficient and sustainable solar operated lawn mower can be produced at minor costs.**

***Keywords*—lawn mower, scotch yoke mechanism, structural analysis, battery charging and working time, solar power, deflection, Von Mises stress**

I. INTRODUCTION

Lawn mowers are nowadays indispensable for maintaining the grass in gardens, playing yards, etc. A typical lawn mower cuts the grass at equal lengths by using one or more cutting blades. The concept of lawn mowers is not new. In 1830, Edwin Budding developed the first lawn mower prototype. It was made of cast iron with a cutting cylinder with several blades in the front and a large roller on the rear. As it had no motor, a gear wheel was used to transmit power to the cylinder blades from the roller [1]. Since then, there has been a rapid development in the lawn mower design. This covered the cutting mechanism, size and components, and the source of power as well.

The cutting mechanism in most of the lawn mowers is composed of one or more blades. In some available mechanisms, the wheels are mechanically attached to the cutting blades in such a way that when the mower is moved in forward direction, the blades will start spinning and thus the cutting process will begin [2].

Regarding the size, small lawn mowers only require human strength to travel across the surface. Walk-behind mowers are self-propelled, but they need a human to guide them. Bigger lawn mowers are either self-propelled according to the walk-behind style, or they are more commonly ride-on mowers that are designed to allow the user to ride and operate them [3].

The available lawn mowers in the market are either electric powered (corded with limited range, or cordless with chargeable batteries) [4], or fuel powered with a gasoline engine [5]. Both demand high maintenance and operational costs and pollute the environment. Furthermore, electric powered lawn mowers are dangerous and can’t be safely operated [6]. Some of their designs are very complicated for elderly. This includes, for example, automatic robotic lawn mowers [7], lawn mowers with image recognition [8], smart programmable lawn mowers [9].

Nowadays, the use of solar energy to generate power is gaining more interest due to the high cost of conventional energy sources (electrical, fuel, etc.). Furthermore, the awareness towards reducing environmental pollution is increasing among the public as well. The implementation of solar power as driving force in operating lawn mowers is not new. However, all the designs available in literature focused more on the application of recent and complicated technologies in the cutting operations, rather than the analysis of the lawn mower itself as a mechanical device. This made it complicated for elderly or even unexperienced people to operate such innovative designs due to complexity of the mechanisms that were proposed by researchers as in [10–13].

The current work proposes a simple but effective, user-friendly design of a solar operated lawn mower that can be easily used by elderly or inexperienced people. All the necessary calculations for estimating the needed motor torque and power, as well as for the battery size and time to charge the batteries are performed. Finally, a structural analysis is carried out on SolidWorks© to demonstrate the effectiveness of the structure and numerical results are compared to analytical results where good agreement is deduced.

Manuscript received September 9, 2022; revised November 14, 2022; accepted January 4, 2023.

doi: 10.18178/ijmerr.12.3.169-174

II. PROPOSED DESIGN AND COMPONENTS' SELECTION

In this section, the proposed design of a solar lawn mower is presented with all its components. These components are explained in detail as well.

A. CAD Design

The computer-aided (CAD) design is produced by using SolidWorks© and it is presented in Fig. 1. The frame is made of carbon fibers which have high strength and low weight. The solar panel (in blue) is adjustable on the roof of the lawn mower. The lawn mower has two handles for easier handling. The cutting blades operate according to the scotch-yoke mechanism [14]. One blade will swing while the other blade is fixed. The height of the blades from the ground is adjustable through a manual arm. This gives the operator the freedom to choose the desired height of grass, which is not always the case in conventional lawn mowers. As already mentioned in the previous section, the DC motor is located directly above the blades, and it takes its power from the battery which is charged through the solar panel. The charge controller is located directly below the solar panel.

B. Components Selection

All the items that are selected for the design are very common in the market and can be purchased easily on Amazon [15] or Alibaba [16].

