VOL. 18, NO. 4, FEBRUARY 2023 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences
©2006-2023 Asian Research Publishing Network (ARPN). All rights reserved.

www.arpnjournals.com

DESIGN AND SIMULATION OF A USER-FRIENDLY SOLAR OPERATED GRASS CUTTING DEVICE

Nader Ghareeb
Department of Mechanical Engineering, College of Engineering, Australian University, Kuwait
E-Mail: n.ghareeb@ack.edu.kw

ABSTRACT

Conventional grass cutting devices are basically operated either by fuel or electrical energy. These are not environment-friendly and, furthermore, they demand high operational and maintenance costs. Encouraging the use of renewable energy resources is essential for sustainability. This paper proposes the design and fabrication of a solar operated lawn mower. Its blade cutting operation is based on the scotch yoke mechanism. The lawn mower components are presented. In addition, all necessary calculations of converting the solar energy into electrical energy are performed, as well as the calculations on the battery capacity needed and the time to charge. Moreover, structural analysis is done to check the strength of the developed frame and of the blades. The 3D CAD prototype is created, and the structural analysis of the lawn mower are performed by using SolidWorks© software. The design and calculations demonstrate that an efficient and sustainable solar operated lawn mower can be produced at minor costs.

Keywords: lawn mower, scotch yoke mechanism, structural analysis, VonMises stresses.

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. Until the 19th century, the scythe was only available option to cut grass up to a certain height. Its simple design comprised a long handle made of wood, with a curved blade attached perpendicularly to the end (Satwik *et al.*, 2015). 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 (Sivagurunathan *et al.*, 2017). Since then, there was 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 (Nagarajan *et al.*, 2017).

Regarding the size, small lawn mowers only require human strength to travel across the surface. Walk-behind mowers is 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 (Dharmik *et al.*, 2021).

The available lawn mowers in the market are either electric powered (corded with limited range, or cordless with chargeable batteries) (Rao, 2014), or fuel powered with a gasoline engine (Schumacher, 2017). Both demand high maintenance and operational costs and pollute the environment.

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 the environmental pollution is increasing among public as well (Bidgar *et al.*, 2017). Although solar power exists long before now, yet it didn't have diverse applications due to other frequently used sources of energy (Akinyemi *et al.*, 2021).

The main objective of this paper is to design and analyse a simple solar operated lawn mower that can be used by many individuals. The implementation of a solar operated lawn mower has many financial and environmental goals. It reduces the long-term costs by eliminating the consumption of fuels and thus the environmental pollution will be reduced as well. The solar lawn mower operates in a way that it uses the radiations from the sun to charge a direct current (DC) battery. This battery then feeds the motor with power, which will enable the rotation of blades for mowing. In other words, the sun radiations during the day light are intercepted by the solar panels. A charge controller is installed between the solar panels and the battery to control the current and voltage flow and charge the battery. Once the battery is charged, it can feed the DC motor with sufficient power so that the lawn mower can operate.

The next section of this paper includes the proposed design and the selection of components, then kinematic and electrical calculations of the proposed design, and finally a structural analysis of the frame. At the end, a conclusion is made.

PROPOSED DESIGN AND SELECTION OF COMPONENTS

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.

ARPN Journal of Engineering and Applied Sciences
©2006-2023 Asian Research Publishing Network (ARPN). All rights reserved.

CAD Design

The computer-aided (CAD) design is produced by using SolidWorks© and it is presented in Figure-1. The frame is made of carbon fibres 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 (Arakelian, 2015). 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 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.

