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Design and Analysis of Manually Driven and Engine Powered Wheat Crop Reaper for Broad Bed Furrows

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Abstract: *Harvesting by using traditional method is time consuming; it needs much labour force and result in grain loss. Importing combine harvester is too expensive and not affordable for small scale farmers. The aim of the study is to design and develop wheat crop reaper for harvesting wheat crops mainly for furrows prepared by BBM and also for traditional furrows. The designed reaper was manually driven and powered with diesel engine for cutting wheat crop stems. With the help of pulley-belt arrangement drive power is transmitted from engine to gearboxes. A spur gearbox and a bevel gearbox are used. One end of bevel gear box output shaft was connected to slider crank mechanism which converts rotary motion of shaft into reciprocating motion of cutter bar. Reciprocating cutter bar slides over fixed bar and created scissoring action between cutter blades which were responsible for cutting the wheat crop stems. Collecting mechanism consist of flat belt with collecting lugged plates bolted on it. This machine is able to run of field easily and the efforts of the farmers are reduced.*

Keywords: *Reaper, BBM, Concept selection, Design, 3D and 2D model*

1. Introduction

Harvesting, an important field operation for any food grain crops, is the cutting process carried out when the crop attains physiological maturity such that a maximum recovery of quality product is obtained. [3]

Timeliness of harvest is of prime importance. Rapid harvest facilitates extra days for land preparation and earlier planting of the next crop. [6]

During the peak season of harvesting, Ethiopian farmers have to face the difficulty of getting their crop timely reaped due to shortage of agricultural laborers. [5]

Reapers are used for harvesting of crops mostly at ground level. Reaper harvesters are other alternative harvesting equipment, provided straw is considered as economic by product for animal feed and industrial applications. [9]

Harvesting using traditional method is time consuming, needs labour force, result grain loss etc. and also importing combine harvester machine will be too expensive and isn't affordable to our country farmers. [1]

Small scale farmers frequently face the problem of labour shortage or are unable to afford the wages to be paid. [4]

2. Concept Generation and Selection

The concept generation stage of product development is where the skill, experience and creativity of design team are used to generate designs which address the identified needs of the clients and the users to create a factor. Ideas are like prototypes. They need to be tested to verify they fit client needs. [8]

2.1. Functional Interrelation

Function tells what the product must do where as its form or structure, conveys how the product will do it. [8].

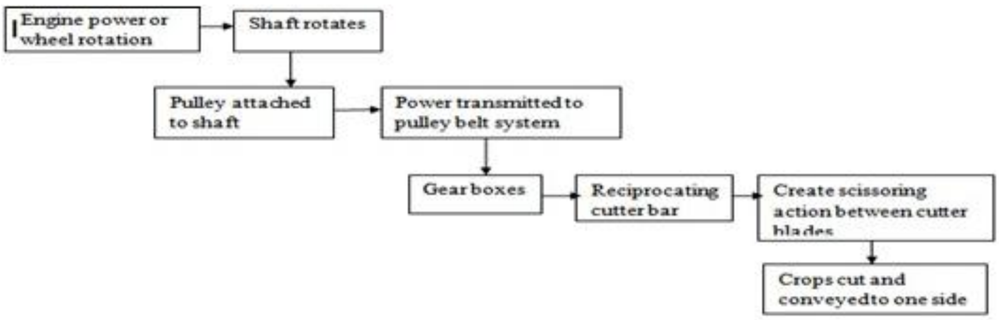

Figure1. *Functional interrelationship of wheat crop Reaper*

2.2. Task Specification

Task specification is a collection of information about the requirements to be embodied in the solution and also about the constraints.

2.3. Establishing Functional Structure

The functional basis uses function and flow words to form a subfunctiondescription as afunction and a flow. [8]

