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Empirical Design of a Sugarcane Bud Cutter

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Abstract: *Sugarcane is one of the world's foremost cash crops, and sugarcane planting and mechanization are the development trends of the industry. Sugarcane planting with traditional methods is costly, time-consuming, and the necessary compression of buds in the field is not achieved easily because of stalk planting in sugarcane. Nevertheless, most of the planting machines in the world do not have the function of bud prevention. The bud chip technology holds great promise for the rapid multiplication of new cane varieties. However, important operating and performance evaluation parameters of the machine are required for proper development of a prototype machine. Therefore, this present research work is focused on the empirical design of a sugarcane bud cutter. In designing the prototype sugarcane bud cutter, the focus was on design considerations and requirements, material selection and justification, and mathematical modelling of the useful parameters using established mathematical and mechanics of machine equations. The result of connecting rod force and the force along sliding which are obtained from the crank and connecting rod is high as compared to the length of the crank and connecting rod. Angular velocity and acceleration have a defined relationship with each other. Besides, it was established that a minimum cutting force, torque, and power of 504.23 N, 33.18 Nm, and 2 hp are required.*

Keywords: *Slider Crank Mechanism, Cutting Force, Empirical Design, Cutting Power, Cutting Torque*

INTRODUCTION

Sugarcane (*Saccharum sp.*) is a clonally propagated grass of the Gramineae family characterized by a high degree of polyploidy and is a crop of major importance, providing an estimated 65% of the world's sugar (Siddhesh *et al.,* 2017). Sugarcane is one of the main cash crops in the world, and sugarcane planting and mechanization are the development trends of the industry (Yadav *et al.,* 2003; Yiqi *et al.,* 2013). Reproductive tissue is harvested as the economic product in nearly all field crops, but this is not the case in sugarcane. In sugarcane, the stalks are the harvested tissue, and stalk size has a major influence on yield. There has been some research reported on the variation in size of individual stalk internodes with position on the stalk and with crop growth.

Sugarcane is vegetatively propagated for commercial cultivation. There are different types of planting materials that include settlings and bud chips, which are used for raising sugarcane crops. For sugarcane buds, a little portion of stem with one bud is known as a "bud chip. Bud chips are used to raise settlings in a nursery. They were found to produce a good crop when transplanted into the main field. The principal advantage of bud chips is the substantial saving in seed material. The seed requirement is reduced to less than one ton per acre.

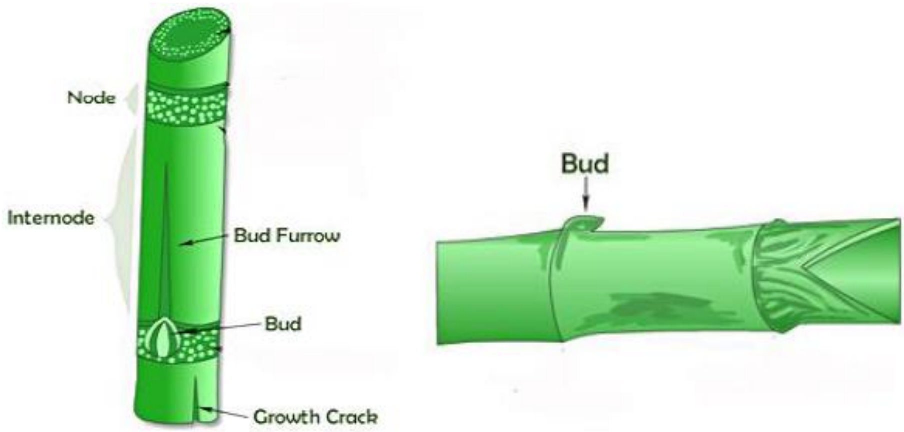

Fig. 1 Sugarcane bud chippers Krishna *et al.* (2017)

