Misr J.Ag Eng. 19 (2) : 361 – 372

The Parameters Affecting the Cutting Process Performance of Agricultural Plants

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ABSTRACT

The act of cutting of agricultural material is one of the most important operations that frequently arise during the cutting, separation and crushing processes of plants. The cutting process of agricultural plants is more complicated than the cutting of engineering materials (as steel, copper alloys, ...etc.). This is due to that most of the engineering materials are homogeneous and isotropic, whereas the plants are non-homogeneous and non-isotropic materials.

In this study, mathematical relations for the act of cutting could be formulated for the cutting energy required for performing the cutting process.

The different parameters affecting the performance of the cutting process have been investigated and categorized into four predominant groups, namely; cutting tool parameters group, plant parameters group, machine parameters group, and a mixed group. Each of these groups of parameters has been studied in details to show the effects of these parameters on the cutting process and therefore, getting the optimum values of these parameters of these groups.

The study showed that the main important parameter of the cutting tool is the knife edge angle, and that of the plant material is the moisture content parameter, whereas, for the machine working performance, the main parameter is the cutting rotational speed. At the end of the study, some recommended values for the cutting process parameters have been provided to get the minimum amount of energy consumed to accomplish the cutting process.

1-Introduction

The cutting process of the agricultural plants plays an important role in the agricultural engineering fields. This cutting process may be a cutting process for the plants during the harvesting operation, and/or crushing and shredding of the plant residues for size reduction to be suitable for further stages of compost processes. There are many parameters governing the cutting process; some of these parameters are related to the cutting machine, some are related to the plant material and the others are related to the cutting tool (knife) properties. The main variables of the cutting machine are the feeding speed, the feeding rate, the cutting drum peripheral speed, and the clearance between the fixed and rotating knives. The stem length, stem diameter, stem fiber contents, hardness, and moisture content are the predominant parameters of the plant residues. Whereas, the main parameters of cutting tool are related to the tool material and geometry (edge angle and edge thickness).

Many researchers manipulated the cutting process of the agricultural plants in different aspects.

Kepner et al. [1] studied the engineering properties of plants and showed that these properties are not so as the common engineering materials (steels, aluminum, etc.), where the strength of the plant materials depends on the fiber cell diameters and lengths. He showed that the wall of the plant consists basically of three layers, the middle lamella, the primary wall and the secondary wall. The secondary wall determines the strength and flexibility of the plant structure.

In another aspect, **Bright and Kleis [2]** measured the initial bulk density of the chopped material for a wide range of chop length and moisture content. He showed that there is a good correlation between the density and moisture content.

Dernedde and Peters [3] presented some results for ryegrass, which showed a maximum density of the plant at dry matter content between 45 and 55%.

Halyk and Hurlbut [4] applied the classical methods in determining the material strength and fundamental constants. They found that the ultimate tensile strength for Lucerne, lay in a range of 9 to 36 MPa with a negative linear correlation with moisture content. While, for grass, their results showed that the tensile strength was reduced with the decrease in the moisture content.

Prince et al [5] observed for Lucerne a wide range of ultimate shear strengths from 0.4 to 18 MPa and also showed that there was a negative linear correlation between shear strength and moisture content.

Metwalli et al [6] investigated the effect of moisture content on the performance parameters of different mechanical methods of cutting and chopping cotton stalks. They concluded that by increasing the moisture content, the cutting efficiency, could be increased, which means decreasing of the power requirement.

Morad [7] studied the effect of kinematics parameter (ratio of cutting tool rotary speed to tractor forward speed) on fuel consumption and energy requirements. He showed that both the fuel and energy requirements decreased as the kinematics parameter decreased.

McRandal and McNulty [8] performed numerous impact cutting tests on field grasses using a two drum vertical spindle rotary mower and they obtained considerable results for the consumed cutting energy. They concluded that the energy balances is a function of both cutting and forward speeds.

The aim of this research is to study the parameters affecting the cutting process performance of agricultural plants, by formulating mathematical model relating these parameters with the cutting force and so obtaining the specific cutting energy of the cutting process.