2.3.1. Overall Function

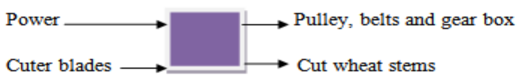

Figure2. *Over all function*

2.3.2. Decomposition of Overall Function

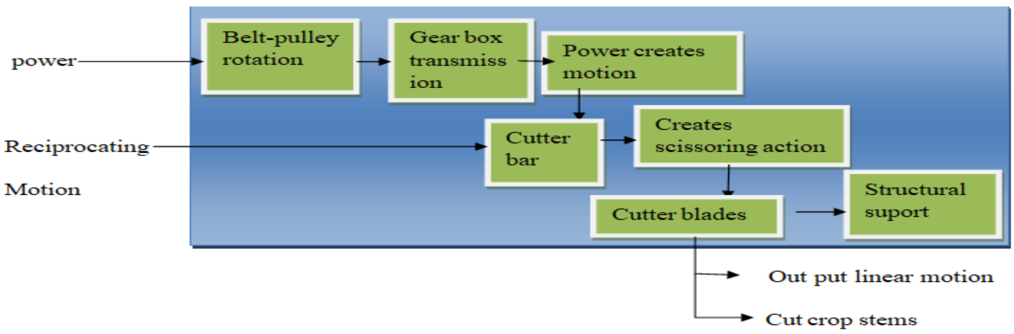

Figure3. *Over all functions decomposition*

2.4. Possible Solution for Sub-Function

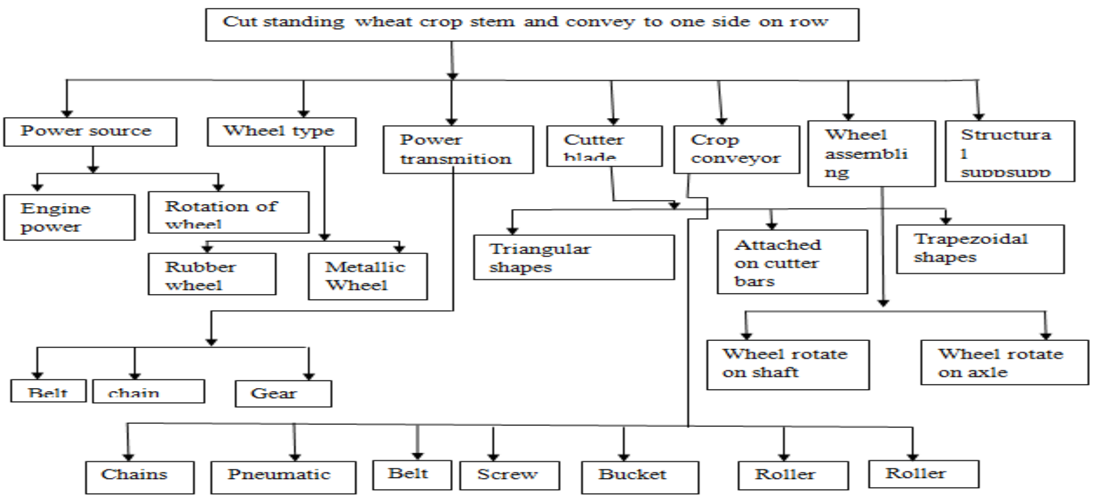

Figure4. *Alternative tree for sub-function*

2.5. Aternative Evaluation Tree Summery

After analysis alternative evaluation the best alternatives are selected

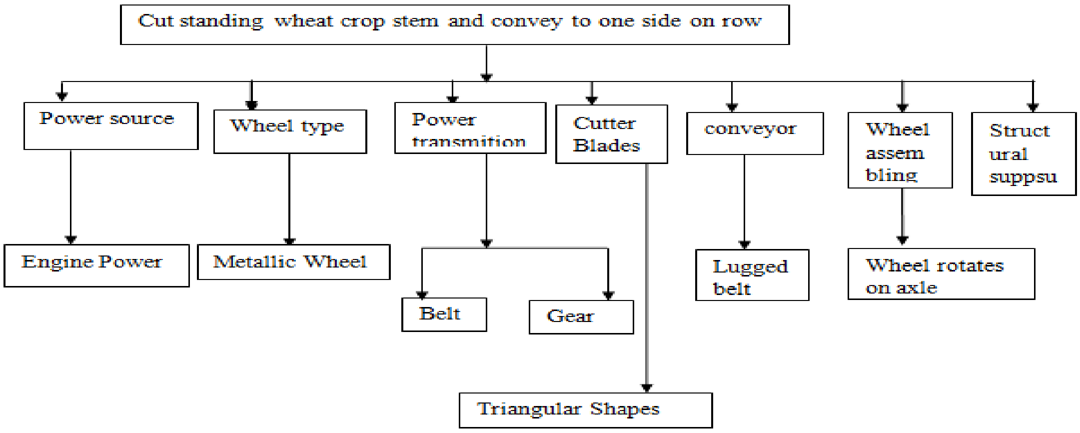

Figure5. *Result from alternative tree evaluation*

3. Embodiment Design of Wheat Crop Reaper

3.1. Introduction to Embodiment Design and Selection of Material

It is a process of giving concrete form to an abstract concept. During the embodiment phase the designers must determine the overall layout design, general arrangement and spatial compatibility, the preliminary form designs or component shapes and materials and the production processes, and provide solutions for any auxiliary functions. [8]

The designed reaper consists of main frame, diesel engine, belt drive, spur gear box, coupling, and cutter assembly, collecting belt, bevel gearbox and metallic wheels. The machine performs two operations harvesting and collecting. There are two cutter blades; one is moving and another is stationery on the main frame. The slider crank mechanism is used to convert rotary motion to linear motion in the cutter bar assembly.

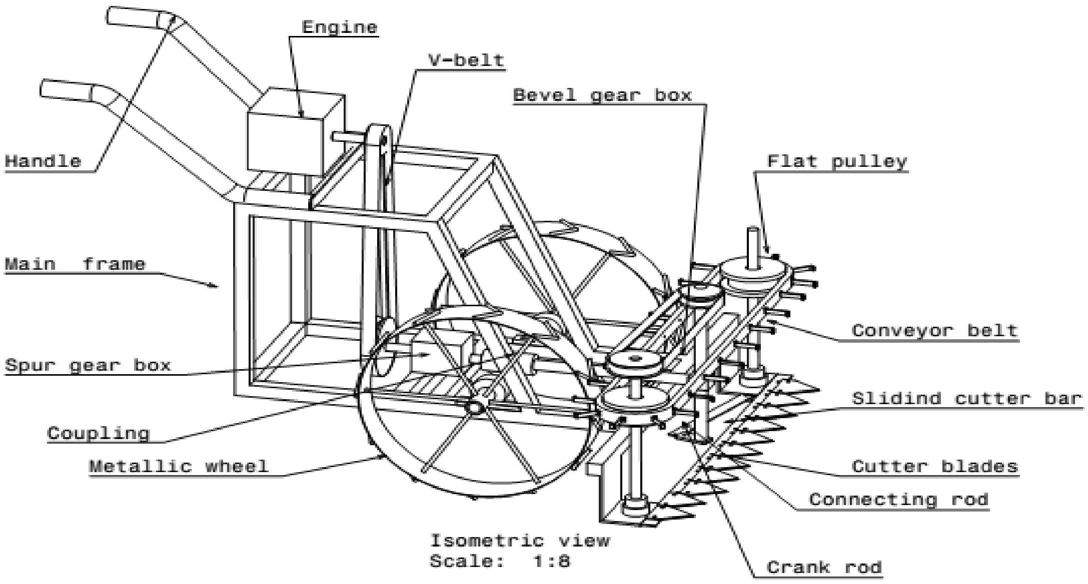

Figure6. *3D Model of wheat crop Reaper*

3.2. Design of Main Frame Assembly

The main frame assembly has been selected on the basis of crop parameters and load requirements. In this design, hollow mild steel section bar of 30 mm x 30 mm and 3 mm thickness was used to give the required strength and rigidity, so that it can withstand all types of load during operation.

The frame of the harvester with the dimension $800 \times 400 \times 500 (l \times b \times h)$ mm^3 is designed.

3.3. Estimation of Force Required to Push the Reaper

According to [6] the power of useful work done by human being is given by:

$$P = 0.35 - 0.092 \log t \quad 3.1$$

Where, P = power in horse power

t = time in minute

For four hours continuous work, power developed by a man is

$$P = 0.35 - 0.092 \log(4 \times 60)$$

$$P = 0.131 \text{ hp}$$

It is known that, $P = \frac{\text{push} \times \text{speed}}{75}$ 3.2

Let speed of operating the machine be $= 0.8 \frac{m}{s}$. Therefore, from equation (3.2)

$$\text{push} = \frac{75 \times 0.0964 \text{ kW}}{0.8 \text{ m/s}} = 9.038 \text{ KN}$$

$$hp = \frac{2\pi \times N_g \times T_g}{4500} \quad 3.3$$

Ng = rpm of ground wheel

Tg = torque developed by the ground wheel

$$V = \frac{\pi \times D \times N_g}{60} \quad 3.4$$

V = Operating speed of reaper, take 0.8 m/s

D = Diameter of ground wheel,

It is taken, D = 0.4 m putting these values in equation (3.4),

$$N_g = \frac{v \times 60}{\pi \times D} = \frac{0.8 \text{ m/s} \times 60}{\pi \times 0.4 \text{ m}} = 38.217 \text{ rpm}$$