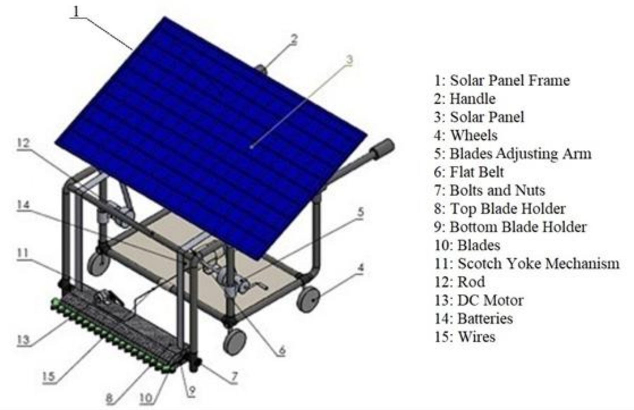

Figure 1. The proposed 3D CAD design of the solar lawn mower

The battery, for instance, is chosen because of its light weight and high quality and is presented in Fig. 2. It is a Lithium-Ion battery of type BiXPower3694 with 36V, 8.4Ah and 300W·h capacity.

Figure 2. The BiXPower 36V Battery [15]

As for the solar panel, a RNG-300D 300-Watt Monocrystalline solar panel was chosen because its dimensions are the most suitable for the proposed solar lawn mower design.

Regarding the motor, a brushless DC motor was selected. It has a power of 1000 Watts and a rotational speed of 1500 rpm. It operates at a voltage of 48 Volts and an operating current of 28A [16].

The justification of those selections is presented through calculations in the next section. The Bill of Quantity (BOQ) for the proposed design is presented in Table I. The total cost of all components is 1100 USD.

TABLE I. THE BOQ OF THE PROPOSED DESIGN

Item no.	Item name (Quantity)	Description	Material
1	Solar panel frame (1)	$1900\times1000\times600mm^3$	Carbon fiber
2	Handle (1)	Φinner = 40mm	Rubber
3	Solar panel (1)	$1650\times977\times40mm^3$	-
4	Wheel (4)	D = 150mm	Rubber
5	Arm for lifting blade system (1)	D = 81mm	Carbon fiber
6	Flat belt (1)	Width = 50mm, Thickness = 3mm	Rubber
7	Bolt and nut (12)	Bolt: M6 Nuts: Φ6	Ai 1350 alloy
8	Top blade holder (1)	$900\times200\times53mm^3$	Carbon fiber
9	Bottom blade holder (1)	900×200×29mm3	Carbon fiber
10	38 teeth blades (1)	980×80×10mm3	Carbon fiber
11	Yoke mech. (1)	L = 40mm	Carbon fiber
12	Rod (1)	L = 1000mm	Al 1060H12
13	DC motor (1)	Power = 1000W, 48V, 1500rpm	Stainless steel
14	Batteries (1)	400W, 48V	Li-ion
15	Wires (1)	L = 5000mm, Thickness = 3mm	Cupper

III. RESULTS AND DISCUSSIONS

This section includes all the necessary calculations that are needed for the proposed design. Firstly, the kinematics of the scotch yoke mechanism are studied. Then, the needed motor torque and power are calculated. The battery running and charging time are determined. Finally, the properties of the solar panel are investigated and its use for selected battery and motor is verified.

A. Kinematics of Scotch Yoke Mechanism

The Scotch Yoke mechanism translates rotary movement into linear movement or opposite as shown in Fig. 3. It is implemented here to convert the rotary motion of the motor into a linear motion of the upper movable blade. Thus, the upper blade will have one translational degree of freedom only. The lower blade is fixed so that the cutting process can occur throughout the relative motion of the upper blade with respect to the lower blade.

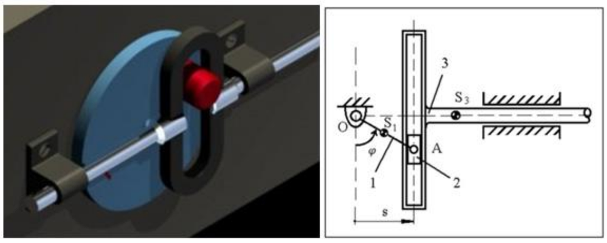

Figure 3. Schematic of the scotch yoke mechanism (left) and a 2D view (right)

The corresponding equations will be firstly presented, and then all the required parameters will be calculated.