2- Computation of the Specific Cutting Energy

The reaction force system on a knife may be said to consist of two active components, the edge force and the wedge force. The edge force cuts creating from high local stresses in the material in contact with the edge. The wedge forces act on the side faces of the kinfe edge, thereby continuing the cut, originally made by the knife edge.

The total force (P) of knife edge pressure necessary to accomplish the cutting process, Fig. 1, could be obtained as [4]:

$$\sum F_y = 0 \quad \Rightarrow$$
$$P = P_e + P_v + T_1 + T'_2 \qquad (1)$$

where,

P_e: is the edge force, which is due to the high local stresses in the material at contact of knife edge , N/m.

P_v: is the reaction force of the crushed material per unit of knife length, N/m.

T_1: is the tangential force (friction force) per unit of knife length, N/m.

T'_2: is the friction force operating along the knife-edge surface, N/m.

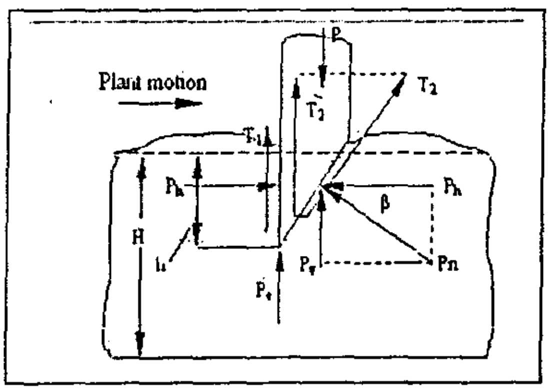

Fig. 1 Forces due to penetration of the cutting tool into a plant stem.

The specific shearing energy 'U', J/m^2 (shearing energy per unit area of plant stem cross section):

$$U = P * W_c * \frac{h}{A} \quad (2)$$

where;

P : is the total cutting force per unit length, N/m.

W_c : is the cutting width of the plant, m.

A : is the plant cross sectional area, m^2.

h : is the preliminary compaction thickness, m.

The specific energy consumption of cutting head of forage harvester for a general wet basis matter, U_w (per unit weight) is expressed by **Yumnam and Pratap** [9]:

$$U_W = \frac{U\,n\,N}{\rho\,V}\left(1 - \frac{\mu}{100}\right) \quad (3)$$

where;

n : is the number of cutting blades in cutting head.

N : is the rotational speed of cutting head, rps.

V : is feed velocity of material to be cut, perpendicular to the cutting-head plane, m/s.

ρ : is the specific weight of dry matter content of material, kg/m^3.

μ : is the moisture content of material on wet basis.

O'Dogherty [10] deduced the cutting force components (P_e, P_v, T_1, T'_2) to be obtained of the cutting force per unit length as follows:

$$\left.\begin{array}{ll} P_e = \delta\, L\, \sigma_y & T_1 = \lambda\,(\upsilon\, E/2H)\, h^2 \\ P_v = (E/2H)\, h^2 \tan\beta & T'_2 = \lambda\,[(1/2)\, P_v \sin 2\beta + P_h \cos^2\beta] \end{array}\right\} \quad (3')$$

$$P = \delta\,\sigma_y + (E/2H)\, h^2\, [\tan\beta + \lambda \sin^2\beta + \lambda\,\upsilon\,(1 + \cos^2\beta)] \quad (4)$$

where; σ_y , E: are the yield tensile stress and modulus of elasticity of the plant material, respectively, N/m^2.

δ : is the thickness of the cutting edge, m.

λ : is the friction coefficient.

υ : is Poisson ratio of plant material

β : is the edge angle of the cutting tool, degree.

H : is the total thickness of material, m.

L : is length of cutting edge, perpendicular to plant motion, m.

In this expression, only the first component represents a useful cutting force required to perform an appropriate cut. The second term expresses force used to overcome other sources of resistance. The second term depends on square of 'h' lasting until the beginning of proper cutting. Its value varies linearly with layer thickness 'H'. The additional resistance increases rapidly with increasing the layer thickness and so reducing the cutting efficiency.