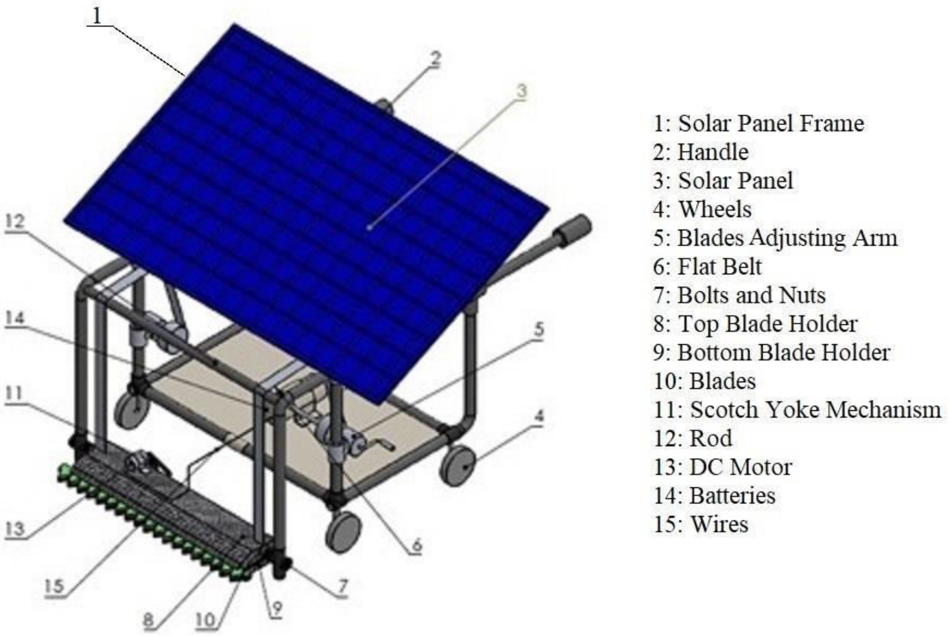

Figure-1. The proposed 3D CAD design of the solar lawn mower and its components.

Components Selection

All the items that are selected for the design are very common in the market and can be purchased easily on amazon.com or alibaba.com.

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

The Bill of Quantity (BOQ) for the proposed design is presented in Figure-3.

Figure-2. The BiXPower 36V battery (from amazon.com).

VOL. 18, NO. 4, FEBRUARY 2023 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences
©2006-2023 Asian Research Publishing Network (ARPN). All rights reserved.

Item number	Item name	Description	Material	Quantity
1	Solar Panel Frame	1900*1000*600 mm	Carbon Fiber	1
2	Handle	Øinner= 40 mm	Silicon Rubber	2
3	Solar panel	1650x977x40 mm	MonoCrystalline	1
4	Wheel	D=150 mm	Rubber +Steel	4
5	Arm for lifting blade system	D=81 mm	Carbon Fiber	1
6	Flat Belt	W= 50 mm Thickness 3 mm	Rubber	2
7	nut and bolt	Bolts=M6 Nuts= Ø6	Al 1350 Alloy	12
8	Top blade holder	900*200*53 mm	Carbon Fiber	1
9	Bottum blade holder	900*200*29 mm	Carbon Fiber	1
10	Blades	980*80*10 mm	Carbon Fiber	38
11	Yoke mechanism	Positioned on Top blade holder L=40mm	Carbon Fiber	1
12	Rod	for connectiong 2 belts L=1000 mm	Al 1060-H12	1
13	DC Motor	P: 1000W Voltage: 48V 1500 RPM	Stainless Steel	1
14	Batteries	400W 48V	-	1
15	Wires	L: 5000 mm Thickness 3 mm	-	1

Figure-3. The BOQ for the proposed design.

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.

The justification of those selections is presented through calculations in the next section.

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 is 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 utilization for the selected battery and motor is verified.

Kinematics of Scotch Yoke Mechanism

The Scotch Yoke mechanism (also known as slotted link mechanism) translates rotary movement into linear movement or opposite as shown in (Figure-4). It is implemented in this project to convert the rotary motion of the motor into a linear motion of the upper movable blade. 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.

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences
©2006-2023 Asian Research Publishing Network (ARPN). All rights reserved.

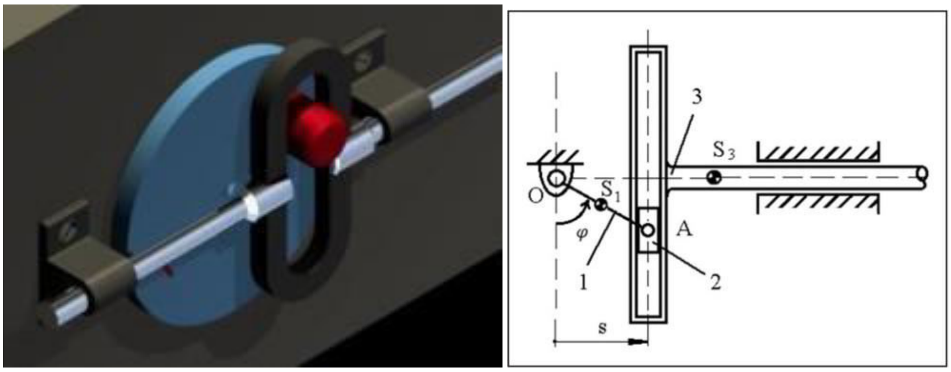

Figure-4. Schematic of the scotch yoke mechanism (left) and a 2-Dimensional.

