Effect of Knife Velocity on Cutting Energy and Efficiency during Impact Cutting of Sorghum Stalk

Y. D. Yiljep[1] and U.S. Mohammed[2]

[1]Agricultural Engineering and Irrigation Programme,
National Agricultural Extension and Research Liaison Services,
Ahmadu Bello University, PMB 1067, Zaria, Nigeria. yiljep56@yahoo.com

[2]Department of Agricultural Engineering/Institute for Agricultural Research,
Faculty of Engineering, Ahmadu Bello University, PMB 1044, Zaria, Nigeria.

ABSTRACT

A laboratory test-rig consisting of a pendulum-like oscillating arm was designed and fabricated for measuring cutting energy requirement and cutting efficiency on sorghum stalk. The sorghum stalk was fixed in a stalk holder to simulate a free-standing stalk in the field. A blade, sharpened at 30% bevel angle, was attached to the lower end of the arm which cut the stalk at 90^{o} to the stalk axis with knife velocities up to 8.5m/s. The experiment was conducted during cutting of sorghum stalk base (20 mm) and stalk height (120mm) above the ground level. The results showed that there was high correlation $p \leq 0.1$ between knife velocity, cutting energy requirement and cutting efficiency. Cutting energy requirement showed negative linear correlation with knife weight and stalk moisture content with cutting efficiency showing positive linear correlation with the parameters. The minimum cutting energy requirements for 20 and 120 mm were 7.87 and 12.55 Nm respectively, at corresponding knife velocities of 2.91 and 3.54 m/s. The maximum cutting efficiencies were 98 and 97% at 5.2 and 7.3m/s knife velocities, respectively.

Keywords: Sorghum stalk, impact cutting, velocity, energy, efficiency

1. INTRODUCTION

The cutting of stalks is an important process in sorghum harvesting, forage harvesting, weeding, stalk shredding and lawn mowing. The cutlass, scythe, knife and hoe which were old traditional tools have been replaced by stalk cutting machines. These are the reciprocating types and the rotary impact types. The latter is being increasingly used in these operations due to its simplicity in construction, low maintenance cost and ability to but both small and large diameter stalks (McRandal and McNulty, 1978).

Cutting using single element differs greatly from that using two opposed elements. The latter case is cutting with counter-edge and thus, the stalk is supported in the vicinity of the cutting element. In this case, there is little or no energy wasted in the stalk deflection before cutting.

Cutting with single element can be referred to as pure impact cutting and depends mainly on the knife speed, cutting edge sharpness and crop inertia. Stalk resistance to bending is insufficient by itself to provide the force necessary to oppose the knife pressure required to penetrate the material, the cutting process depends on the stalk inertia to give the required opposing force. Thick stalks have lighter inertia than thin stalks and therefore, require relatively lower knife speed than in their stalk cutting (Akritidis, 1974; Prasad and Gupta, 1975; Oke et al., 1984; Mohammed, 1990 and Jekendre, 1999).

The energy required for the cutting unit of stalk cutter may be categorized as: frication in the moving parts of the machine and air friction; kinetic energy required to accelerate the chopped material; energy required to overcome friction of the chopped material against the stationary parts of the machine; and energy required to cut the stalk (Dernedde and Peters, 1971; O'Dogherty et al., 1995; Kronbergs, 2000; Chattopadhyay and Pandey, 2004). Blevins and Hansen (1956); Richey (1958); Liljedahl et al. (1961); McRandal and McNulty (1978) also considered energy expended in stubble deflection. In the case of a slasher or harvester, the relationship between peripheral speed of the rotating blade and the translatory speed of the machine (speed index) is also an important factor (Kepner et al., 1978).

Despite the extensive studies conducted on properties of plants, stems and blade characteristic in relation to cutting performance (cutting energy requirement and cutting efficiency), none was able to provide such comprehensive relationship for thick-stemmed crops such as sorghum, millet and maize.

The aim of this study is to develop a sorghum impact cutting rig and determine its cutting energy and cutting efficiency for various knife velocities.

2. MATERIALS AND METHODS

2.1 Experimental Sorghum Stalks Used

The experimental material for the study was a tall fara fara Sorghum variety KSV-13, planted in the experimental field of the Department of Agricultural Engineering, Ahmadu Bello University, Zaria, Nigeria, and managed to maturity for the experiment. The same variety was used throughout the experiment to eliminate the effect of varietal differences in cutting performance. Sharp knives (sharpened using grinding machine and smoothened with a hand stone), made of high speed saw blade, 4mm thick, were used during the experiment. Stalks of physiologically matured sorghum plants of the same diameter were selected and cut to equal lengths of two meters to keep both stalk diameter and height constant. The experiment was conducted the same day to minimize variation in crop material properties.