By substituting about P from Eq. (4) into Eqs. (2 and 3), the specific cutting energy based on wet matter can be obtained as:

$$U_W = [\delta\,\sigma_y + (E/2H)\,h^2\,(\tan\beta + \lambda\,\sin^2\beta + \lambda.\upsilon(1+\cos^2\beta))]\;W_C\,\frac{h}{A}\,\frac{n\,N}{\rho\,V}\left(1-\frac{\mu}{100}\right) \qquad (5)$$

By proposing that the cross sectional area of the plant stem is circular, each of the plant thickness H and the cutting width W_C can be put as d (stem diameter), Fig. 2. After completing the cutting process of plant stem, the distance h = H; and depending on the previous two points, Eqn. (5) can be arranged and written as;

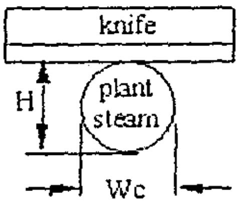

Fig. 2 Knife and plant cutting process.

$$U_W = [\frac{2\sigma_y\delta}{d\,E} + (\tan\beta + \lambda\sin^2\beta + \lambda.\upsilon\,(1+\cos^2\beta))]\,\frac{n\,N}{V}\,\frac{2\,d\,E}{\pi}\,\frac{1}{\rho}\left(1-\frac{\mu}{100}\right) \qquad (6)$$

Equation (6) can be put in a simple form as;

$$U = (G_4 + G_1)\,G_2\,G_3 \qquad (7)$$

where;

$G_1 = [\tan\beta + \lambda\,\sin^2\beta + \lambda.\upsilon\,(1+\cos^2\beta)]$...Knife group

$G_2 = \frac{n\,N}{V}$ .... Machine group,

$$G_3 = \frac{2dE}{\pi}\frac{1}{\rho}\left(1-\frac{m_w}{100}\right) \text{.................... Material's group}$$

$$G_4 = \frac{2\sigma_y \delta}{dE} \text{.................................. Mixed group}$$

where:

G_1: refers to the properties of the cutting tool (dimensionless group).

G_2: refers to performance of the machine.

G_3: refers to the type of plant material.

G_4: mixed parameters' group (dimensionless group).

3- Case Study

In this case study, cotton stalks and maize (corn) stalks are taken as plant materials. The mechanical and physical properties of the two plants are given in table 1.

Table. 1 Mechanical and physical properties of cotton and corn plants [10].

Property	Cotton stalks	Maize (corn)
Tensile strength, σ_y [MPa]	30	60
Modulus of elasticity, E [MPa]	400	10,000
Density, ρ [kg/mm^3]	1500×10^{-9}	1500×10^{-9}
Dry coefficient of friction, λ	0.6	0.7
Stem size, d [mm]	15	15
Moisture content, %	45	75

The specific cutting energies for different values of the affecting parameters is computed from Eqn. (7) and represented graphically in figures (3-7), where in each graph plot, the remaining parameters are kept constant.

4- Discussion of Results

From the preceding equation (7) and figures (3-7), the parameters governing the amount of energy consumed in the cutting process could be categorized into four parameters' groups. Decreasing this amount of cutting energy means increasing the performance of the cutting process. The first group G_1 is related to the cutting tool geometry, especially the edge angle (β), decreasing this group will lead to decrease the consumed energy. Similarly, the second parameters' group G_2 is related to the performance of the machine and lowering its value results in decreasing the consumed energy. This group depends on the feeding speed (V) and tool rotational speed (N). The third group G_3 is related to the plant material properties and this group will have its lower value when the cutting process is achieved at maximum value of moisture content (μ) (harvesting process). On the other hand, the last group

G_4 is a mixed parameters' group including the tool geometry (δ) and plant material properties. This group has no considerable effect on the cutting process energy, as shown in Fig. 3. This is due to that G_4 has a very small value relative to G_1, as illustrated in Eq. 7, especially for cotton and maize, where they have low strength and big stem sizes. Hence, the cutting tool tip thickness can be said that it has no effect on the energy consumed in cutting cotton and corn.

