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REACTION FORCE AND ENERGY REQUIREMENT FOR CUTTING OIL PALM FRONDS BY SPRING POWERED SICKLE CUTTER

ABDUL RAZAK JELANI*; DESA AHMAD**; AHMAD HITAM*; AZMI YAHYA** and JOHARI JAMAK*

A study was conducted to investigate the effect of cutting angle and frond maturity on the specific reaction force (ROCSA) and energy requirement (RENCSA) for cutting oil palm fronds. A spring powered sickle cutter was used in this experiment. The experiment conducted was to determine the magnitude of reaction force that would be transferred to the harvester in the cutting operation. Cutting angles of 90°, 60" and 45" were tested on the three levels of frond maturity (F1, F2 and F3).

Experiment carried out showed significant effects of cutting angle on the RQCSA and RENCSA but not by frond maturity. Increasing the cutting angle from 45" to 90" increased the ROCSA to about 72%. The maximum and minimum values of ROCSA were 24.5 N cm^{-2} and 10.8 N cm^{-2} respectively.

The ratio of reaction force to the maximum cutting force (R/Fc_{max}) was also studied. The ratio gives the percentage of cutting force being transferred to the harvester during the cutting process. It was found that R/Fc_{max} was significantly affected by the cutting angle and frond maturity. The maximum and minimum ratios were 35% and 14% at cutting angles of 70° and 45" for cutting F3 and F1, respectively.

INTRODUCTION

The method of 'free cutting' had been proven effective by Hummel and Nave (1979) who employed impact cutting by means of a blade to harvest soyabeans. Free cutting means a

* Palm Oil Research institute of Malaysia, P.O. Box 10620, 50720 Kuala Lumpur, Malaysia.

** Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.

cutter cutting without a countershear. In most of cutting operations, a countershear is used to provide the reaction force. But, in a free cutting, the cutting reaction force comes from the inertia force of the stationary object as a result of fast cutting speed.

Pacheco and Rekhugler (1980) developed a spring powered impact shaker for harvesting apple. The prototype could deliver up to 1151 J impact energy with a 86.6 kg mass moving at 5.16 m s^{-1}. Pallerin et *al.* (1982) used the same concept to develop an impact shaker to harvest semi-vigorous open-centre apple trees. A spring accele- rated mass was used to produce the impact.

The work by Pacheco and Rekhugler (1980) and Pallerin et al. (1982) have shown that spring activated can be a way of powering a cutting tool. This method may be effective in cutting oil palm fronds and fruit bunches. There are two reasons how this method seems possible, viz. (i) a pulled spring can store energy, and (ii) the pulled spring can move at a very high speed once it is released. The ability of storing energy and spontenous release at a very high speed are the main requirement for cutting oil palm materials in order to overcome the material hardness. Therefore, an ordinary sickle 'powered' by an activated spring can be an efficient tool for cutting even without hydraulic or pneumatic power which are heavy and costly.

A cutting tool with unidirectional cutting forces has the advantages of being free from vibrating, making it easier to handle. Razak (1997), studied the force and energy require- ments for cutting oil palm fronds by two designs of cutter, *viz.* sickle and claw cutter. The experiment conducted showed significant ef- fects of cutter design, cutting angle and frond maturity. The maximum specific cutting force for sickle and claw cutters were 119.7 N cm^{-2} and 224.6 N cm-", respectively. On the other hand, the maximum specific cutting energy were 641.6 N-cm cm^{-2} and 1133 N-cm cm^{-2} for sickle and claw cutters, respectively.

Slicing cut method is defined as the cut with oblique angle of 45" to 90" *(Figure 1)*. The oblique angle *(Figure 2)* is the angle between the direction of motion and the line perpendicular to the knife edge. Generally, it was reported that the oblique angle is inversely proportional to the