2.2 Measurement of Stalk Dimensions, Weight and Density

The methods and tools used for the above were;

2.2.1 Length

A stanley steel tape with 0.1cm divisions was used in measuring stalk height and height of cut.

2.2.2 Diameter

A vernier caliper with 0.005 cm divisions and 15 cm maximum reading was used in measuring the minor and major stalk diameters at height of 5 cm above the ground level.

2.2.3 Weight

The weights of the blade and stalk samples were recorded using weight balance with an accuracy of 0.001 kg.

2.2.4 Density

The density of the stalk was found by displacement method using kerosene instead of water to avoid water absorption by the sample. The weight of the sample in the air and the weight of the kerosene displaced were recorded and density was calculated as in equation (1).

$$\rho = W_a/W_k \text{ x } S_k \qquad (1)$$

where,

ρ = density of stalk, kg/m^3; W_a = weight of stalk in air, kg; W_k = weight of kerosene displaced by sample, kg; S_k = mass density of kerosene, kg/m^3.

2.2.5 Moisture Content

The moisture content of the sorghum stalk was measured according to ASAE Standard S.352 (ASAE Year Book, 1979). About 2.25kg sample of stalk (one half from each of the severed parts) was kept in an oven for 24 hours at 105^{o}C. The loss in weight of the sample was recorded and the moisture content in percent was determined as in equation (2).

$$M.C_{wb} = (W_i \text{ x } W_d/W_i)\text{x}100 \qquad (2)$$

where,

$M.C_{wb}$ = moisture content (%); W_i = Initial weight of sample (kg); W_d = dried weight of sample (kg).

2.3 Instrumentation

An oscillating-impact–cutting-rig was designed and constructed for this study. It is similar to Izod impact cutting machine for metals. It consists of the frame, swinging arm, weights holder, stalk holder and angle indicator (Figures 1 and 2).

2.3.1 Principle of Operation

The apparatus works on the principle of a compound pendulum where a long arm suspended at its top end and has a knife fixed at the lower end is made to oscillate in the vertical plane. It is normally displaced to one side of the equilibrium position by an angular deflection θ^o_i. By the principle of conservation of energy, the swinging arm when released is expected to oscillate to the other side of equilibrium line and deflection through an angle θ^o_o. However, due to frictional losses in the parts and air resistance, θ^o_o is normally less than θ^o_i. There is a continuous exchange of energy of the swinging arm from maximum potential energy when the arm is at its extreme position (upswing) before it is released to swing down loosing potential energy and gaining kinetic energy to maximum kinetic energy when the arm is at the equilibrium line. The material to be cut is normally placed at the point of maximum kinetic energy of the swinging arm and held by the stalk holder. When the arm is released, it gains speed till it meets and cuts the material placed in the path of the knife.