Figures 4 and 5 show that increasing the parameters β and N leads to increase the amount of consumed cutting energy for cotton and corn stalks. Also, these figures illustrate that the increasing rate of the energy consumption in case of corn stalks is higher than of cotton stalks. Conversely, figures 6 and 7 show that the cutting energy is reverse proportionate with the moisture content (μ) and feeding velocity (V) of the plant material during the crushing process.

5- Conclusions

The specific cutting energy is an important evaluating parameter for the harvesting and crushing the agricultural plants. Decreasing this parameter means increasing the performance of the cutting process. In this study, the specific cutting energy for any general plant material could be formulated and arranged in a simple mathematical form to be easily applied by the people working in the agricultural fields.

The conclusions of this study can be summarized as follows:-

1. The predominant parameters affecting the cutting process are related to the cutting tool, machine, machine specifications and plant material properties.
2. The cutting energy consumed in the harvesting process is much lower than the energy consumed in the crushing process due to the effect of moisture content.
3. The cutting tool edge thickness has no considerable effect on the cutting energy such that for cotton and corn stalks and hence can be ignored during the cutting process of cotton and corns plants.

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Nomenclature

A : Cross sectional area, [m^2].
D : Stem diameter, [m]
E : Modulus elasticity of the plant material, [N/m^2].
h : Instantaneous knife travel, [m].
H : Total thickness of plant material, [m].
n : Number of cutting blades in the cutter-head.
N : Rotation speed of the cutter-head, [rpm].
~~P : Specific cutting force, [N/m]~~
U : Specific shearing energy per unit area, [J/m^2].
U_W : Specific cutting energy per weight wet plant material, [J/Kg].
V : Feed velocity of the plant material perpendicular to cutter-head plane, [m/s].
W_C : Cutting width of the plant stem, [m].

Greek symbol

β : Knife-edge angle, [degree].
δ : Knife edge thickness, [mm].
λ : Friction coefficient between knife and plant material.
ρ : Dry material density of plant material, [g/m^3].
υ : Poisson ratio.
μ : Moisture content.

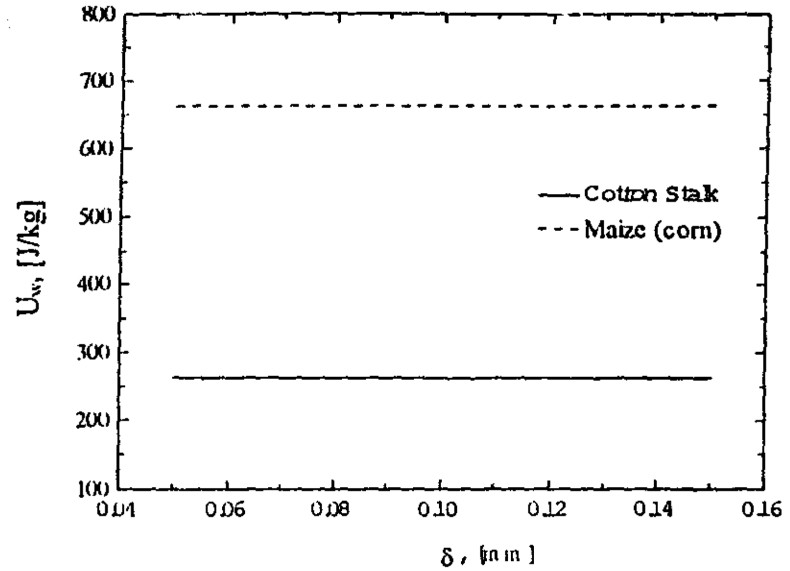

Fig. 3 Variation of specific cutting energy versus knife edge thickness.