The translational motion of the upper blade is described through Eq. (1):

$$S = L_{OA} \times \sin \varphi \qquad (1)$$

S : Displacement of scotch yoke and thus of the blade [m]

L_{OA} : Length of the arm connecting the motor shaft at O to the scotch yoke at A [m]

φ : Angle between the arm and the vertical axis [rad]

The velocity of the blade is the derivation of displacement over time:

$$dS/dt = d\varphi/dt \times L_{OA} \times \cos \varphi \qquad (2)$$

dS/dt : Velocity of scotch yoke and thus of blade [m/s]

dφ/dt : Angular speed of the blade [rad/s]

$$d\varphi/dt = (2 \times \pi \times n)/60 \qquad (3)$$

n : Rotational speed [rpm]

Similarly, the acceleration is the derivation of the blade velocity over time:

$$d^2S/dt^2 = L_{OA} \times d^2\varphi/dt^2 \times \cos \varphi - L_{OA} \times (d\varphi/dt)^2 \times \sin \varphi \qquad (4)$$

$d^2\varphi/dt^2$: Acceleration of the scotch yoke and thus of the blade [m/s²]

The first term of Eq. (4) is zero as the angular speed is constant and its derivative will become zero.

In the proposed design, L_{OA} = 0.04 m, a typical lawn mower motor rotational speed is 1500 rpm at full load, and the maximum torque occurs at φ = π/4 (this is verified in the next subsection):

$$S = 0.04 \times \sin (\pi/4) = 0.028 \text{ m}$$

$$d\varphi/dt = (2 \times \pi \times 1500)/60 = 157 \text{ rad/s}$$

$$dS/dt = 157 \times 0.04 \times \cos \pi/4 = 4.44 \text{ m/s}$$

$$d^2S/dt^2 = - 0.04 \times 157^2 \times \sin \pi/4 = -697.12 \text{ m/s}^2$$

The minus value here means that there is a deceleration at this value of the angle φ.

B. Motor Torque and Power Needed

According to [17], the input torque of scotch yoke mechanism is expressed as:

$$T_{in} = [1/(d\varphi/dt)] \times [d(K.E.)/dt] \qquad (5)$$

T_{in}: The input torque of the scotch yoke (same as motor torque if friction is ignored) [N·m]

K. E.: Total kinetic energy of the mechanism [Joule]

According to the same reference above, the total kinetic energy of the mechanism in Fig. 3 is derived as:

$$K.E. = 0.5 \text{ x } (d\varphi/dt)^2 \times (I_{S1} + m_1 r^2_{S1} + m_2 L^2_{OA} + m_3 L^2_{OA} \cos^2\varphi) \qquad (6)$$

I_{S1}: Axial moment of inertia of link 1 [kg.m²]

m_i : Masses of the corresponding links (i=1, 2, 3) [kg]

r_{S1} : Distance between the centre of the joint O and the centre of mass S1 of link 1 [m]

Substituting the equation of total kinetic energy in the equation of input torque gives:

$$T_{in} = 0.5 \times m_3 \times L^2_{OA} \times (d\varphi/dt)2 \times (-\sin 2) \qquad (7)$$

The angle φ which yields maximum torque (T_{max}), is calculated by setting $d(T_{in}/d\varphi) = 0$

This will give (cos2φ = 0), and thus, φ = π/4

From the CAD drawing, the mass m_3 = 0.2 kg.

The maximum input torque is expressed as:

$$T_{max} = -0.5 \times 0.2 \times 0.042 \times (157)^2 \times \sin \pi/2 = -3.94 \text{ N·m}$$

The motor power needed for the lawn mower can be calculated as:

$$H_1 = |Tmax| \times d\varphi_1/dt \qquad (8)$$

H_1 : Power needed of motor (Watts)

$$H_1 = 3.94 \times 157 = 619 \text{ Watts}$$

As already mentioned in the previous section, a 1000 Watts power and 1500 rpm rotational speed brushless DC motor is selected. It operates at a voltage of 48 Volts and has an operating current of 28 Amperes.