Putting this value in equation (3.3)

$$T_g = \frac{Hp \times 4500}{2\pi \times N_g} = \frac{0.0964 \text{ kW} \times 4500}{2\pi \times 38.217 \text{ rpm}} = 1.807 \text{ kNm}. \ T_g = 1.807 \text{ k Nm}$$

3.3.1. Determination of Forces Acting on the Cutter Bar of Reaper

$$F = Fc + Ff + Fi \quad 3.5$$

Where F= total resisting force on cutter bar, N or Kg

F_c = average resistance to cutting, N or Kg

F_f= frictional force N or kg

F_i = inertia force of knife section, N or Kg

3.3.2. Cutting Force in the Cutter Bar

The total cutting force (F_C) on the cutter bar is given by

$$Fc = \frac{EFtZ}{Xc} \quad 3.6$$

F_C = total cutting force in cutter bar, N

E = 1.25 N-Cm/Cm^2 for wheat crop and 2.0 $\frac{N-cm}{cm^2}$(for paddy)

F_t = knife load area for single stroke cutter. It is calculated, 20.625 Cm^2

Z = Number of knife section in the cutter bar is 10 for 80 cm cutter bar

Xc = Displacement of knife, start to end of cutting = 3.75 cm for the designed knife section Putting values in equation (3.6),

$$Fc = \frac{1.25\frac{Ncm}{cm\,2} \times 20.625\ cm2 \times 10}{3.75\ cm} = 68.75\ N$$

3.3.3. Inertia Force in Cutter Bar

It is given by,

$$F_i = M_k r\omega^2(1 - \frac{X}{r}) \qquad 3.7$$

Where, M_k = mass of knife section, kg

r = radius of crank, cm

ω = angular velocity, rad/sec

x = length of stroke, cm

At initial and final points of stroke, F_i would be maximum. So, $F_{i\,max} = M_k r\omega^2$

3.3.3.1. Determination of Crank Radius and Stroke Length of the Cutter Bar

The ratio m/L, where L is the pitman length, called eccentricity (ξ), plays an important role in deciding crank radius (r) and stroke length (s). [3]

$$r = \frac{s}{2}\sqrt{1-\xi^2} \qquad 3.8$$

$\theta a = \sin^{-1}\left(\frac{m}{L+r}\right)$ and $\theta b = \sin^{-1}\left(\frac{m}{L-r}\right)$…3.9

The cutter bar assembly of the wheat crop reaper has the flowing lay out. The crank radius and stroke length is determined based on the above principle.

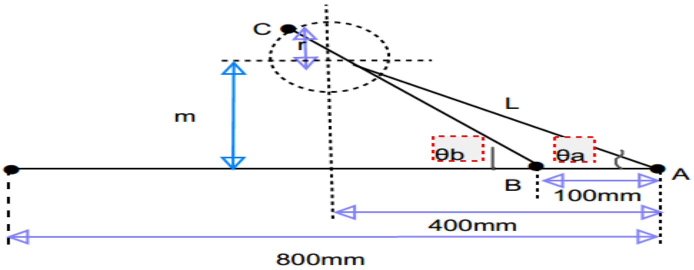

Figure7. *FBD of cutter bar assembly*

Taking Value of m=70 mm and L= 325 mm then by using equation (3.8) solve for r value.

$$\xi = \frac{m}{L} = \frac{70}{325} = 0.215$$

$$r = \frac{100}{2}\sqrt{1 - 0.215^2} = 48.831mm \text{ and from equation} \qquad (3.9)$$

$$\theta a = \sin^{-1}\left(\frac{m}{L+r}\right) = \sin^{-1}\left(\frac{70}{325+48.831}\right) = 10.792^0$$

$$\theta b = \sin^{-1}\left(\frac{m}{L-r}\right) = \sin^{-1}\left(\frac{70}{325-48.831}\right) = 14.683^0$$

For reapers weight of cutter bar per meter length is 20 to 22 N. [6] let's take 20 N and weight (M_k) of 80 cm long cutter bar is 16N.

Newton's second law $F = ma$, $m = \frac{F}{a}$.Taking gravitational accelerationa $= 9.81\frac{m}{s^2}$, $Mk = \frac{16}{9.81} = 1.63$ kg.For V_k =1 m/s and r = 48.831 mm of a 80 cm long cutter bar using the above equation (3.7)

$$V = \omega \times r,\ \ \omega = \frac{v}{r} = \frac{1}{0.049} = 20.303\ \text{rpm}$$

$$F_{i\ max} = 1.63 \times 0.049 \times 412.212 = 32.923N$$

3.3.4. Frictional Force in the Cutter Bar

The frictional force (F_f) acts on the knife slides over the finger bar and was given by

$$F_f = F_{f1} + F_{f2} \qquad 3.10$$

F_{f1} = Force due to weight of cutter bar which was calculated by

$$Ff1 = Mk \times f \qquad 3.11$$

f = 0.2- 0.3, take average of it 0.25

$$Ff1 = 1.63 \times 9.81 \times 0.25 = 3.998N$$

F_{f2} = force caused by normal component of force exerted by connecting rod on the knife

$$Ff2 = \left[\frac{(Fc + Fimax + Ff1)\tan\theta b}{(l - f \times \tan\theta a)}\right] f \qquad 3.12$$

Taking L= 325, f= 0.25 for wheat, $\theta a = 10.792^0$ and $\theta b = 14.683^0$

$$Ff2 = \left[\frac{(68.75N + 32.923\ N + 3.998\ N)\tan 14.683}{(0.406 - 0.25 \times \tan 10.792)}\right] \times 0.25$$

$Ff2 = 14.401$ N. So, Frictional force in the cutter bar (F_f)

$$Ff = 4.725\ N + 14.401N = 19.646\ N$$

Therefore, total resisting force (F) acting on the cutter bar is calculated using equation (3.5)

$$F = Fc + Ff + Fimax = 68.75\ N + 19.646N + 32.923N = 121.319\ N$$

3.4. Power Requirement for the Reaper

The Power required to overcome the resistance to motion of cutter bar (P) is given by

$$P = F \times v \qquad 3.13$$

Where, P = power in watts

F = resistive force, N

V = knife speed, m/s

Putting values F = 121.319N and v = 1 m/s in equation above (3.13).

$$P = 121.319\ N \times 1\frac{m}{s} = 121.319\ \text{watt.}$$

According to [6] the average power produced by a man during continues work is 74.6 watts. Since power requirement for cutting wheat crops from Broad Bed Furrows is equal to 120.799 watts, the developed 80 cm size cutter bar length reaper for cutting of wheat crops is not feasible for one person. Number of persons required to operate the machine is $= \frac{121.319\text{watts}}{74.6\text{watts}} = 1.626.$ therefore, two persons is sufficient to operate the machine properly with good efficiency.