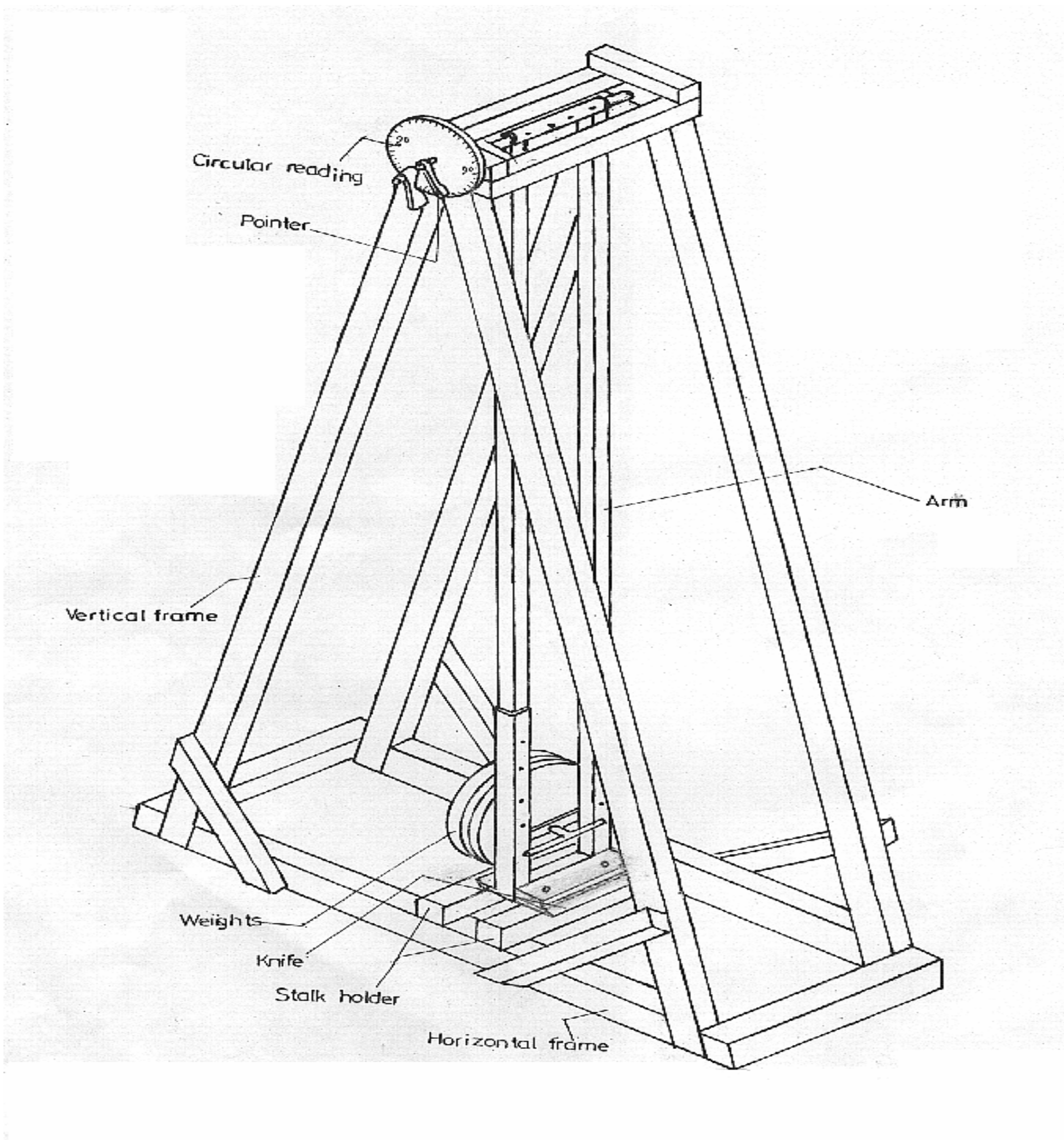

Figure 1. Isometric view of the oscillation impact cutter

2.3.2 Calibration of the Test Rig

Using method of least squares, the regression equation for determining maximum angular upswing deflections without cutting from known initial angular deflection was obtained as shown in equation (3).

$$\theta^{\circ}_{o} = 1.002\theta^{\circ}_{i} - 2.093 \quad (3)$$

where,

θ^{o}_{o} = maximum angular upswing deflection without cutting (^{o}); and θ^{o}_{i} = initial angular deflection of swinging arm (^{o}).

During the experiment, a stalk was fitted firmly in the stalk holder to simulate natural stand of stalk in the field. The holder is located at the lowest oscillating point where the equilibrium line is located. The arm is then given an appropriate angular displacement, θ_i. Where released, it gained speed as it moved downwards till it attained maximum speed which corresponded with maximum kinetic energy achieved recorded as θ_c.