In that case, the factor of safety (F.O.S.) of the motor is expressed as:

$$F.O.S. = H_{allowable} / H_{nominal} = 1000 / 619 = 1.61 > 1 \text{ (safe)}$$

The motor efficiency is the ratio of the output mechanical power over the input electrical power:

$$Efficiency = H_{out} / H_{in} = H_{allowable} / V \times I \qquad (9)$$

V : Voltage of the selected motor [48 V]

I : Operating current of the selected motor [28 A]

C. Battery Selection

The battery stores the solar power during the daytime to be used later while operating the lawn mower. Thus, it will provide a constant source of stable and reliable power. The choice of the battery depends basically on the voltage and operating current of the motor that it will run. It should have the same voltage of the DC motor, otherwise more than one battery could be connected in series to reach the necessary voltage [18].

For that reason, a 48 V lithium battery has been selected. According to the manufacturer's manual, its capacity (CP) is 342 amperes hour [Ah] and its efficiency is about 90%.

Now, the running time of the battery is calculated based on the operating current of the selected motor and considering the efficiency of the battery as:

Running Time (RT) = [(battery capacity × battery efficiency) / (motor_operating_current / motor efficiency)] (10)

$$RT = [(342 \times 0.9)/(28 \times 0.744)] \approx 8.2 \text{ hours}$$

This means, the battery will feed the selected motor with the necessary power up to 8.2 hours before it needs to be recharged.

The electric power used over time by considering all losses is measured as:

EP = Motor_Voltage × CP × battery efficiency × motor efficiency (11)

EP : Electric power used by the battery [kWh]
CP : Capacity of the selected battery [kAh]

$$EP = 48 \times 0.342 \times 0.9 \times 0.744 \approx 11\text{kWh}$$

D. Solar Panels Selection

The solar panel converts the sunlight into electricity as direct current (DC). Monocrystalline solar panel though more expensive, yet it is very efficient compared to polycrystalline.

As for the solar panel, a panel with a rated power of 300 W, 36 V and monocrystalline type is selected. According to the manufacturer data, it is compatible with all voltages ranging between 12–72 Volts.

The time needed to charge the battery to 50% of its capacity as always recommended by the battery manufacturer is calculated as:

$$t = (0.5 \times CP \times V) / (SP \times 2) \tag{12}$$

t: Time needed to charge 50% of the battery from solar panel [hours]

V : Voltage of battery [volts]

SP : Solar panel power [watts]

$$t = (0.5 \times 342 \times 36) / (300 \times 2) = 10.26 \text{ hours}$$

IV. Structural Analysis

During the design of any engineering product, structural analysis is one of the significant phases. The product must be able to withstand operating loads for its intended task. In other words, the system's structural integrity must be guaranteed [19]. SolidWorks© was used for modeling the developed design due to its effectiveness [20]. For simplicity, 4-node tetrahedral finite elements were used for modeling the frame and the blades. The frame was modeled by using 5481 finite elements. For each blade, there were 9104 finite elements. The 3-D model of the frame is presented in Fig. 4.

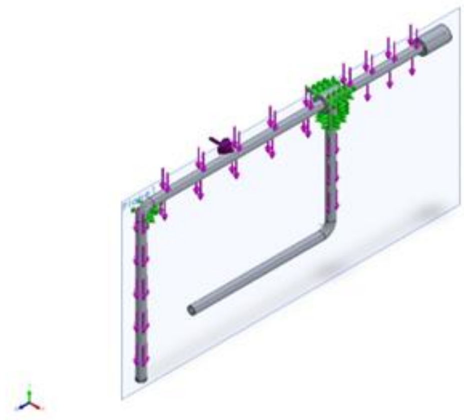

Figure 4. The 3D model at the frame.

A finite element size of 10mm was used to create the mesh. As for the material, carbon fiber was selected for the frame due to its' excellent tensile properties and low density. It has a density of 2000kg/m^3 and a yielding strength of 2500MPa [21]. The maximum deflection is 0.108mm at the location of the blades as shown in Fig. 5.