3.5. Wheel design for the Reaper

The Reaper's ground wheel, with external diameter of 400 mm, was designed as an integral part of the moving mechanism connected to the main frame at the down directly. [11] Analyzed the shear strength (τ) of the ground wheel considering the wheel as thin-walled vessels.

$$\tau = \frac{T}{2A_m\ \ t_s} \qquad 3.14$$

Where: - T=the torque produced by the wheel (1.807 kNm)

A_m=the area of the wheel calculated based on the median diameter of the wheel t_s = thickness of the wheel wall (0.003m).

r_m = the median radius of the wheel

r= the outer radius of the wheel (0.2m)

$Am=\pi\times rm\ 2=\pi(r-0.5\times ts)2$…3.15

$A_m=\pi(0.20-0.5\times 0.003)^2=0.124m^2$

Therefore, the shear stress on the wheel, $\tau=\frac{1.807\times 10^3}{2\times 0.124\times 0.003}=2.429$ Mpa

Thus the calculated shear stress was much less than the maximum allowable shear stress of the mild steel sheet metal used in the construction of the wheel, 80.8 MPa, hence the wheel is safe for the design and operation.

3.6. Handle

The handle was made from mild steel circular hollow pipe. The length of the handle is 520mm and diameter of the handle is 40 mm. The designing of handle also approximate 100cm height is sufficient for pushing of any machinery [6]. For the design 45^0 angles is selected.

3.7. Selection and Design of Cutting Unit of Wheat Crop Reaper

Cutter assembly consists of a sliding cutter plate and a stationery cutter plate.

3.7.1. The Length of Cutter Bar

It is selected on the basis of row to row spacing of crops. In general, row to row spacing in what crop ranges 15-20 cm [6]. But this design considers width of BBM. So, let a cutter bar length L_C = 0.75m is selected for the design. Because the design considers the width of BBM (Broad Bed Maker) furrow which is around 0.8m.

3.7.2. Number of Knife Section

Number of knife section = $\frac{L_c}{\text{size of knife section}}$ 3.16

Number of knife section $=\frac{0.75m}{0.076m}=9.868$

Take number of knife section 10. Adjusted length of cutter bar is therefore,

$10\times 0.076m$= 0.76 m, take length of cutter bar 0.8 m of mild steel.

3.7.3. Size and Shape of Knife

Material for the knife section is high carbon steel. It is selected and designed based on the following parameters:

Gripping of Stalk by Cutting Pitch

The crop is cut by impact and shear action between the knife section and guard lip. For normal cutting action, the stalk should be pinched between cutting edge of knife and guard lip. [6]

$<\alpha+<\beta=<\emptyset_1+\emptyset_2$………..…3.17 $<\alpha$ =Angle between cutting edge and axis of knife section

$<\beta$= Angle between cutting edge and axis of axis of finger guard lip

$<\emptyset_1+\emptyset_2$= angle of friction between the crop and cutting edge of knife section and twin guard lip

Therefore, for operating speed of 0.8 m/s of machine, the knife section having an angle α of 31^0 or below is selected.

Rake Angle, Sharpness and Thickness of Cutting Edge

Thickness of knife 25 µm is selected for this design in order to have light weight and rake angle of 22^o with sharp cutting edge is selected for the knife section.

Pitch of Serrated Knives

In order to avoid slipping off the stalks, the knives section should be serrated. The pitch of serrated knives is selected two three times smaller than the diameter of paddy and wheat stalk. i.e. pitch should be 1-1.2 mm. [6] For this design 1.2mm pitch is selected because it can be designed and fabricated simply.

Clearance between knife

The quality of cutting is governed by the clearance between the cutting pair. A clearance of 0.5-1 mm can be selected. For this design 0.75 mm clearance is selected which is average value.

Velocity of Knife Section

The velocity of knife section is expressed as:

$$Vk = R \times Vm \qquad 3.18$$

Where, Vk= knife velocity

Vm= forward speed of a machine

R= velocity ratio

For best results, according to [6] for α of 31° the knife velocity should be 1m/s. the value of R falls between 1.3 - 1.4 with available cutter blades. Taking R as 1.4 and V_m of 0.8 $\frac{m}{s}$ and putting values in equation above (3.18)

$Vk = 1.3 \times 0.8\ m/s = 1.04\ \frac{m}{s}$, Take V_k = 1 m/s.

Also, it is known

$$V_k = \frac{X \times N_k}{30} \qquad 3.19$$

Where, x = stroke length

N_k= rpm of knife section

Therefore, $N_k = \frac{30 \times V_k}{X} = \frac{30 \times 1 \frac{m}{s} \times 100\ \frac{cm}{m}}{7.6\ cm} = 394.737$ rpm . Let's take, Nk = 400 rpm

For a standard 76 mm knife section, the above velocity translates into 400 rpm of knife section. The actual average knife speed of cutter bar of reaper from equation (3.19) would be

$$V_k = \frac{N_k \times X}{30} = \frac{400 \times 7.6}{30 \times 100} = 1.013\ m/s.$$

This value is almost equal to the assumed and given standard.

Forward Speed of Machine

The normal walking speed of human labour is about (0.7 to 0.8 m/s). [6]Therefore, forward speed of machine can be selected as 0.8m/s.

3.8. Design of Power Transmission System

The 2.7 KW(3.671 hp), 4000 rpm and rope start type of diesel engine act as the driving force to operate the cutting and conveying mechanism of the machine is selected and move forward by pushing it from the back. Diesel engine is selected because diesel engine has good efficiency, power and its availability.