Sugarcane planting with traditional methods is costly, time-consuming, and the necessary compression of buds in the field is not achieved easily because of stalk planting in sugarcane. Furthermore, as the demand for sugarcane grows among both small-scale and large-scale farmers, the use of a bud chipping tool will be necessary. However, most of the planting machines in the world do not have the function of bud prevention. More so, the real-time automatic planter is usually fixed-length cutting, and the efficiency is higher than that of artificial planting (Patil *et al.,* 2004; Mandal and Maji, 2008; Singh and Singh, 2016; Kumar *et al.,* 2019). Nevertheless, the bud injury rate is higher and the pre-cutting planter uses pre-cut seeds to avoid seed bud damage and has higher efficiency than the real-time cutting machine (Namjoo and Razavi, 2014; Han *et al.,* 2019). Before sugarcane bud-cutting machines were manufactured, people employed other means of chipping methods to cut the buds from sugarcane. They primarily used a sharp-edged knife to ensure that each bud has a small portion of stem. The method was proven to be laborious, time-consuming, and dangerous. A cane knife was then used in the cultivation of sugarcane, for harvesting and bud cutting alike. The cane knife is a large hand-held cutting tool that was primarily used for sugarcane cultivation in dominant cane-growing countries such as Peru, Brazil, Colombia, Australia, South Africa, Ecuador, Cuba, Jamaica, the Philippines, and parts of the United States. That was until technology advanced and people began to design and devise new ways to better cut buds for sugarcane cultivation; hence the urgency of the sugarcane bud cutter design.

Despite the fact that commercial sugar cane cultivation in Nigeria has suffered a serious setback due to the poor performance of the government-owned sugar companies, which have been privatized since 2002, the country has a huge potential for growing sugar cane on a large scale, particularly along the entire length and breadth of the rivers Niger and Benue. It has been observed in rural areas that most people cut the sugarcane buds manually. It takes a lot of time to cut the buds. Although there are existing machines that can very well perform this task effectively and efficiently, a majority of them are relatively expensive. Thus, in order to realize anti-damage bud and automatic cutting of sugarcane in a single bud segment, a sugarcane cutting system based on machine vision was designed by Deqiang *et al*. (2020). The seed cutting system of their design includes a mechanical part, an electrical part, and a visual processing part.

The core of the system uses machine vision to identify the segments of sugarcane stalks. The feasibility of the system and the identification effect can be better verified based on designing a prototype for seed cutting. The results of the off-line identification of sugarcane stalk segments show that the recognition rate is 93% and the average time is 0.539 s. The developed machine's throughput capacity with a single cutting unit can reach 2400 buds/h. Besides, the on-line test illustrated that the positioning precision of the cutting point can meet the demand of agriculture, and the rate of bud damage is zero. Furthermore, Suraj *et al.* (2016) proposed that the traditional method of sugarcane bud cutting requires a large amount of human labor and a large volume of sugarcane stalk per hectare. To solve this problem, Kiran *et al.* (2016) suggested mechanizing sugarcane planting via the application of machine vision systems and image processing methods to identify nodes in sugarcane and plant them as seeds by planting machines in order to reduce farmers' efforts and increase production of agricultural products. Abel *et al.* (2016) designed and fabricated a semi-automated sugarcane bud chipping machine for agriculture. In this machine, two operations are carried out at a time. The operations that can be carried out on this machine are sugarcane internode cutting and sugarcane bud scooping. In the sugarcane internode cutting operation, sugarcane is cut at its nodal part into small pieces, and in the sugarcane bud scooping operation, the eye of the bud is scooped. Krishna *et al.* (2017) concluded that the bud chips are less bulky, easily transportable, and more economical seed material. Also, the left-over cane can be well utilized for preparing juice, sugar, or jiggery. In a sugarcane inter-node cutting operation, sugarcane is cut at its nodal part into small pieces, and the bud is separated from the sugarcane for seedling purposes. The existing (traditional) tools used for bud cutting of sugar cane are unsafe, messy, and require skill and training. The risk of injury is also too high. This necessitates the development of a bud cutting machine for sugar cane. The specially designed blades are prototyped using stainless steel material attached to the hub. The hub is mounted to the shaft, which is driven by the worm gear through a chain drive. The bud chip technology holds great promise for the rapid multiplication of new cane varieties. The prototype was tested, and the initial results indicated that the equipment has reduced the manual effort required for generating the sugar cane buds as compared to traditional tools. The whole equipment is simple with additional safety measures. However, important operating and performance evaluation parameters of the machine, such as cutting force, cutting power, slider crank mechanism, speed reduction mechanism, materials justification, and so on, were not established in their respective research works. Thus, there is a need to carry out empirical design on sugarcane bud cutters and this will help in developing an effective machine. In this paper, empirical design that depends upon empirical formulae based on practice and past experience is used to determine the operating parameters that can be used for further development of sugarcane cutter machines.