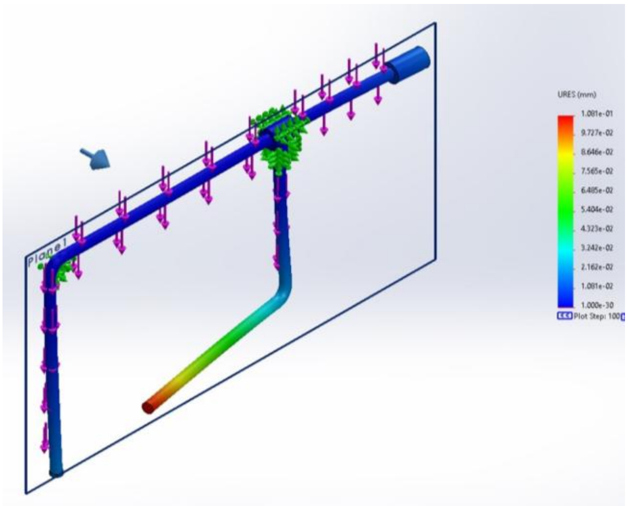

Figure 5. Displacement at the frame.

To validate the deflection results at the location of the blades, the analytical solution could be found by considering the frame as a cantilever beam as presented in Fig. 6.

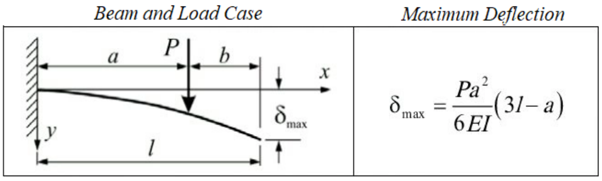

Figure 6. Deflection formula of a cantilevered beam [22].

From the CAD drawing, the dimensions are a = 350mm, L = 450mm, and the load P represents the weight of 1 blade (37kg). The frame holds the weight of fixed and movable blades. Since only one side is considered, then P = 37 × 9.81 = 362.97N.

The frame has a diameter of 40mm. Its moment of inertia I = 126 × 10^{-9} m^4.

By using the equation in Fig. 6, the maximum deflection is found to be 0.118mm.

Comparing analytical results to numerical results from SolidWorks, the percentage error is:

% error = |(analytical–numerical)/analytical| × 100 (12)
= |(0.118 – 0.108)/0.118| × 100 = 8.47%

The maximum VonMises stress was found in SolidWorks to be 0.37MPa at the location of maximum bending moment as shown in Fig. 7. This value is much below the yielding stress and thus the design is safe. No validation of results could be made here due to the complexity of the stress calculation at critical locations of the frames and of the blades in the next part.

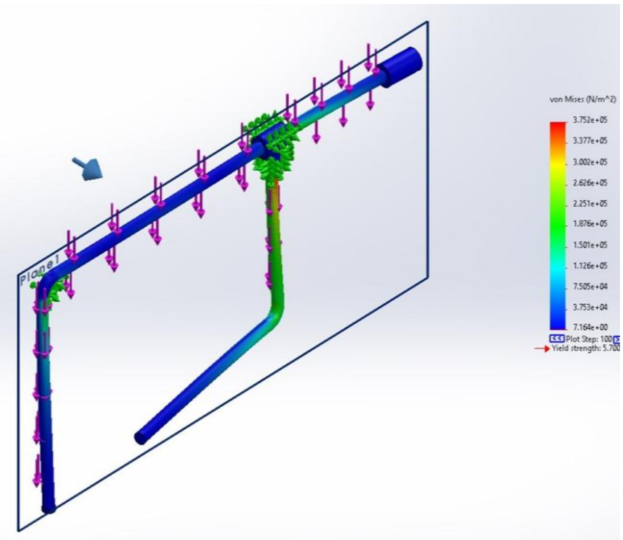

Figure 7. VonMises stress at the frame.

