ORIGINAL PAPER

DESIGN AND DEVELOPMENT OF SPECIAL CUTTING SYSTEM FOR SWEET SORGHUM HARVESTER

OMID GHAHRAEI 1*, M. H. KHOSHTAGHAZA2 AND DESA BIN AHMAD3

1 Mechanical Engineering Department, Faculty of Engineering, Islamic Azad University (IAU), Majlesi Branch, Majlesi New Town, Isfahan, Iran.
2 Mechanics of Farm Machinery Department, Faculty of Agriculture, Tarbiat Modares University (TMU), Tehran, Iran.
3 Biological and Agricultural Department, Faculty of Engineering, University Putra Malaysia (UPM), Serdang, Selangor, Malaysia.
*Corresponding Author: oghahraee@iaumajlesi.ac.ir and ghahraeiom@yahoo.com Fax: 00983355452294

Manuscript received: September 24, 2006; Reviewed: October 27, 2008; Accepted for publication: November 5, 2008

ABSTRACT

Sweet Sorghum is similar to racemose maize with about 3m height and 0.5-3cm thickness of stalk. Sweet Sorghum has sweet flavor stalk, which is used for sugar production. Developed cutting mechanism in this research has a rotary disk with 50 cm diameter and four cutting blades that spin clockwise. The stalks are cut with the impact and inertia forces at the linear velocity of 27 m/s, by cutting blades. This system has a simple bar mechanism guiding the whole-stalk to one side. The cutting quality tests were achieved by two series of blades with 30°and 45° blade angles on the stalk. The results showed that the stalk cutting surface with 30° blade angle was smooth and without fracture on filaments and vasculums, compared to that of 45° blade angle. Blade penetration was accomplished very well with 30° blade angle.

Keywords: Design, Development, Rotating Cutting System, Sweet Sorghum, Harvester

INTRODUCTION

Sweet Sorghum belongs to Gramineae, and it is similar to racemose maize. Its water need is less than other similar plants such as maize because of its deep root development. Therefore, Sweet Sorghum is planted in warm and low water areas of the world in all of the soils, and the period of planting till harvesting for this plant is short (90-120 days). Currently, Sweet Sorghum is planted in 95 countries of the world [10]. This plant is sensitive to cold weather, and the minimum temperature for its life is 7-10°C. Suitable soil pH for its growth is 5-8.5, since it is semi-sustained to saltiness. In other words, Sweet Sorghum has extensive adaptability and resistance to saline-alkaline soils and water longing [9, 11].

Sweet Sorghum has sweet taste stalks, and it can be used for sugar production similar to sugarcane. In weather condition of Iran, we can acquire sugar by 4 ton/hectare [6]. Production of Alcohol from this plant is four times that of sugar beet molasses. The developed countries in this industry prepare alcohol from Sweet Sorghum syrup. For example in 1985, Brazil prepared 3387 liter Ethanol from 33.7 ton of stalks in one hectare. Refused stalks can be used in cellulose industries, fiberboard production and animal food [2]. Nowadays, another usage of Ethanol is as car and vehicle fuel. In other words, Ethanol is one of the best fuels with lowest amount of damaging exhaust production and air pollution, because of its high content of oxygen [9].

In kinds of Sweet Sorghum, 7-15.9 percent of expressed juice is formed from sugar (Glucose, Fructose, Sucrose and Starch) in which 50 percent of that pure sugar is Sucrose [14]. Sweet Sorghum planting is more advantageous than sugarcane and sugar beet (Since it needs less water, produces maximum sugar production per hectare and has short growing period) [7].

Sweet Sorghum is planted on ridges by 10 cm distance a part, 3-4 cm depth and 75 cm between rows by planting machine. So far, special commercial harvester for this plant has not been developed in Iran. However, few researches on this harvester were accomplished in U.S.A Moisture of Sweet Sorghum stalks during harvesting time is about 80-90%. When moisture is low, stalk syrup amount decreases, and more cutting force is needed for cutting stalks [3].

The best harvesting time for Sweet Sorghum is at the proper stage of maturity. The syrup amount and quality will be affected by the composition of the stalk juice specially sugar content. Therefore, selecting the true time for harvesting near the maturity stage is important. The proper harvesting time is when the majority of the seeds reach the soft- to hard-dough stage of maturity. In spite of maturity of stalks, harvesting before freezing can prevent the ruining of juice for syrup production. [4].