MATERIALS AND METHODS

In designing the prototype sugarcane bud cutter, our concentration was on;

i. Design considerations and requirements
ii. Material selection and justification
iii. Mathematical modelling of the useful parameters using established mathematical and mechanics of mechanics equations

A. Design Considerations and Functional Requirements

Design Considerations

In this section, factors that need to be considered in broad terms were evaluated. To ensure that the proposed machine performs very well, proper considerations were made to specify and identify some problems which hindered effective performance, as in the former machines, in literature reviews, and effort was put into to recognize the factors and limitations.

The selected factors include:

i. Materials and labour
ii. Processing parameters of the materials
iii. Other mechanical properties which depend on the proposed application since the object of all manufacturing are to start with a raw material and add work to it until it is at finished or semi-finished state.
iv. Functionality
v. Reliability
vi. Durability
vii. Materials
viii. Simplicity
ix. Portability and space
x. Operational procedure
xi. Power supplier
xii. Usability
xiii. Maintenance
xiv. Cost
xv. Safety

Functional Requirement

Establishing a functional requirement for the proposed machine is one of the vital elements in the design process, and this task is usually performed at the same time as the feasibility analysis. The functional requirements of the machine will control the design of the project throughout the design process. The following design requirements were drawn:

i. Determination of sugarcane bud cutter force (N)
ii. Estimation of power required by the sugarcane bud cutter (watts)
iii. Determination of approximate length of the belt (m)
iv. Determination of load on shaft pulley and belt tensions (N)
v. Determination of speed of driver and driven pulley
vi. Determination of torque transmitted by electric motor
vii. Selection of bearing for shaft

B. Materials Selection and Justification

The materials selection for the empirical design of the sugarcane bud cutter is based on its mechanical and physical properties. Hardness, strength (yield and ultimate strength based on material properties and performance using stress and strain curve), fatigue, and percentage elongation are examples of mechanical properties. On the other hand, the physical properties of the materials include density, shape, and size. Also, the service requirements of the materials were considered. The service requirements in material selection involve the properties a material should have to serve the purpose for which it is designed; examples include: hardness, strength, stiffness, toughness, corrosion resistance, resistance to heat, conductivity, etc. Besides, fabrication is an important aspect of machine design, and as such, fabrication requirements were considered. It entails workable properties a material should have, and they include machinability, forgeability, malleability, ductility, weldability, castability, etc. Furthermore, economic requirements in material selection were looked into, and they entail the affordability of the material for fabrication and commercialization. It would not be profitable to manufacture at a high cost and sell below the manufactured cost. Table-1 shows the components, material selected, and justification.

Table-1 Material selected and justification

S/N	Sugarcane Bud Cutter Components	Material Selection	Justification
i	Shaft	Stainless steel	Toughness Does not wear easily during operation High tensile strength Ability to resistance corrosion Ability to withstand shear force and compressive force.
ii	Frame	Mild carbon steel angle bar	It's plasticity ability Does not wear easily
iii	Cutter	High carbon steel	Toughness and strength High resistance to wear
iv	Bearing	Chrome carbon steel	High strength, resistance to wear and corrosion
v	Angle bar	Mild carbon steel	Ability to withstand shear force and compressive force.
vi	Metal Sheet	Mild carbon steel	Toughness and strength
vii	Yoke and Sliding Bar	Mild carbon steel	Toughness and strength
viii	Bolts and nuts	Mild carbon steel	Toughness, strength, and do not wear easily

C. Mathematical Modelling of the useful Parameters using established Mathematical and Mechanics of Machine Equations

The free body diagramof the slider crank mechanism is shown in Fig. 1 (Khurmi and Gupta, 2008). As shown, the slider is attached to the connecting rod BC of length b. If the crank AB of radius is assumed to rotate in an anticlockwise direction with uniform angular velocity rad/s and an angular acceleration rad/s^2. In other words, the eccentricity of the crank makes an angle with the *X*-axis and the slider reciprocates along a path parallel to the *X*-axis, an eccentricity CD = *e*, as shown in Fig. 2.