3.8.1. Selection of Belt

The belts or ropes are used to transmit power from one shaft to another by means of pulleys which rotate at the same speed or at different speeds. [10]

The belt drives primarily operate on the friction principle. [7]

V-Belt Length and Arc of Contact

The belt length for an open drive is approximated by the following formula.

$$L = 2C + \frac{\pi}{2}(D + d) + \frac{(D-d)2}{4C} \quad 3.20$$

And for the crossed belt drive the length is given by the following formula.

$$L = 2C + \frac{\pi}{2}(D + d) + \frac{(D+d)2}{4C} \quad 3.21$$

Where, D and d = are the outside sheave diameters for large and small pulleys respectively

C = Center to Center distance between sheaves

L = Length of Belt

Angle of contact or lap for open belt drive,

$$\theta = (180^0 - 2\alpha) \times \frac{\pi}{180} \text{rad} \quad 3.22$$

$$\text{Sin}\alpha = \frac{d_1 - d_2}{2C}$$

Angle of contact or lap for cross belt drive,

$$\theta = (180^0 + 2\alpha) \times \frac{\pi}{180} \text{rad} \quad 3.23$$

$$\text{Sin}\alpha = \frac{d_1 + d_2}{2C}$$

Speed of V-Belt Drives

As a belt bends to conform to the sheave curvature, the outer section stretches and the inner section is compressed. [2] The belt speed is calculated as:

$$V = \pi N_2 d = \pi N_3 D \quad 3.24$$

Where, v= belt speed in m/s

N2, N_3 = angular speeds of rotation of sheaves 2 and 3, respectively, in rpm

D, d = pitch diameters of pulleys large and small, respectively, m

Velocity Ratio of a Belt Drive

It is the ratio between the velocities of the driver and the follower or driven. It may be expressed, mathematically, as discussed below:

Let, d_1 = Diameter of the driver,

d_2 = Diameter of the follower,

N_1 = Speed of the driver in r.p.m.,

N_2 = Speed of the follower in r.p.m.

Length of the belt that passes over the driver, in one minute = $\pi d_1 N_1$. Similarly, length of the belt that passes over the follower, in one minute = $\pi d_2 N_2$. Since the length of belt that passes over the driver in one minute is equal to the length of belt that passes over the follower in one minute, therefore, $\pi d_1 N_1 = \pi d_2 N_2$, when there is no slip, then $V_1 = V_2$. [7]

And velocity ratio,

$$\frac{N2}{N1} = \frac{d1}{d2} \quad 3.25$$

The velocity ratio of a belt drive may also be obtained as discussed below.

$$V_1 = \frac{\pi d_1 N_1}{60} \quad 3.26$$

And peripheral velocity of the belt on the driven pulley,

$$V_2 = \frac{\pi d_2 N_2}{60} \quad 3.27$$

3.8.2. Selection and dimensions of pulley (from engine to spur gear box)

The diameter of the pulley may be obtained either from velocity ratio consideration or centrifugal stress consideration. [10]

$$\sigma_t = \rho \times V^2 \qquad 3.28$$

Where, σ_t =Centrifugal stress or tensile stress in the pulley rim, Centrifugal stress or tensile stress in the pulley rim = 4.5 MPa = 4.5×10^6 N/m2

ρ = Density of the rim material, 7200 kg/m3 for cast iron

V = Velocity of the rim

Let, N1 = Engine rpm

d_1 = Diameter of small pulley (driving pulley)

N_2 = Input to spur gear box rpm

d_2 = Diameter of Large pulley (driven pulley)

Calculation of pulley diameter starts from smaller pulley diameter. The material selected for the pulleys cast iron, because of their low cost.

From equation (3.28)

$V^2 = \frac{\sigma_t}{\rho} = \frac{4.5\times10^6}{7200} = 625$, V= $\sqrt{625}$ =25 m/s and putting in equation (3.28)

$d_1 = \frac{V\times60}{\pi\times N_1} = \frac{25\times60}{\pi\times4000} = 0.119\ \text{m} = 119\text{mm}$, take f d_1 = 125mm from a standard. To get reduced speed rpm at the cutter bar of a reaper let select standard diameter of driven pulley diameter (d_2) aim to get optimum angular rpm speed (N_2). $d2 = 2 \times d1 = 2 \times 125 = 250$ mm. So, take d_2 = 250mm which is also in the standard.

Velocity of Pulley

Engine speed in rpm is already given N_1 = 4000 rpm and from equation (3.25) it can be derived that, $N_1d_1 = N_2d_2$. By using this equation lets calculate rpm speed which is in put to spur gear box.

$$N_2 = \frac{N_1 \times d_1}{d2} == \frac{4000 \times 0.125}{0.25} = 2000\text{rpm}.$$

So, take N_2 = 2000rpm

The velocity ratio of a belt drive may also be calculated as discussed above. The peripheral velocity of the belt on the driving pulley by using equation (3.26),

$$V_1 = \frac{\pi \times 0.125 \times 4000}{60} = 26.18\frac{m}{s}$$

And peripheral velocity of the belt on the driven pulley by using equation (3.27),

$$V_2 = \frac{\pi \times 0.25 \times 2000}{60} = 26.18\ m/s.$$

The values of V_1 and V_2 are equal; this indicates that there is no slip between the belts and pulleys. So, belt slippage is almost negligible.

Belt Length and Angle of Contact or Lap

Center distance between the two pulleys (C) is given by $C = 2 \times d2$. But, of course space availability matters. $C = 2 \times 250 = 500\text{mm}$. Therefore, with in available space let's take the value center distance for pulleys between the engine and spur gear box, C = 500 mm. Belt length for V-belt pulley between engine and spur gear box is calculated by using equation (3.20), for open belt systems.

$$L = 2 \times 500\text{mm} + \frac{\pi}{2}(250\text{mm} + 125\text{mm}) + \frac{(250\text{mm} - 125\text{mm})^2}{4 \times 500\text{mm}}$$

$L = 1000mm + 589.049mm + 7.713mm$

$L = 1596.862mm$

Subtracting 36 for A type belt it is found, the inside length of belt= $1596.862 - 36 = 1560.862$ mm. From a standard, the nearest standard inside length of v-belt is 1600mm. therefore, pitch length of the belt.

$$L = 1600 + 36 = 1636mm$$

Angles of contact or lap for open belt pulley drive from equation (3.22)

$\theta = (180^0 - 2\alpha) \times \frac{\pi}{180}$ rad and $\text{Sin}\alpha = \frac{d_1 - d_2}{2C}$

$\text{Sin}\alpha = \frac{125 - 250}{2 \times 500} = \frac{-125}{1000} = -0.125$

$\alpha = \sin^{-1}(-0.125) = -7.181$

Therefore, $\theta = \left(180^0 - 2(-7.181)\right) \times \frac{\pi}{180}$ rad

$\theta = \left(180^0 + 14.362\right) \times 0.017 \text{ rad} = 3.304\text{rad}$

$\theta = 3.304$ rad

The calculated value of angle of wrap, θ is given in radian. To change the unit in degree, $1^0 = \frac{\pi}{180}$. [6]

Therefore, $\theta = \frac{1^0 \times 3.304 \text{rad}}{0.017 \text{rad}} = 194.362^0$

$$\theta = 194.362^0$$

This angle of contact or lap is for small pulley since the two pulleys are made of the same material.