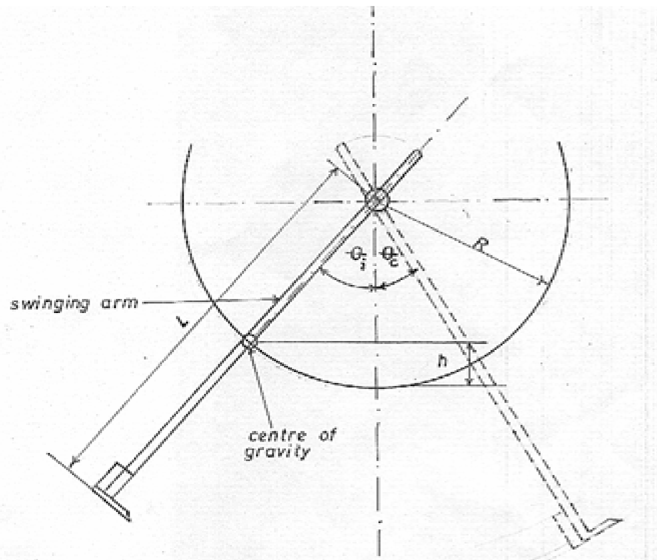

Figure 2. Displacement of the swinging arm

The cutting energy conserved during cutting of the stalk was determined by the difference between θ_o and θ_c. Expressions for determining cutting energy requirement and peripheral knife speed were given as stated by Feller (1959), Prasad and Gupta (1975) and Mohammed (1990) and presented as in equations (4) and (5).

$$E = E_e(\cos\theta_c - \cos\theta_o) \quad (4)$$

$$V = V_v\,(1- \cos\theta_i)^{1/2} \quad (5)$$

where,

E_e = stalk cutting energy requirement (determined to be 492.50 Nm in this study); θ_c= maximum angular displacement after cutting (^{o}); θ_o= maximum angular displacement in the absence of cutting (^{o}); V_v = peripheral knife speed at the cutting position (determined to be 7.78 m/s in this study); θ_i= maximum angular displacement before cutting (^{o}).

For cutting efficiency measurements, five stalks were placed in the stalk holder. The percent number of stalk cut gave the cutting efficiency. A cutting height of 120mm above the stalk holder was used to represent free-standing stalk without support near the cutting point and 20mm cutting height to approach condition of supported stalks.

3. RESULTS AND DISCUSSION

3.1 Effect of Knife Velocity on Cutting Energy Requirement

Figure 3 presents the relationship between knife velocity and cutting energy requirement for stalk base and top. It shows that the cutting energy requirement decreased with increase in knife velocity and their maximum values of 7.87 and 12.55 Nm corresponding to knife velocities of 2.91 and 3.54m/s respectively for cutting the stalk base at 20 and 120 mm above the ground level. Beyond the minimum values the energy increased with further increase in knife velocity for both cases. The decrease in cutting energy requirement at knife speeds less than 3 and 5m/s for stalk base and top respectively can be explained by the fact that at lower velocities, impact force was too small to sufficiently cut the stalk.

The increase in the energy with knife speeds higher than those at minimum values is because at high knife speeds, more energy imparted by the knife is just wasted, since more energy is transmitted in accelerating the separated parts of the stalk after cutting. Feller (1959) observed that in cutting tall alfalfa stalks, the amount of energy transmitted to the separate parts of the stalks was large in relation to the energy requirement for actual cutting itself. He (Feller, 1959) further reported that alfalfa and Sudan grass stalks can be cut by impact action at speeds ranging from 1.48 to 9.75 using sharp knife.

The result is in agreement with that of Gwani (1986) for cutting sorghum and maize stalks although he did not obtain the minimum value for the cutting energy requirement and the corresponding knife speed. The range of knife speed corresponding to the minimum cutting energy requirement obtained for cutting the stalk base is close to the 2.65 m/s speed obtained by Prasad and Gupta (1975) for cutting maize stalk base.