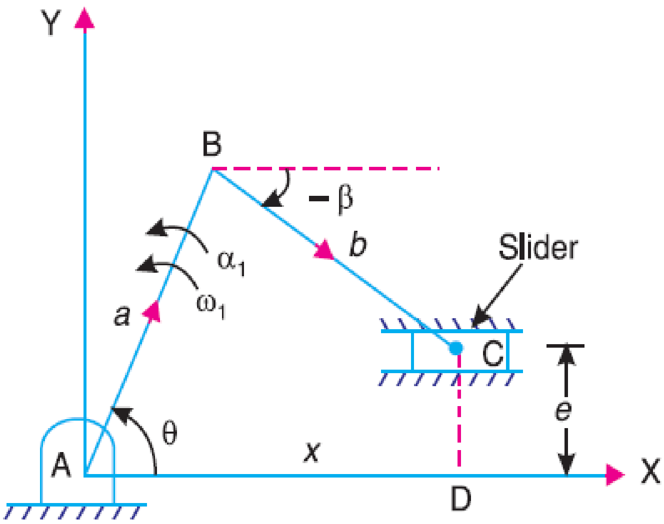

Fig.1 Analysis for slider crank mechanism

Fig. 2 is the resolution of Fig. 1 showing all direction in X and Y axis.

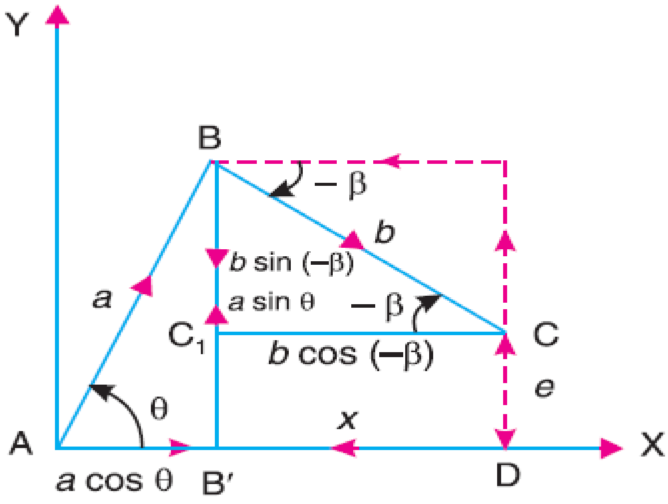

Fig. 2 Slider crank mechanism directions analysis

The expressions for displacement, velocity and acceleration analysis as derived from Fig. 2 is shown in Equation (1) -(6).

$$x^2 + (-2acos\theta)x + a^2 - b^2 + e^2 - 2easin\theta = 0 \quad (1)$$

From Equation (1), the output displacement (x) may be determined if the values of a, b, e and θ are known. Also, the position of the connecting rod BC is given by Equation (2).

$$\beta = sin^{-1}(\frac{-asin\theta}{b}) \quad (2)$$

The linear velocity is determined from Equation (3).

$$\frac{d_x}{d_t} = V_s = \frac{a\omega_1 \sin(\beta-\theta)}{cos\beta} \quad (3)$$

The angular velocity of the connecting rod BC (i.e., ω_2) may be determined from equation **(x)** and it is given by;

$$\omega_2 = \frac{-a\omega_1 cos\theta}{bcos\beta} \quad (4)$$

The linear acceleration of the slider (a_S) is determined using Equation (5).

$$\frac{d^2{}_x}{dt^2} = a_s = \frac{a\alpha_1 \sin(\beta-\theta) - a\omega^2 \cos(\beta-\theta) - b\omega^2}{cos\beta} \quad (5)$$

The angular acceleration of the connecting rod BC (i.e., α^2) was determined using Equation (6).

$$\alpha_2 = \frac{a(\alpha_1 cos\theta - \omega_1{}^2 sin\theta) - b\omega_2{}^2 sin\beta}{bcos\beta} \quad (6)$$

The cutting force is the force requires to successfully cut the sugarcane bud. The weight (W) of the evaluated sugarcanes and cutting blade is given by Equation (7).