3.8.2.1. Belt Tension

The following expression gives the relation between the tight side T_1 and slack side tensions T_2, in terms of coefficient of friction and the angle of contact.

$$2.3 \log\left(\frac{T_1}{T_2}\right) = \mu\theta \text{Cosec}\beta \qquad 3.29$$

Where, μ =Coefficient of friction between the belt and sides of the groove.

θ = angle of contact, in radians, *i.e.* angle subtended by the arc, along which the belt touches the pulley, at the centre)

β = angle of grove

Taking angle of groove $2\beta=38^0$, $\beta=19^0$ and $\mu = 0.3$ because rubber belt is selected.

$$\log\left(\frac{T_1}{T_2}\right) = \frac{(0.3 \times 3.304 \text{cosec} 19)}{2.3} = 1.324$$

Taking antilog of 1.324, $\frac{T_1}{T_2} = 21.086$

$T_1 = 21.86 T_2$ 3.30

Power Transmitted per belt, $P = (T_1 - T_2)$ V

2.7 kw $= (T_1 - T_2) 26.18 \frac{m}{s}$

$T_1 - T_2 = 0.103$ KN 3.31

Substituting 30 into 31

$21.086T_2 - T_2 = 0.103$ kN, $T_2 = 20.086T_2 = 0.103$ kN, $T_2 = 0.005$ kN and $T_1 = 0.108$ kN

In put values: P = 2.7 KW, V_b = 26.18 m/s,

θ =3.304 rad and μ =0.3 rubber belts used,

Then T_1= 0.108 kN and T_2 = 0.005 kN,

Power transmitted per belt, $P = (T1 - T2)vb = (0.108 - 0.005)26.18 = 2.697kW$

$$\text{Number of belts required} = \frac{\text{Total power transmitted}}{\text{Power transmitted per belt}} = \frac{2.7KW}{2.697\ KW} = 1.001 \approx 1$$

Therefore, number of v-belts required here is one.

Pulley Width (B) and Belt Width (B)

If the width of the belt is known, then width of the pulley or face of the pulley (B) is taken 25% greater than the width of belt. [10] B = 1.25b, where b = width of belt.

The thickness of the pulley rim (t): varies from $\frac{D}{300} + 2$ mm to $\frac{D}{200}$ +3 mm for single belt. t =2.417 to 3.625 mm for drive pulley (D =125 mm) t = 2.833 to 4.25 mm for driven pulley (D = 250 mm)

Dimensions of arms:-

- The number of arms taken as 4 for pulley diameter from 200 mm to 600 mm
- The pulleys less than 200 mm diameter are made with solid disc instead of arms. The thickness of the solid web is taken equal to the thickness of rim measured at the centre of the pulley face.[10]

3.8.3. Shaft Design

A shaft is a rotating machine element which is used to transmit power from one place to another. The power is delivered to the shaft by some tangential force and the resultant torque (or twisting moment) set up within the shaft permits the power to be transferred to various machines linked up to the shaft.[10]

Determination of Shaft Diameter

When the shaft is subjected to a twisting moment (or torque) then the diameter of the shaft may be obtained by using the torsion equation.

$$T = \frac{\pi}{16} \times \tau \times d^3 \qquad 3.32$$

The twisting moment (T) may be obtained by using the following relation:

$$T = \frac{P \times 60}{2\pi N} \qquad 3.33$$

T = Twisting moment (Torque) acting upon the shaft

τ = Torsional shear stress

d = Diameter of shaft

P = Power transmitted (in kilowatts) by the shaft

N = Speed of the shaft in rpm

When the shaft is subjected to a bending moment then the maximum stress (tensile or compressive) is given by the bending equation.

$$M = \frac{\pi}{32} \times \sigma_b \times d^3 \qquad 3.34$$

M = Bending moment

σ_b =Bending Stress

When the shaft is subjected to combined twisting moment and bending moment, then the shaft must be designed on the basis of the two moments simultaneously.

$$\sigma_{b\ max} = \frac{1}{2}\sigma_b + \frac{1}{2}\sqrt{(\sigma_b)^2 + 4\tau^2} \qquad 3.35$$

$M_e = \frac{1}{2}[M + \sqrt{M^2 + T^2} = \frac{\pi}{32} \times \sigma_b \times d^3$ 3.36

The expression $\frac{1}{2}[M + \sqrt{M^2 + T^2}$ is known as equivalent bending moment and is denoted by Me. From this expression, diameter of the shaft d is obtained.[10].In actual practice, the shafts are subjected to fluctuating torque and bending moments.

$T_e = \sqrt{(K_m \times M)^2 + (K_T \times T)^2}$ 3.37

The equivalent bending moment:

$M_e = \frac{1}{2}\left[K_m \times M + \sqrt{(K_m \times M)^2 + (K_t \times T)^2}\right]$ 3.38

K_m = Combined shock and fatigue factor for bending.

K_t = Combined shock and fatigue factor for torsion.

This shaft transmits power from the source to the pulleys and carries machine parts such as tensioned belts and bearing, therefore they are subjected to bending in addition to twisting then stresses due to combined torsional and bending loads are used to determine the shaft diameter. It is known that torque transmitted by shaft,

$$T = \frac{P \times 60}{2 \times \pi \times N} = \frac{2.7kw \times 60}{2 \times \pi \times 4000} = 6.446 \text{ Nm}$$

Since the overhang of the pulley is taken 100 mm, bending moment of the shaft due to belt tension assuming weight pulley negligible.

Material selection

Based on the availability in country and strength mild steel is selected. Properties of mild steel, density =7861.093 kg/m3 and maximum tensile strength=500Mpa, yield Strength=250Mpa. Therefore ,$\sigma b = \frac{\text{yield strength}}{\text{factor of safety}}$.

Let take factor of safety be 1.5 and σb = 166.67 Mpa.