view (right) All the equations will be firstly presented and then the required parameters will be calculated. The translational motion of the upper blade is described through the following equation:

$$S = l_{OA} \text{ x Sin } \varphi \quad (1)$$

S : Displacement of the 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 the displacement over time:

$$\dot{S} = \dot{\varphi} \text{ x } l_{OA} \text{ x Cos } \varphi \quad (2)$$

$\dot{S}$: Velocity of the scotch yoke and thus of the blade [m/s]
$\dot{\varphi}$: Angular speed of the blade [rad/s]

$$\dot{\varphi} = 2 \text{ x } \pi \text{ x } n/60 \quad (3)$$

n : Rotational speed [rpm]

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

$$\ddot{S} = l_{OA} \text{ x } \ddot{\varphi} \text{ x Cos } \varphi - l_{OA} \text{ x } \dot{\varphi}^2 \text{ x Sin } \varphi \quad (4)$$

$\ddot{S}$: Acceleration of the scotch yoke and thus of the blade [m/s^2]

The first term of the equation 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 $\varphi = \pi/4$ (This is verified in the next subsection):

$S = 0.04 \text{ x Sin } (\pi/4) = 0.028$ m
$\dot{\varphi} = 2 \text{ x } \pi \text{ x } (0.5 \text{ x } 3000)/60 = 157$ rad/s
$\dot{S} = 157 \text{ x } 0.04 \text{ x Cos } \pi/4 = 4.44$ m/s
$\ddot{S} = -\ 0.04 \text{ x } 157^2 \text{ x Sin } \pi/4 = -697.12\ m/s^2$ the minus value in $\ddot{S}$ means that there is a deceleration at this value of the angle φ.

Motor Torque and Power

According to (Berendsohn, 2019), the input torque of the scotch yoke mechanism is expressed as:

$$T_{in} = \frac{1}{\dot{\varphi}} \text{ x } \frac{dK.E.}{dt} \quad (5)$$

Tin : 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 Figure-4 is derived as:

$$K.E. = 0.5 \text{ x } (\dot{\varphi})^2 \text{ x } (I_{S1} + m_1 r^2_{S1} + m_2 l^2_{OA} + m_3 l^2_{OA} \text{ Cos}^2 \varphi) \quad (6)$$

I_{S1} : Axial moment of inertia of link 1[$kg.m^2$]
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 S_1 of link 1[m]

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

$$T_{in} = 0.5 \text{ x } m_3 \text{ x } l^2_{OA} \text{ x } (\dot{\varphi})^2 \text{ x } (-\text{Sin } 2\varphi) \quad (7)$$

The angle φ which yields maximum torque (Tmax), is calculated by setting $\frac{dT_{in}}{d\varphi} = 0$

This gives (Cos 2φ = 0), and thus, $\varphi = \pi/4$ From the CAD drawing, the mass m3 = 0.2 kg. The maximum input torque is expressed as:

ARPN Journal of Engineering and Applied Sciences
©2006-2023 Asian Research Publishing Network (ARPN). All rights reserved.

$$T_{max} = -0.5 \times 0.2 \times 0.04^2 \times (157)^2 \times \sin \pi/2 = -3.94 \text{ N.m}$$

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

H_1: Power needed of motor (Watts)

$$H_1 = |T_{max}| \times \dot{\varphi}_1 \quad (8)$$

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

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:

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

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

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

V : Voltage of the selected motor [48 V]
I : Operating current of the selected motor [28 A]

$$Efficiency = \frac{1000}{48 \times 28} = 0.744 \text{ or } 74.4\%$$

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 battery depends basically on the voltage and operating current of the motor that it will run. It should possibly have the same voltage of the DC motor; otherwise more than one battery could be connected in series to reach the necessary voltage (Amrutesh *et al.*, 2014).

For that reason, a 48 V lithium battery is selected. According to the manufacturer's manual, its capacity (CP) is342 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:

$$Running\ Time\ (RT) = \frac{Battery\ capacity \times battery\_efficiency}{Motor\ operating\ current\ /\ motor\_efficiency} \quad (10)$$

$$RT = \frac{342Ah \times 0.9}{28\,A / 0.744} \approx 8.2 \text{ hours}$$

This means that 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:

$$EP = Motor\_Voltage \times CP \times battery\ efficiency \times motor\ efficiency \quad (11)$$

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

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

Selection of Solar Panel

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:

$$t = \frac{0.5 \times CP \times V}{SP \times 2} \quad (12)$$

t : Time needed to charge 50% of the battery from solar panel [hours]
V : Voltage of battery [volts]
SP : Solar panel power [watts]

$$t = \frac{0.5 \times 342 \times 36}{300 \times 2} = 10.26 \text{ hours}$$

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 (Chang, 2015).