Harvesting of Sweet Sorghum in research farm of Isfahan University has been accomplished by special sickles called "Dastghaleh". With extension of planted areas, the need for a special harvester for Sweet Sorghum was necessary [1]. It was not possible to use maize chopper to harvest Sweet Sorghum, because earlier experiments showed that cut and chopped stalks of Sweet Sorghum with a chopper must be utilized for syrup extraction within several hours. Otherwise with a short time more existing sugars in the stalks would be changed to Alcohol, because microorganism activity and efficiency of sugar extraction would be decreased. However, after 30 days keeping of whole-stalks of harvested Sweet Sorghum, fermentation of stalk sugar is little [5].

Generally, Sweet Sorghum stalks are harvested by hand in small farms and by a mower in large farms (chopped stalks with 6- to 8-inch sections) then picked up and squeezed in the field. It is better to cut and remove the seed head and peduncle (between top node and base of seed head) because they contain less sugar than the main stalk. Also, the leaves should be removed or allowed to dry before squeezing and extracting the juice from the stalks [4].

Some U.S.A researchers have designed a research harvester for Sweet Sorghum. It cuts stalks from low point by means of special cutting disk, and a chained mechanism transfers whole-stalks of Sweet Sorghum to its accumulator [13]. Due to necessity needed for mechanized harvesting in our country, we decided to design and develop the special harvester for Sweet Sorghum. This research was accomplished in 12 months.

MATERIALS AND METHODS

Cutting System and Cutting Mechanism Selection

The first stage was the design of a special cutting system for this plant with due attention to physical properties of Sweet Sorghum stalk. All of the used mechanisms in the harvesting machines were designed according to two systems: Cutter-bar Cutting System (with the help of scissor shearing method) (CCS) and Rotating Cutting System (with the impact and shear method) (RCS) [8].

CCS was used for cutting the annual plants stalks (thin stalks). RCS was used more often for more thick stalks (up to 0.5 cm) with more cutting resistance. RCS uses inertia force and impact force for cutting of stalks, but CCS uses come and go movement of blade for cutting of stalks. With due attention to specification of those systems and physical properties of Sweet Sorghum stalk, RCS was selected.

Mechanisms that work on the basis of RCS are: Saws

Cutting Mechanism (SCM), Coulter Cutting Mechanism (CCM) and Disk Cutting Mechanism (DCM) [8].

SCM has main problems in that it cannot work under the condition of harvester trembling while the harvester is moving on the ground; therefore, manufacturing of special toothed disks (like saw) is very expensive [8]. CCM is made of two small disks with sharp edges functioning as scissors. This method is used for up to 2 cm diameter stalks.

The only mechanism which can cut all kinds of thick stalks more than 2 cm diameter is DCM with different blade shape, different number of blades and different blade angles for different plant with thick and juicy stalks and with different cutting resistance; therefore, for Sweet Sorghum stalks, rotating cutting system (impact) with the kind of disk cutting mechanism was selected.

Design Information and Details

In designing the cutting system, maximum cutting force for cutting of Sweet Sorghum stalk was 31 N/mm based on the cutting for maize stalk with 87% moisture (maize stalk is exactly similar to Sweet Sorghum stalk). For thick stalks like maize, sunflower, etc., blade linear velocities were in the range of 25-30 m/s, and advance velocities between 4.5-9 km/h [12]. We considered blade linear velocity of 27 m/s.

According to design calculations, for better continuous cutting in rows, four blades were considered. The cutting blades were made from special heat treated steel (with hard surface and soft pith).

Recommended blades for rotating cutting of maize stalk were with angles of 23-45° that need minimum cutting force. According to needed power calculation for one thick stalk, a one phase electromotor (1.1 kW and 1420 rpm) was selected.

With due attention to rotary inertia forces for these stalks rotational speed must be low (900-1000 rpm) [12]. Disk diameter was 50 cm. Amount of blade offset from around the disk was 4 cm (a few more than maximum stalk diameter of Sweet Sorghum). Considering a disk effective diameter of 29 cm and blade linear velocity of 27 m/s, disk rotational speed calculated was 889 rpm. Details of design specifications of the parameters are shown in Table 1.

Based on the diagram of the cutting force (F) according to the blade movement in stalk diameter (d) (Figure 1), initial area of this curve (similar to a triangle) is calculated by equation (1) [12].

$$E_0 = F_{\max} \frac{d}{2} \quad (1)$$

Considering $F_{\max}$ of 930 N (by multiplying special cutting force of 31 N/mm and maximum stalk diameter of 30mm), and d of 30 mm for maximum stalk diameter, the total needed energy for cutting of one stalk is 13.95 J.