Bending moment $(M) = (T1 + T2) \times L = (0.108kN + 0.005kN) \times 0.1m = 11.3$ Nm.Taking km $= 1.5$ and kt $= 1.0$

$$M_e = \frac{1}{2}\left[K_m \times M + \sqrt{(K_m \times M)^2 + (K_t \times T)^2}\right] = \frac{\pi}{32} \times \sigma_b \times d^3$$

$$\frac{1}{2}\left[1.5 \times 11.3 + \sqrt{(1.5 \times 11.3)^2 + (1 \times 6.446)^2}\right] = \frac{\pi}{32} \times 166.667 \times 10^6 \times d^3$$

$$17.542 = 16362494.46d^3$$

From this $d = 10.235$mm. Let's take d = 20mm from standard on safer side.

3.8.4. Gear Selection

The slipping of a belt or rope is a common phenomenon, in the transmission of motion or power between two shafts.

Spur Gear Design

The main advantage of gear drive is that it transmit same velocity ratio and also it is used to transmit a very large power with very good reliable service. [7]

The tooth profile of the 20° full depth involutes' system may be cut by hobs. The increase of the pressure angle from 14 $1/2^0$ to 20° results in a stronger tooth, because the tooth acting as a beam is wider at the base.[10]

Let's take Spur gearbox consist of pinion with 18 teeth and let's take four times pinion to have good speed reduction. Increase of the pressure angle from 14 $1/2^0$ to 20° results in a stronger tooth, because the tooth acting as a beam is wider at the base.[10] So, gear with 72 teeth desired.

$N_2T_2 = N_3T_3$ 3.39

Where, T_2 = Pinion teeth

N_2 = input rpm

N_3 = output rpm

T_3 = gear teeth

N_2=2000, T_3 = 72 teeth, T_2 = 18 teeth. Putting these value in equation above $N_3 = \frac{N_2 \times T_2}{T_3}$ =$N_3 = \frac{2000 \times 18}{72}$ = 500, take N_3=500 rpm

Shaft Design for Spur Gear

Input rpm to spur gearbox isN_2=2000rpm.by using equation (3.33) for torque calculation

$$T = \frac{2.7kw \times 60}{2 \times \pi \times 2000} = 12.89Nm$$

Using values of T1and T2 from above calculation moment can be calculated,

M = (0.108kN+0.005kN) 0.2m=22.6Nm. Using equation (3.38) shaft size can be determined.

$$\frac{1}{2}\left[1.5 \times 22.6 + \sqrt{(1.5 \times 22.6)^2 + (1 \times 12.89)^2}\right] = \frac{\pi}{32} \times 166.667 \times 10^6 \times d^3$$

$$35.08 = 16362494.46d^3$$

From this calculation , d = 12.895mm. On the safer side, let's take d = 15mm and selected material is mild steel.

Bevel gear selection and design

Bevel gearbox is used to change the direction of motion by 90˚.[10]

$N_4T_4 = N_5T_5$ 3.40

Where, T_4 = Input to bevel gear teeth

T_5 = output of bevel gear teeth

$N_4 = N_3$ = Input rpm to bevel gear = 500 rpm

N_4 = 500rpm, T_4 = 10 and T_5=16 using equation (3.40), N_5 can be calculated

$N_5 = \frac{N_4 \times T_4}{T_5} = \frac{500 \times 10}{16}$ = 312.5 rpm

Let's, take final rpm at cutter is N_5 = 312.5 rpm

Design of Belt and Pulley for Bevel Gear Output Shaft

As usual a v-belt is selected. Because v-belt drive gives compactness due to small distance between centers of pulleys. Center to center distance C = 400mm, by using equation (3.20) belt length can be calculated.

$$L = 2 \times 400 + \frac{\pi}{2}(90 + 80) + \frac{(90 - 80)2}{4 \times 400} = 1067.133mm$$

Subtracting 36 for A type belt it is found, the inside length of belt= $1067.133 - 36 = 1031.133$mm. From a standard, the nearest standard inside length of v-belt is 1067mm. therefore, pitch length of the belt

$$L = 1067 + 36 = 1103mm$$

Let assume the smaller diameter from the standard d_1=80mm and D_2=90mm.these small diameter pulleys are light weight and to provide motion for flat belts.

For power rating of 2.7 kW and minimum pitch diameter of 75 mm pulley, it is it is A type v-belts pulley from standard.[11] From this top width of belt (b) = 13 mm and thickness (t) = 8mm.

$B = 1.25 \times b = 1.25 \times 13 = 16.25$mm. Usually the groove angles of 32° to 38° are used. For the design select groove angle of 38°.

The thickness of the pulley rim (t): varies from $\frac{D}{300} + 2$ mm to $\frac{D}{200}$ +3 mm for single belt.

t =2.267 to 3.4 mm for drive pulley (D =80

t = 2.3 to 3.45 mm for driven pulley (D = 90 mm).

3.9. Coupling Selection

Sleeve or muff-coupling from the market is selected to connect the two shafts together at their ends for the purpose of transmitting power and reduce the transmission of shock loads from one shaft to another.[10] The output shaft of spur gearbox is coupled with input shaft of bevel gearbox with the help of sleeve or muff-coupling. This coupling was used because the shafts of both gear boxes were in same line.

3.10. Design of Crop Conveyor Unit

The collecting belt is used to carry cut crops with the aid of lugs sideways

Dimensions of Lugged Belt Pulleys

The maximum tension in the belt (T)= Maximum stress × Cross-sectional area of belt [10]

$$T = \sigma_{max} \times b \times t \qquad 3.41$$

$$T = \sigma_{max} \times b \times t. \text{ but, } \quad \sigma_{max} = \frac{\sigma ult}{f.s}$$

$$T = \frac{sult}{f.s} \times b \times t \qquad 3.42$$

Where, σ_{max} = Maximum safe stress,

b= Width of the belt, and

t= Thickness of the belt

f.s = factor of safety

If the width of the belt is known, then width of the pulley or face of the pulley (B) is taken 25% greater than the width of belt. B=1.25b, where b = width of belt. [10] For a lugged flat belt the belt speed is given by

$$V_b = \frac{\pi D_p N_p}{60} \qquad 3.43$$

Where, V_b= peripheral speed of flat belt

D_p= diameter of lugged belt pulley, m

N_p = speed of lugged belt pulley, rpm

Diameter of pulley (D_p) is given by the following equation.

$$D_p = \frac{V_b \times 60}{\pi \times N_p} \qquad 3.44$$

Peripheral speed of flat belt can be estimated as, V_b= 1.33m/s to 1.5 m/s. [6]

Let's take V_b = 1.5 m/s and N_p = 312.5 rpm Since, the drive from the shaft which is used for driving the bevel gear shaft having 312.5 rpm is used to drive the conveyor belts . Here two pulleys of the same size are used for conveyer belt. The material selected for the pulleys cast iron, because of their low cost. Diameter of pulley from equation above (equation3.44)

$D_p = \frac{1.5 \times 60}{\pi \times 312.5} = 0.092m = 91.673mm$. From standard taking, D_P =100mm. From equation (3.44), velocity of conveyor belt can be calculated

$$V_b = \frac{\pi \times 0.1 \times 312.5}{60} = 1.636 \text{ m/s}$$

The thickness of the pulley rim (t) varies from $\frac{Dp}{300} + 2$ to $\frac{Dp}{200} + 3$ for single belt [10]. Therefore, substituting values t = 2.33 to 3.5mm.