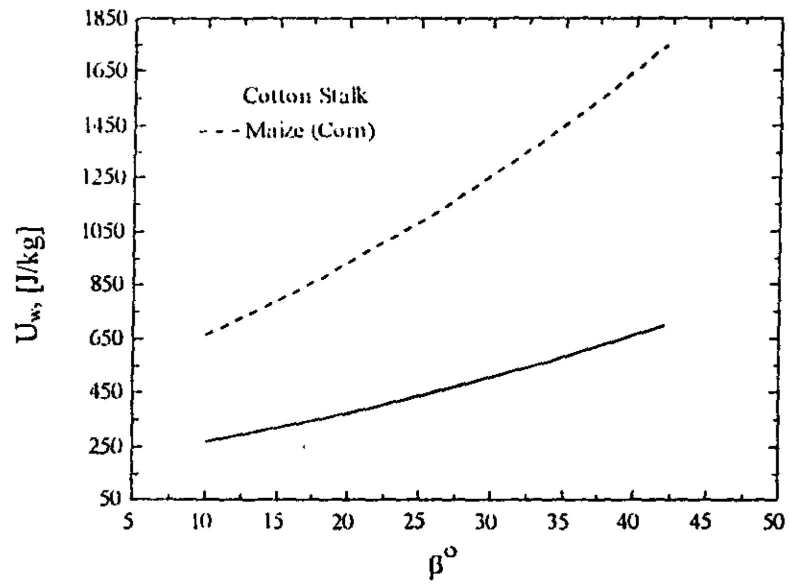

Fig. 4 Variation of specific cutting energy versus knife-edge angle.

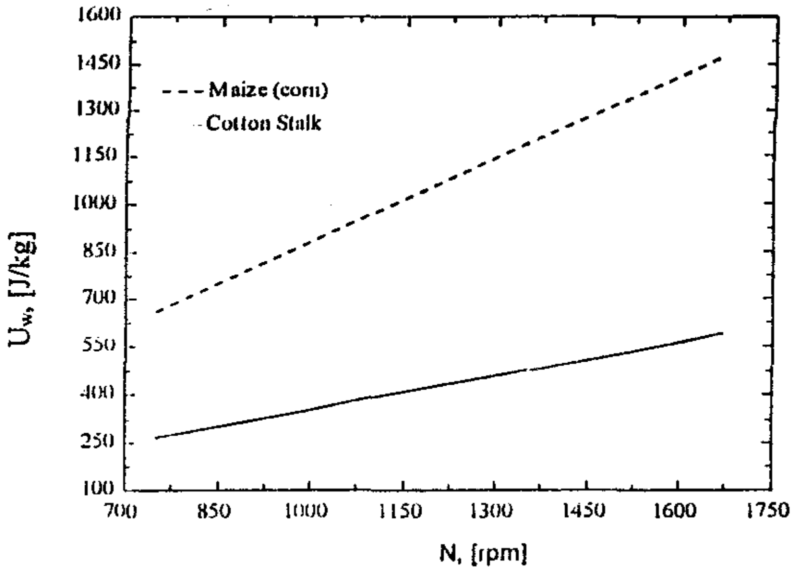

Fig. 5 Variation of specific cutting energy versus drum rotational speed.

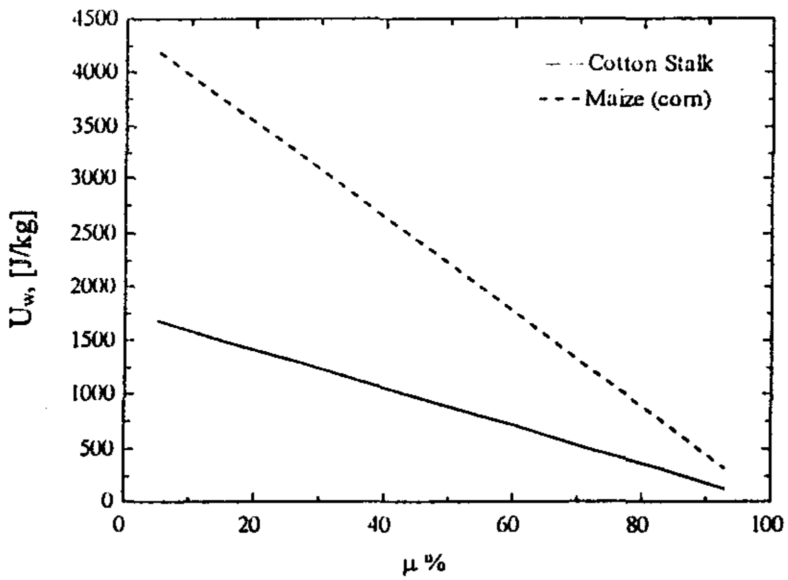

Fig. 6 Variation of specific cutting energy versus moisture content.