By considering maximum stalk diameter of 30 mm, the passed angle by blade in 30 mm will be π/30 radian or 6°.

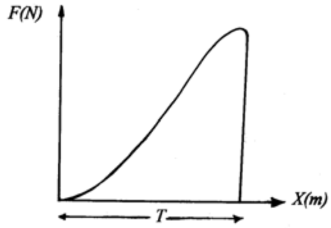

Figure 1: Diagram of Cutting Force (F) Versus Blade Movement (X) in Stalk Diameter (T)

According to equations (2) and (3) [8], the passed time for cutting of one stalk is 0.001124 s (with rotational speed of 889 rpm). So the needed power for cutting of one stalk will be 12411 W.

$$t = \frac{\theta \cdot \theta}{2\pi \cdot n} \quad (2)$$

$$P = \frac{E_0}{t} \quad (3)$$

With due attention to the high cutting power, a lot of this power must be obtained by the mass of system.

For thick stalk plants the advance velocities are recommended between 4.5 to 9 km/h [12]. Considering the planting distance between two stalks on one ridge (10 cm), the needed times for passing the disk from one stalk to another stalk in advance velocity of 4.5 km/h and 9 km/h are 0.08 s and 0.04 s, respectively. The passed angles of disk in these times are 7.45 rad (≈ more than 2π rad) and 3.72 rad (≈ more than 2π rad), respectively.

According to design calculations and existence of two cuttings in every cycle, two blades are needed. But in special conditions when the stalk distance is less than 10 cm or advance velocity is more than 9 km/h, for better continuous cutting in the rows, four blades will be considered.

Flywheel is a rotational mass used for saving of energy in the machines. Special energy is saved in the cutting system by the disk mass and inertia forces at the time of rotation, and it helps in cutting. Using equations (4) and (5), the mass of cutting system and the needed power can be calculated [7].

Table 1: Design Specifications.

Parameter	*Value*	*Parameter*	*Value*
Disk diameter	50 cm	The width of removable frame	75.5 cm
The number of blades	4	The length of removable frame	120 cm
The linear velocity of blades	27 m/s	Electromotor power	1.1 kW
Rotational speed of cutting disk	889 rpm	Rotational speed of electromotor	1420 rpm
Allowable advance velocities	4.5-9 km/h	Maximum ability of height changing in cutting disk from the ridge surface	22 cm

Figure 2: The Developed Blades with Angles of 30° and 45°

$$E = E_1(1 - \frac{t_1}{t}) \quad (4)$$

$$M = \frac{E}{C.v^2} \quad (5)$$

By considering 13.95 J for E_1, 0.001124 s for t_1, 0.004s for t, 27 m/s for v and 0.01 for C (for thick stalk is given 0.01), E and M will be 13.56J and 1.85 kg, respectively. So the total needed mass for four cutting in every cycle will be 7.4 kg.

Equation (6) enables us to calculate the final needed power on the disk shaft in the cutting system.

$$P = \frac{(E_0 - E)}{t_1} \quad (6)$$

By putting the values of 13.95 J, 13.56 J, 0.001124s in place of E_0, E and t_1, respectively, P will be 347 W. The amount of power for two cuttings in one cycle would be 694 W in near to real condition (by considering energy saving with the system mass). A one phase electromotor of 1.1 kW and 1420 rpm was used for starting the developed cutting system.

Development of Cutting Blades

Cutting blades (rotating and impact implements) must be made from special heat treated steel. In this research we used a special carbon tool steel with a standard number of 1.1744. The blades were made with the dimension of 10×5×1 cm, and were changed to special heat treated steel with hard surface and soft pith under solid carburetion procedure. The carbon from carbon monoxide gas was entered to steel surface up to 22% of profile surface. Finally, two series of blades were made with the angles of 30° and 45° (Figure 2).

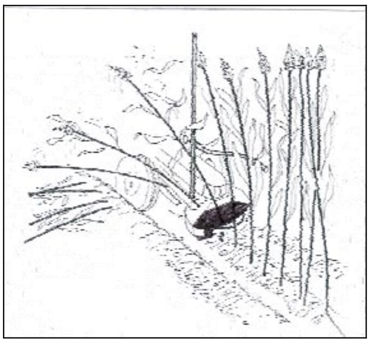

Figure 3: The Figure of cutting system while harvesting the Sweet Sorghum stalks

Cutting System Tests

For evaluation of the developed system, it was installed on a removable frame. Harvesting tests in Sweet Sorghum farm with advance velocity of 5 km/h and two series of blades with angles of 30° and 45° on the stalks between 1.5 to 3 cm diameters were accomplished (Figure 3).