As for the blades, they were made of standard galvanized steel with density of 7850kg/m^3, a young's modulus of 200GPa, and yielding strength of 250MPa [23]. The maximum deflection was found to be 1.47mm in the middle of the blade as depicted in Fig. 8.

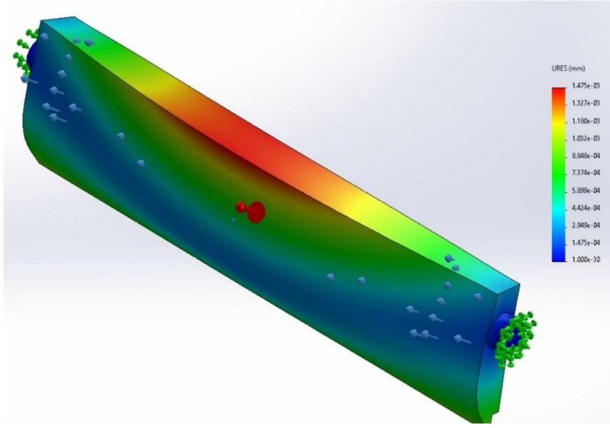

Figure 8. Displacement at the blade.

To validate the numerical results from the software, the analytical value of the calculation will be calculated. Both blades can be considered as a single simply supported beam with the weight of both blades as a concentrated load in the middle as presented in Fig. 9.

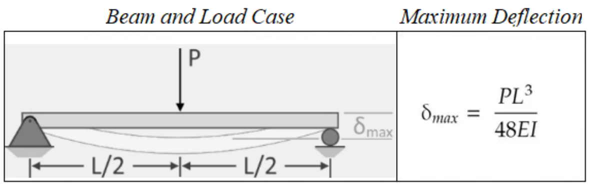

Figure 9. Deflection formula for a simply supported beam [22].

From the CAD design, each blade has dimensions 980mm × 80mm × 10mm. The weight of both blades is 37kg × 2 × 9.81m/s^2= 725.94N.

The moment of inertia I will be I = b × h^3/12 = 53.34mm^4 where b is the blade width (80mm) and h is the thickness of both blades together (20mm).

Applying equation in Fig. 9 gives the analytical value of deflection to be 1.33mm.

By comparing analytical results to numerical results from SolidWorks and using (12), the percentage error is:

% error = (analytical – numerical)/analytical × 100 (12)
= |(1.33 – 1.47)/1.33| × 100 = 10.17%

The maximum VonMises Stress was 0.82MPa as seen in Fig. 10.

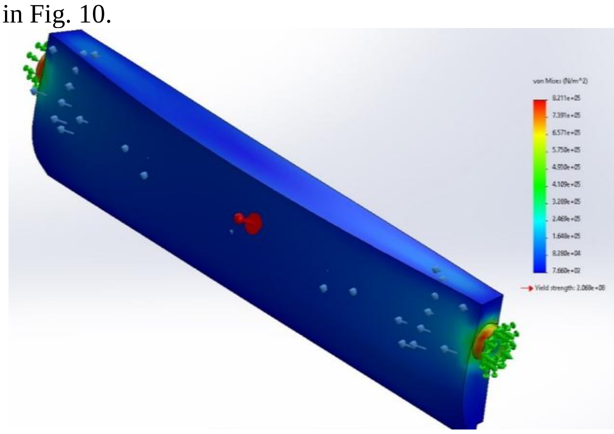

Figure 10. VonMises stress at the blade.

V. Conclusion

The objective of this paper was to design and analyse a simple, environment-friendly solar operated lawn mower. A 3D CAD prototype was initially created, and all components were selected. The necessary calculations that support the selection of the essential components were performed. From those calculations it was concluded that the selected battery needs about 10 hours to charge, and it has a working time of about 8 hours. Structural analysis was carried out on the 3D CAD prototype by using SolidWorks©. The numerical results from structural analysis regarding deflection were compared to numerical calculations and there was a maximum of about 10% difference between both results. Furthermore, the design has proven to be safe, where all stresses were below the yielding stress of the selected material.

Conflict of Interest

The author declares no conflict of interest.

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