W= (Mass of estimated sugarcane + mass of cutting blade) g (7)

To know the torque required to cut the selected sugarcane samples, it became necessary to determine the cutting torque. The cutting torque is given by Equation (8)

$$T = Wr \quad (8)$$

The cutting force (F_c) is given by Equation (9).

$$F_t = \frac{T}{r} \quad (9)$$

The connecting rod force (F_C) is given by Equation (10)

$$F_c = F_t cos\theta \quad (10)$$

The force along sliding (Fs) is given by Equation (11)

$$F_s = F_c cos\theta \quad (10)$$

The cutting power is given by Equation (11)

$$P_c = \frac{T \times 2\pi N}{60} \quad (11)$$

where,
r = Radius from axis of rotation to point of application of force
Fs = Force along sliding
Fc = Connecting rod force
Ft = Tangential force of the crank
Pc = Cutting power

RESULTS AND DISCUSSION

The empirically designed sugarcane bud cutter basically works on the principle of the Single Slider Crank Mechanism (SSCM). It converts rotary motion into a reciprocating machine to cut the sugarcane buds. A single slider crank chain is a modification of the basic four-bar chain. It consists of one sliding pair and three turning pairs. In this system arrangement, a fixed link and the crank link are rotated about the fixed link where it converts this rotary motion into the reciprocating motion of the slider by means of a connecting rod. This is the inversion of the single slider crank, which is obtained by fixing the link. This mechanism is one of several capable of producing the straight-line, backward-and-forward motion known as reciprocating. Essentially, the crank-slider converts rotational motion into linear motion, or vice versa. The result of the evaluated parameters for the sugarcane cutter is shown in Table-2.

Table-2 Result of the evaluated parameters

S/N	Parameters	Determined Values	Unit
1	Length of crank	0.20	m
2	Length of connecting rod	0.75	m
3	Angular velocity	20.05	rad/sec
4	Angular acceleration	10.15	rad/sec^2
5	Linear velocity of slider	1.28	m/sec
6	Linear acceleration of the slider	62.49	m/sec^2
7	Angular velocity of the connecting rod	4.51	rad/sec
8	Angular acceleration of the connecting rod	-47.89	rad/sec^2
9	Weight of the evaluated sugarcanes and cutting blade	255.25	N
10	Cutting force	504.23	N
11	Cutting power	1495	watt
		2	hp
12	Connecting rod force	436.67	N
13	Force along sliding	378.17	N
14	Cutting torque	33.18	Nm

As shown in Table-2, the results of the length of crank, length of connecting rod, angular velocity, angular acceleration, linear velocity of slider, linear acceleration of the slider, angular velocity of the connecting rod, angular acceleration of the connecting rod were determined as 0.20 m, 0.75 m, 20.05 rad/sec, 10.15 rad/sec^2, 1.28 m/sec, 62.49 m/sec^2, 4.51 rad/sec, and-47.89 rad/sec^2 respectively. Furthermore, the weight of the evaluated sugarcanes and cutting blade was obtained as 255.25 N and this was used to evaluate the cutting force, cutting torque, and cutting power of the sugarcane bud cutter. It was established from the empirical design that a minimum cutting force, torque, and power of 504.23 N, 33.18 Nm, and 2 hp are required for the operation if eventually fabricated. Besides, the connecting rod force and the force along the sliding which are obtained from the crank and connecting rod are high as compared to the length of the crank and connecting rod. Angular velocity and acceleration have a defined relationship with each other. They also satisfy the required conditions as expected.

CONTRIBUTION TO KNOWLEDGE

An empirical design of a sugarcane bud cutter was successfully carried out using mathematical models and mechanics of machine established equations. The designed parameters can be used to fabricate a prototype sugarcane bud cutter machine.

CONCLUSION

This research work focused on the empirical design of a sugarcane bud cutter. Mathematical modelling and established mechanics of machine equations were used to design the operating parameters of the proposed machine. A single-slider crank mechanism was used to determine crank and connecting rod length, linear and angular velocity, and acceleration of the mechanism. More so, the results of the length of crank, length of connecting rod, angular velocity, angular acceleration, linear velocity of slider, linear acceleration of the slider, angular velocity of the connecting rod, angular acceleration of the connecting rod were determined as 0.20 m, 0.75 m, 20.05 rad/sec, 10.15 rad/sec^2, 1.28 m/sec, 62.49 m/sec^2, 4.51 rad/sec, and-47.89 rad/sec^2 respectively. Furthermore, the weight of the evaluated sugarcanes and cutting blade was obtained as 255.25 N and this was used to evaluate the cutting force, cutting torque, and cutting power of the sugarcane bud cutter. It was established from the empirical design that a minimum cutting force, torque, and power of 504.23 N, 33.18 Nm, and 2 hp are required by the operation if eventually fabricated.

CONFLICT OF INTEREST

There is no conflict of interest for this research work.

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