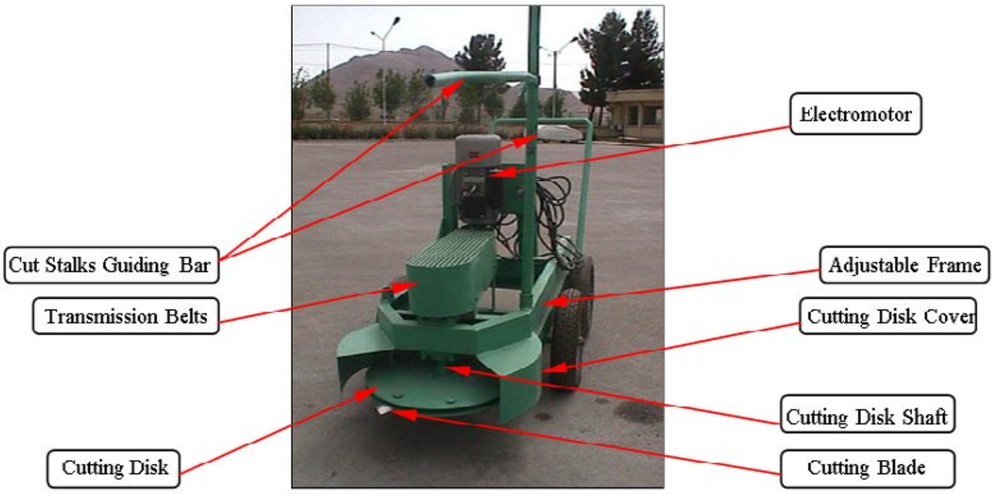

Figure 4: The Developed Cutting System on the Removable Frame

Details of the developed cutting system on the removable frame and the cutting disk system with blades are shown in Figures 4 and 5, respectively.

RESULTS

Cutting Quality Test Results

The tests were conducted on three rows of Sweet Sorghum: Rows A (150 stalks with 0.5-1.3 cm average diameter), B (150 stalks with 1.5-2.2 cm average diameter) and C (150 stalks with 2.2-3 cm average diameter). Meanwhile, two kinds of blades with angles of 30° and 45° were selected. Cutting of stalks in row A, caused to throw stalks and to fracture of vascular tissues and filaments in cutting locality, and cutting surface that was not clean and smooth.

According to theoretical rules, the results were expected with two kinds of blades, because narrow stalks needed high rotating velocity of 2000-3000 rpm and linear velocity of 50-75 m/s [3]. But harvester blades in this test had linear velocity of 27 m/s for thick and heavy stalks.

Cutting of stalks in row B had smooth surface, relatively, and stalk filament and vascular tissues fracture was less (cutting quality with 30° blade angle was better than 45°. Stalks in row C cut with blade angle of 30° had very smooth and clean cutting surface on stalk filaments and vascular tissues. Blade with 45° angle accomplished a fine cutting on stalks, relatively. These tests were conducted to observing of cutting surface quality.

Field Test Results

The field test of harvester (developed cutting system on the removable frame) was conducted on one hectare farm district (100×100 m). It had 12 rows with 100m length.

Figure 5: Cutting Disk System and Blades with the Angle of 45°

There were about 950 stalks in every row. Advance velocity was 5 km/h and total harvesting time including gathering of harvested stalks was approximately 45 minutes (Figure 3). Field harvesting around the farm was without any crushes of stalks or uncut stalks.

DISCUSSION

According to the test results, cutting quality for stalks with 2.5-3 cm thickness with 30° blade angle was satisfactory. Our criterion for cutting surface quality is a smooth and clean cutting surface with no fracture on stalk filaments and vascular tissues.

Cutting quality with 45° blade angle was quite good, but in second priority. With due attention to blade resistance against the hard materials in the farm soils, the blades with 45° angle is recommended for this harvester, because of low height of cutting section (because gathering of sugar is the lowest points of stalks).

Electrical force of electromotor for the harvester was available with a Generator that was moved parallel with a harvester, and stalks were falling on beside the row that was harvested before with guide-bar mechanism.