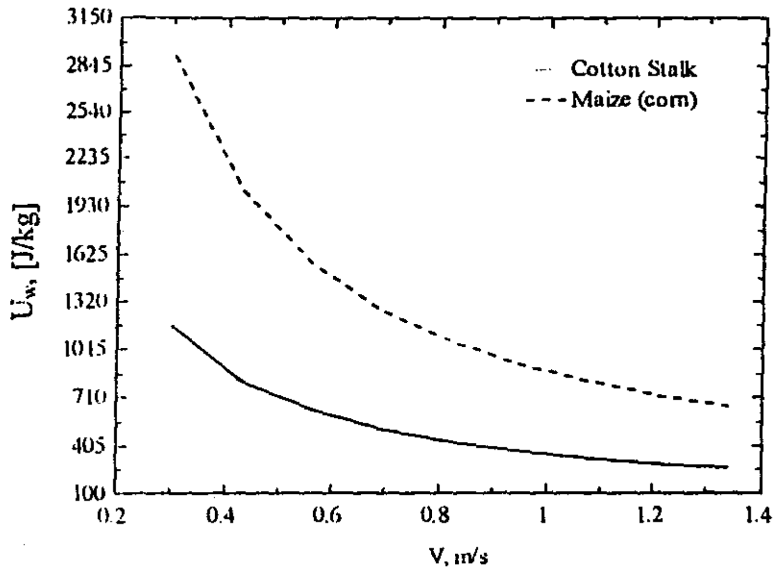

Fig. 7 Variation of specific cutting energy versus material feed velocity.

الملخص العربي

دراسة العناصر المؤثرة على أداء عملية تقطيع النباتات الزراعية

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تعتبر عملية تقطيع النباتات الزراعية واحدة من أهم عمليات التشغيل، حيث تتم بواسطتها عمليات تقطيع وفصل وفرم النباتات الزراعية. وعملية تقطيع النباتات الزراعية تعتبر أكثر تعقيدا من عمليات تقطيع المواد الهندسية مثل الفولاذ، النحاس السباتكي...الخ، وذلك ناتج عن أن معظم المواد الهندسية تكون متجانسة ومتماثلة الخواص في جميع الاتجاهات، بينما المواد الزراعية غير متجانسة وغير متماثلة في الخواص، بالإضافة إلى أن خواصها تعتمد على اتجاه الألياف وتتأثر بنسبة كبيرة بنسبة الرطوبة. في هذا البحث، تم إعداد صيغة رياضية تحكم عملية القطع وذلك لحساب طاقة القطع المطلوبة لإنجاز عملية التقطيع.

لقد تم بحث تأثير العناصر المختلفة على أداء عملية التقطيع وصنفت إلى أربعة مجموعات: المجموعة الأولى عناصرها مرتبطة بمواصفات أداة القطع، المجموعة الثانية عناصرها مرتبطة بخواص النبات المراد تقطيعه، المجموعة الثالثة عناصرها مرتبطة بخواص آلة التشغيل، المجموعة الرابعة تضم عناصرها مزيجا من خواص الآلة وخواص المادة الزراعية.

وقد تم دراسة كل من عناصر هذه المجموعات بشكل تفصيلي لمعرفة تأثيرها على أداء عملية القطع وذلك من أجل الحصول على قيم مثالية من العناصر الأولية لهذه المجموعات.

بينت الدراسة أن العنصر المهم والرئيسي لأداة القطع هو زاوية حافة السكينة، وفيما يتعلق بخواص المادة الزراعية وجد أن العنصر المهم هو محتوى الرطوبة في النبات، بينما من أجل أداء عمل الآلة بكفاءة عالية فإن العنصر الرئيسي هو سرعة دوران أداة القطع.

وفي نهاية الدراسة، تم التزود ببعض القيم الخاصة بعناصر عملية القطع من أجل الحصول على أقل كمية من الطاقة المستهلكة لإنجاز عملية القطع.

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