As for the modelling part, and for the sake of simplicity, the frame was modelled as a beam in SolidWorks©. A finite element size of 10mm was used to create the mesh out of volumetric finite elements. The reaction forces at thelocation of the wheels were applied to the model. The blades were modelled as beams for simplicity as well. Concerning the frame which was made of carbon fiber with a density of 2000kg/m3 and a yielding strength of 2500MPa (What is Carbon Fiber, 2022), the maximum deflection is 0.1mm at the location of the blades (Figure-5). However, the maximum VonMises stress was found to be 0.37MPa (Figure-6) at the location of maximum bending moment. This value is much below the yielding stress and thus the design is safe. Here, it must be noted that only one side of the frame was considered due to symmetry.

ARPN Journal of Engineering and Applied Sciences
©2006-2023 Asian Research Publishing Network (ARPN). All rights reserved.

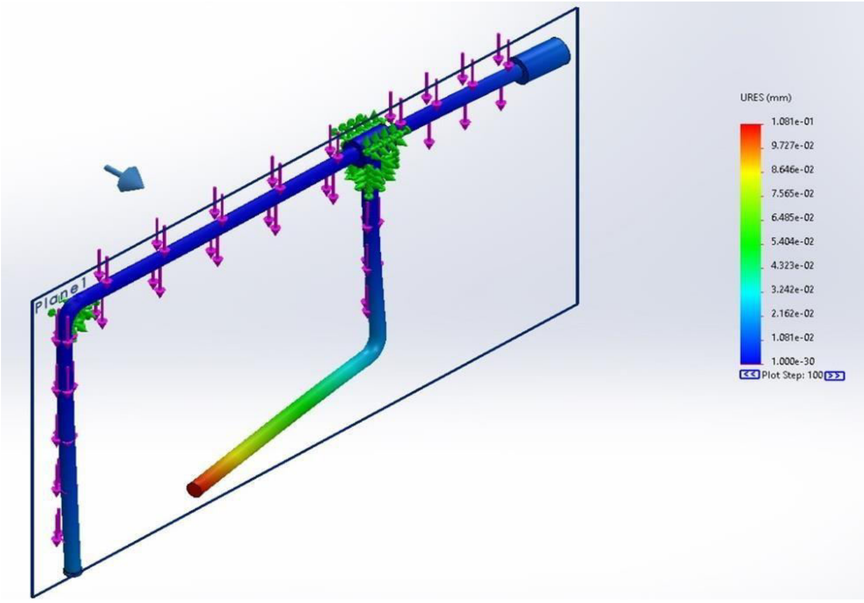

Figure-5. Displacement at the frame.

As for the blades, it was made of standard galvanized steel with density of 7850 kg/m^3 and yielding strength of 250MPa. The maximum deflection was found to be 1.47mm in the middle of the blade (Figure-7), while the maximum VonMises Stress was read to be 0.82MPa (Figure-8). Its location is also at the location of maximum bending moment. This is at the connection between the frame and the blades. The maximum stress is also below the yielding stress for steel, and this indicates that the design is safe too.

CONCLUSIONS

The objective of this work was to design and analyze a user friendly solar operated lawn mower that has no negative impact on the environment. A 3-D CAD prototype was created, and all components were selected. All necessary calculations that support the selection of the components were performed. Structural analysis was carried out on the CAD prototype. The design proved to be safe, and all stresses were below the yielding stress of the material selected.

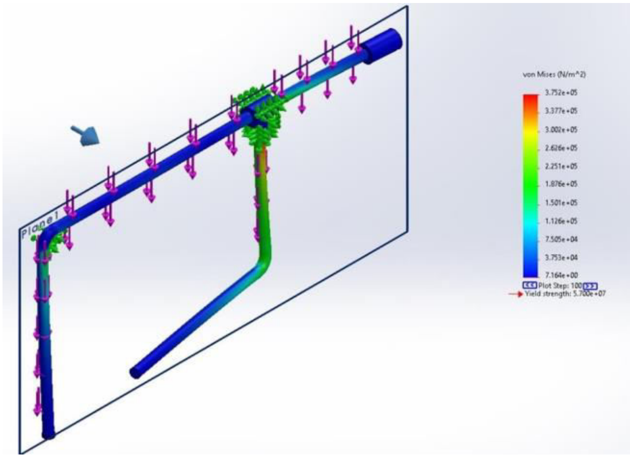

Figure-6. VonMises stress at the frame.