It is expected that with completion of stalk guiding system to accumulator and be able to connect to the tractor, a one row completed harvester can harvest one hectare with an advance velocity of 5 km/h.

CONCLUSION

In this paper, a special cutting system for Sweet Sorghum harvester was designed and developed. It can be concluded that:

1) Cutting system has a cutting disk (with 50 cm diameter) with four blades that cut the whole-stalks by impact force. It is expected that the developed cutting system will be able to work under different farm conditions as planting compression or extra advance velocity of harvester.

2) Removable frame of developed system has changeable cutting heights from the ridge surface till 22 cm. The machine has four tires with 38 cm diameter that can help the machine move between the rows. This system has simple bar-mechanism for guiding of cut stalks to one side to stop being crushed under the tires.

3) This simple harvester (installed cutting system on the removable frame) has performed well in harvesting Sweet Sorghum grown in small or large farms (Figures 3 and 4).

REFERENCES

[1] Almodarres, A. Project report of studying about the better racial and the better farming of Sweet Sorghum in 1984-1986. Publication Center of Isfahan Agricultural Administration. Isfahan, (1987).

[2] Assis, F. N. D., Medez, M. E. G. and Schuch, L. O. B. Response of a Sweet Sorghum cultures to different sowing patterns in Petotas. R. S. (1982-83). Petotas. Brazil. UEPAE, (1984).

[3] Behroozilar, M. Engineering principles of agricultural machines. Islamic Azad University Scientific Publication Center. Tehran, (2000).

[4] Bitzer, M. J. and Fox, J. D. Production of Sweet Sorghum for Syrup in Kentucky. Cooperative Extension Service, University of Kentucky, College of Agriculture, Lexington. AGR-123. (2000).

[5] Eiland, B.R., Clayton, J. E. and Bryan, W. L. Harvesting and storage of sweet sorghum biomass in Florida. In Proceedings of the American Society of Sugarcane Technology. (1984) 3: 18-21.

[6] Ghavami, R. Studying of the kind and amount of carbohydrate in Sweet Sorghum stalk in growing stages. Unpublished M. S. Thesis. College of Science. Isfahan University, (1991).

[7] Hajrasooliha, SH. Yearly report of experiments in Haft-tappeh sugarcane factory. Publishing of Agricultural Ministry. Tehran. Iran, (1989).

[8] Jafarinaeimi, K. Development of measurement system of cutting force and design of cutting system for Atriplex harvester. Unpublished M. S. Thesis. College of Agriculture. Tarbiat Madres University (TMU), (1996).

[9] Makrantonaki, M. S., Papalexis, D., Nakos, N., and Kalavrouziotis, I. K. Effect of modern irrigation methods on growth and energy production of sweet sorghum (var. Keller) on a dry year in Central Greece. Agricultural Water Management. (2007) 90:181–189.

[10] Mirjalili, A. Attention necessity to Sorghum in Iran. Resalat newspaper. (1996) 2987: 11

[11] Nasir, E. B, Dambroth, M. and G. Gerhard, H. L. Sweet Sorghum a new source of row material for the sugar industry. Plant Res. and Dev. (1990) 31: 7-17.

[12] Persson, S. Mechanics of cutting plant Monograph. No. (7). American Society of Agricultural Engineers, (1987).

[13] Rains, G.C, Cundiff, S. and Vaughan, D. H. Development of a whole-stalk sweet sorghum harvester. ASAE. (1990) 33(1): 56-62.

[14] Subromanian, V., Rao, K. EP., Mengesha, M. H. and R, J. Total sugar content in Sorghum stalks of selected cultures from the world germplasm collection. J. Sci. Food Agr. (1987) 39: 289-295.

LIST OF SYMBOLS

E_0	total needed energy, J;
F_{max}	maximum cutting force, N;
d	stalk diameter, m;
t	cutting time, s;
θ	passed angle in cutting, rad;
n	rotational speed, rpm;
P	total needed power for cutting, W;
E_0	the total needed energy, J;
E	energy saving of system, J;
E_1	the total used energy, J;
t_1	time between two continues cutting in maximum number of cutting in every cycle, s;
t	time between two continues cutting in maximum allowable advance velocity, s;
M	needed mass in cutting system, kg;
v	blade linear velocity, m/s;
C	coefficient of velocity;
$(E_0 - E)$	subtraction amount of total energy and energy saving of system, J;