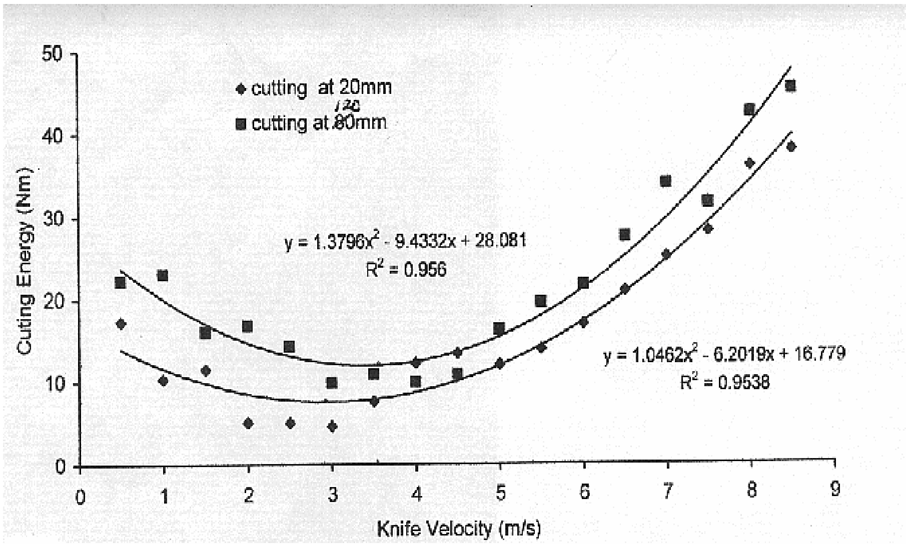

Figure 3. Effect of knife velocity on cutting energy

3.2 Effect of Knife Velocity on Cutting Efficiency

The effect of knife velocity on cutting efficiency is presented in Figure 4. The curves show increased cutting efficiency with increases in knife velocity up to maximum values of about 98 and 97% corresponding to knife velocities of 5.2 and 7.3m/s for cutting stalk base at 20 and 120mm above the ground level, respectively. Further increase in the speed after 7.3m/s resulted in a decrease in cutting efficiency at the rate of 2.3% per meter per second of the peripheral speed. There was high significant effect of knife speed on cutting efficiency at $p<0.01$ level of significance. After the maximum values, the cutting efficiency decreased with further increase in knife velocity for both cases. The regression analysis indicated a high correlation with coefficients of determination of 0.90 and 0.97 for cutting sorghum stalks at 20mm and 120mm, respectively.

The lower value of minimum cutting energy requirement at less knife velocity when cutting at 20mm as against 120mm above the ground level was because it enjoyed greater ground support at the vicinity of the cutting point. Thus, it behaved as cutting with converter-edge which attacks low energy consumption as little or no energy is expended in stalk deflection. The higher maximum value of cutting efficiency at less knife velocity attributed to cutting at 20mm is due to the same reason as explained for cutting energy requirement.

These results are higher than those reported by Mohammed (1990) who, using a prototype sorghum harvester, obtained 89.7 and 83% cutting efficiency at 40 and 90 speed indices for the base top cutters, respectively. Godesa (2004) obtained similar cutting speeds during flailing of potato vines with the speed depending on height of cut and centre of mass stalk.

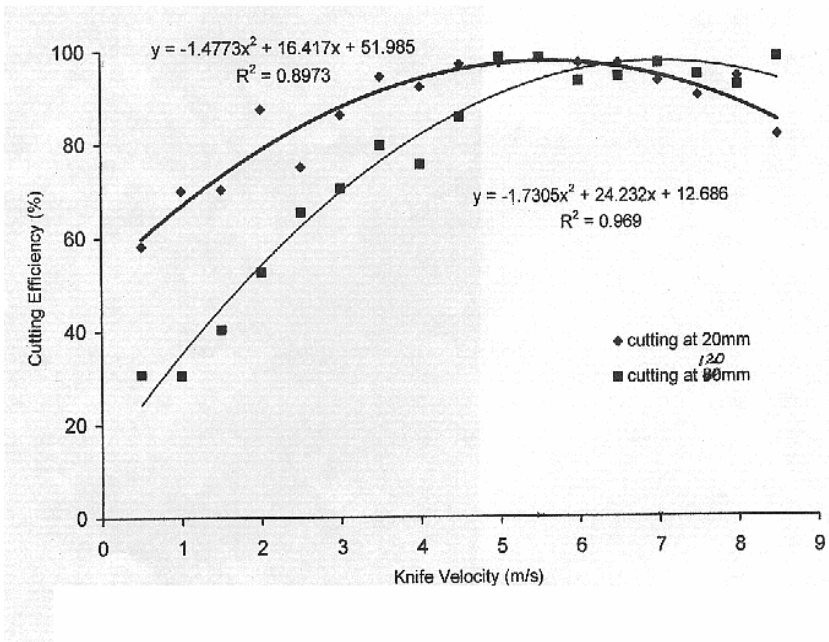

Figure 4. Effect of Knife Velocity on Cutting Efficiency

4. CONCLUSIONS

From the results obtained in this study, the following conclusions are drawn;

i. Knife speed of 3.50 and 5.75 m/s respectively, for cutting at stalk base and top were observed to be optimum corresponding to minimum cutting energy of 9.5 and 6.0 Nm, respectively.

ii. Maximum cutting efficiency of 100% was obtained for cutting at the base, corresponding to knife speeds between 5.2 and 7.3 m/s.

iii. This study has established the relationship between sorghum stem and knife variables with cutting performance in terms of cutting energy requirement and cutting efficiency.

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