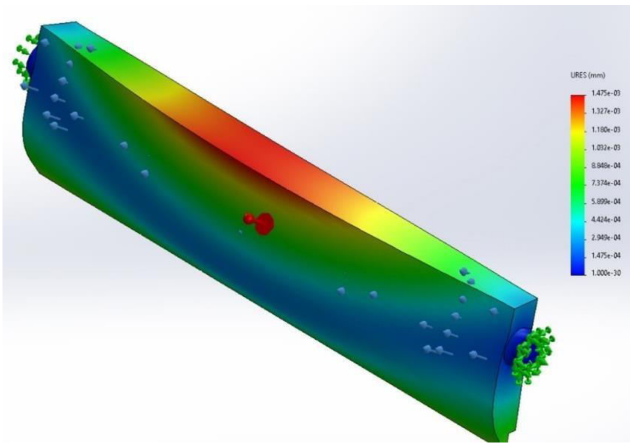

Figure-7. Displacement at the blade.

VOL. 18, NO. 4, FEBRUARY 2023 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences
©2006-2023 Asian Research Publishing Network (ARPN). All rights reserved.

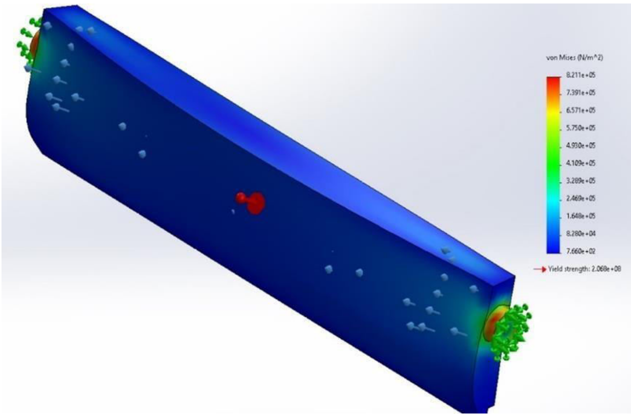

Figure-8. VonMises stress at the blade.

REFERENCES

Akinyemi A., Damilare A. 2020. Design and Fabrication of a Solar Operated Lawnmower, International Journal of Innovative Science and Research Technology. 5(10): 1161-1197.

Amrutesh P., Sagar B., Venu B. 2014: Solar Grass Cutter with Linear Blades by Using Scotch YokeMechanism. Int. Journal of Engineering Research and Applications. 4(9): 10-21.

Arakelian V., Le Baron J. P., Mkrtchyan M. 2015: Design of Scotch Yoke Mechanisms with Improved Driving Dynamics. Proc IMechE Part K. 0(0): 1-8.

Berendsohn R. 2019. Types of Lawn Mowers. Available Online at: https:/www.popularmechanics.com/home/lawn-garden/a26431726/types-of-lawn-mower/, Accessed on July 27, 2022.

Bidgar P., Nikhil P., Vickey U., Sandip W., Sharmila M. 2017. Design and Implementation of Automatic Solar Grass Cutter. International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering. 6(4): 2433-2437.

Chang K. H. 2015. e-Design. Academic Press, USA

Dharmik G., Dhruvik M., Dixit P. Rakesh D., Dhaval D. 2020: Solar Based Grass Cutter, Project Report, Government Polytechnic, Himatnajar-383001, India.

Nagarajan N., Sivakumar N., Saravanan R. 2017: Design and Fabrication of Lawn Mower. Asian Journal of Applied Science and Technology. 1(4): 50-54.

Rao K. P., Rambabu V., Rao K. S., Rao D. V., 2014: Mobile Operated Lawnmower. International Journal of Mechanical Engineering and Robotics Research. 3(4): 107-117.

Satwik D., Rao N. R., Reddy G. S. 2015: Design and Fabrication of Lever Operated Solar Lawn Mower and Contact Stress Analysis of Spur Gears. International Journal of Science, Engineering and Technology Research (IJSETR). 4(8): 2815-2821.

Schumacher L. 2018. How Do Lawn Mowers Work? Available Online at: https://home.howstuffworks.com/how- to-mow-your-lawn.htm, Accessed on July 27, 2022.

Sivagurunathan R., Sivagurunathan L., Hao J. 2017: Design and Fabrication of Low-Cost Portable Lawn Mower. Scholars Journal of Engineering and Technology (SJET). 9(10): 584-591.

What is Carbon Fiber - Properties of Carbon Fiber, Material Properties, Available Online at: https://material-properties.org/carbon-fiber-density-strength-melting-point, Accessed on July 24, 2022.