The pulleys less than 200 mm diameter are made with solid disc instead of arms. The thickness of the solid web is taken equal to the thickness of rim measured at the centre of the pulley face. Take belt thickness (t) =5 mm and σ_{ult} =35 Mpa, factor of safety (f.s) = 1.5 and using equation (3.42) belt width can be calculated.

Power from engine source is 2.7 kw. Power needed to rotate the conveyor pulley is from engine via different shaft. So, let's assume $P = 2.7 \times 90\% = 2.43$ kW

$$P = (T1 - T2)\, V,$$

$$2.7 \text{ kW} = (T1 - T2)1.5$$

$$T1 - T2 = 1.62 \times 10^3 \qquad 3.45$$

Taking angle contact (θ) =3.14 because the diameter of the two pulleys is equal, angle of groove 38^0 and μ = 0.22

$$2.3 \log\left(\frac{T_1}{T_2}\right) = 0.22 \times 3.14 \text{Cosec} 19$$

$\log\left(\frac{T_1}{T_2}\right) = 0.923$, By taking antilog of 0.923

$$T_1 = 8.366 T_2 \qquad 3.46$$

Substituting 3.46 in 3.45, T1=1.84kN and T2 = 0.22kN

$$1.84\text{kN} = \frac{35}{1.5} \times b \times 5$$

b= 21.029mm

Then, belt width (b) = 21.029mm.Therefore, from standard b = 25mm can be selected. Is belt is found it is easy to calculate width or face of pulley (B) = 1.25b. So, B = 31.25mm

3.10.1. Length of Lugged Belt of Conveyor Pulley

The length of lugged belt is given by

$$L = 2C + \pi \frac{D+d}{2} + \frac{(D-d)2}{4C} \qquad 3.47$$

Where, L= length of belt, mm

C= center to distance between lugged belt pulleys, cm

D= diameter of driving pulley, cm

d= diameter of driven pulley, cm

It is calculated based on length of cutter bar and length of vertical plat form required for supporting the crop. Length of cutter bar = 80 cm. Now, center to center distance (C) between driving and driven pulleys is given by

$$C = \frac{10}{2} + 80 + \frac{10}{2} = 90 \text{ cm} = 900\text{mm}$$

The length of flat belt is given by equation (3.47)

$$L = 2 \times 0.9 + \frac{\pi\,(0.1 + 0.1)}{2} + 0$$

$$L = 1.8 + 0.314 + 0 = 2.114\text{m}$$

The length of flat belt required for lugged belt conveyor would be 2114mm

3.10.2. Number of Lugs on Belt

The number of lugs on conveyor belt is given by

$$N_l = \frac{L}{P_l} \quad 3.48$$

Where, N_l = Number of lug on belt

L = length of belt, mm

P_l = pitch of lugs, mm

To have good collecting mechanism, let pitch of lugs on the belt is p = 100mm.According to [6] by number of lugs on conveyor belt $=N_l = \frac{L}{P_l}$, $N_l = \frac{2114}{100} = 21.140$, take number of lugs 22. Material selected for the lug is aluminum because it is light weight. $\text{Adjusted length of belt} = P \times \text{number of lugs} = 100 \times 22 = 2200 \text{ mm}$

3.10.3. Lug Height Determination

The lug height should be such that the branches of cut crop can be conveyed continuously without any blockage. [6] That means,

output of conveyor ≥ cutter bar output

$$h.W.\rho 2 \geq \rho 1.W2.\frac{Vm}{Vc} \quad 3.49$$

$h \geq \rho 1.W2.\frac{Vm}{\rho 2}$ WVc, Take $\frac{\rho 2}{\rho 1} = q = \frac{A1}{A2}$ then

$$h \geq \left(\frac{W}{q}\right) \times \left(\frac{Vm}{Vc}\right) \quad 3.50$$

Where, h = height of lug, cm

W = cutting width, cm

V_m = machine speed, m/s

V_c = Conveyor belt speed, m/s

ρ_1 = density of crop plants in field

ρ_2 = density of cut crop on vertical platform

q = gathered crop parameter $= \frac{\rho_2}{\rho_1} = \frac{A_1}{A}$ A_1 = one m^2 area in the field

A_2 = area of circle of bunched cut crop from $1m^2$area in the field

Also q= $4\pi C^2$

C = circumference of the cut crop bunch whose area is A_2

According to [6], $\text{For wheat crop: A2} = 1.5 \times 10 - 5 \times 500 = 0.0075 \text{ m2} = 0.01 \text{ m2}$.Putting the values of A_1 and A_2, q can be calculated$q = \frac{1}{0.01} = 100$. Putting values in equation (3.50), height of lug can be calculated as follows

$$h \geq \left(\frac{80}{100}\right) \times \left(\frac{0.8}{1.5}\right) \geq 0.427\text{cm} = 4.27\text{mm}$$

$\text{The height of lug(h)} = 4.27\text{mm} + 50\text{mm} = 54.27\text{mm}$. Hence, lug on conveyor belt is kept as, h = 55mm.

4. Conclusion

The harvesting machines used in the world aren't suitable for the small scale farmers. The designed and developed reaper in this paper has ability to cut wheat crops stems up to 0.8m furrow width. That means, the newly designed and developed reaper fits for BBF (Broad Bed Furrow) prepared with BBM (Broad bed Maker) which makes 0.8m wide furrows. This machine also helps to harvest from traditional furrows. The reaper is designed to cut wheat crops at the height of 100 mm from the ground level, for the reason that the farmer needs the straw as an important by product for animal feeds and other purposes. The detailed design and analysis of wheat crop reaper which includes main frame assembly, cutting mechanism systems, conveying unit and power transmission system from the engine to spur gear box, bevel gear box and to the cutter bar assembly has been carried out. The 2D and 3D model of the wheat crop reaper components were generated using CATIAV5R17 software. The designed machine is moderately compact and easy to handle.

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