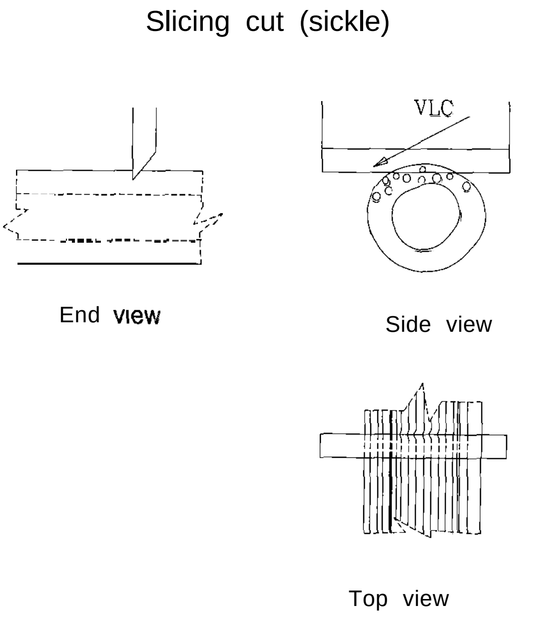

*Figure 1. Views **of** slicing cut showing the directions **of** motion.*

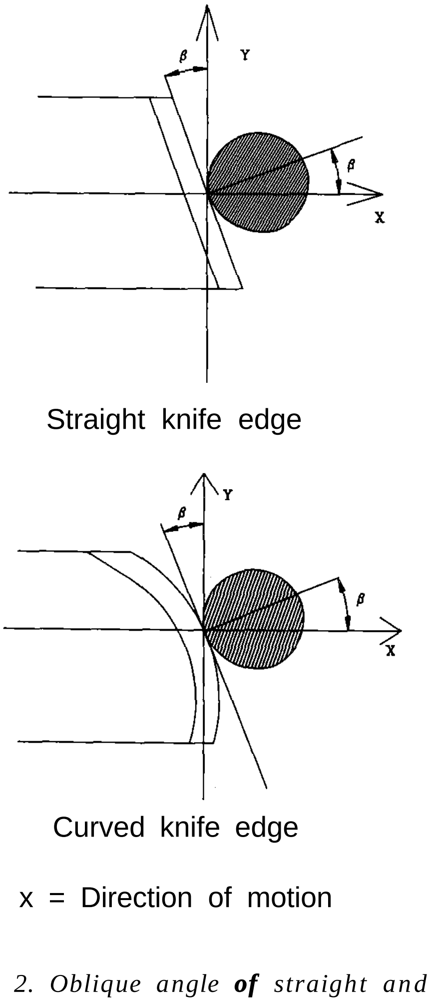

*Figure 2. Oblique angle **of** straight and curved edges.*

cutting force (Persson, 1987). Many researchers found out that slicing cut method requires less normal force on the material than other identified methods. For a sickle without countershear utilizing a slicing method, the velocity of cutting must be very great to overcome the resistance of the fibres. The reaction force comes mainly from the inertia and also the anchoring force provided by the material. Once the necessary force and velocity are achieved, the sharp edge of the knife would create the opening whenever the frond starts bending due to its own weight. This condition would assist the knife to cut through the material easily as the fibres are already in a stressed state.

According to Persson (1987), free cutting is only possible if the reaction force corresponding to the maximum force arises in the material. The components of the reaction force in free cutting are as follows:

- The mass inertia (resistance to acceleration) of the material being cut; and
- Static reaction forces due to bending of the material and angular displacement of the cross-sectional area cut.

Preliminary study by Razak (1997) showed that cutting of frond with sickle (slicing method) required lower force compared to cutting with claw method. The reason is that in the slicing cut, the cutting oblique angle is very great at the beginning of cutting, hence the cutting edge only need to slice into the material (not penetrating it). In this situation, the frond will start to bend due to its own weight and this phenomenon will cause the fibres to be in a stressed state enabling the cutting operation could be done easier.

The objective of this experiment was to investigate the effect of cutting angle and frond maturity on the specific reaction force and energy for cutting oil palm fronds by using a spring powered sickle cutter.

EXPERIMENTAL PROCEDURE

Since the conventional cutter performs without a countershear, a reaction force was expected to exert on the person who handles the cutter. A study was therefore, carried out to investigate the effect of cutting angle and frond maturity on the reaction force produced from the cutting.

Definition

The 'cutting force' is defined as the external force needed to be applied by the cutting tool on a material to accomplish the cut. More precisely, the cutting force is 'the resultant of stresses applied on the material'. Although the cutting force can have its components in XYZ directions, but only the X component along the line of cut contributes to the cutting energy as the active cutting force (Wieneke, 1972; O'Dogherty, 1981). The cutting force consists of two parts, *viz.* edge and wedge forces. The edge force cuts the material by creating a high local stress on the material in contact with the edge or close to the edge, while the wedge force pries apart the sides of the cut widening it for passage of the knife.

Terminology

The terms used in this study are mostly derived from Persson (1987) and, Prasad and Gupta (1975):

- Cutting angle (S). The angle between the edge of the knife and longitudinal axis of the material being cut.
- Specific cutting force per unit cut area (FOCSA). The maximum value of cutting force per unit cross-sectional area of material under the knife (kg cm^{-2}).
- Specific cutting energy per cut area (ENCSA). The cutting energy for cut per unit cross-sectional area (kg-cm cm^{-2}).

Design of Spring

Experiments conducted by Razak (1997) showed that the maximum specific cutting force (FOCSA) required to cut the most matured frond (F1) by the sickle cutter at 90" cutting angle was about 225.6 N cm^{-2}. Taking the biggest size of frond which has about 80 cm^2 cross-sectional area, the maximum force considered for the design purpose was 18 048 N.

A five centimetre diameter extension spring (stiffness = 2368 N cm-l) having a total length of 15 cm was chosen. The coil diameter was 7 mm with the total number of 12 coils. With this physical characteristics, the spring would be able to accelerate at 18 048* m s^{-2} moving as fast as 73** m s^{-1}. It could produce 265 x 103*** Joule of strain energy which is considerably enough to cut through the fronds

Note:" $F_d = ma$

where F_d = designed force, N

m = mass of body, kg

Therefore $a = F_d m^{-1}$

= (18 048 N)/1 kg

= 18 048 m s^{-2}

** $v^2 = u^2 + 2as$

where v = final velocity, m s^{-1}

u = initial velocity, m s^{-1}

a = acceleration, m s^{-2}

s = displacement, m

if u = 0 m s^{-1}, s = 15 cm

and a = 18 048 m s^{-2}

Therefore $v^2 = 2as$

$= 2(18\,048 \text{ m s}^{-2})(15 \times 10^{-2} \text{ m})$

v = 73 m s^{-1}

*** If the spring is pulled to 15 cm and carries a sickle weighing one kilogramme, the value of stiffness (k) is given by the following equation:

$$v = x_o (k/m)^{½}$$

where x_o = length of pulled, m

m = mass of sickle carried, m

rearranging the formula

$$(k/m)^{½} = v/x_o$$

$$k = (v/x_o)^2.m$$

$$= (73 \text{ m s}^{-2})/0.15 \text{ m})^2 (1 \text{ kg})$$

$$= 2368 \text{ N cm}^{-1}$$

The modulus of rigidity (G) can be calculated as follows:

$$k = G.D^4/64R_s^3.n$$

where G = modulus of rigidity, N mm^{-4}

D = coil diameter, m

R_s = spring radius, m

n = number of coil

rearranging the formula

$$G = 64.R_s^3.n.k/D^4$$

$$= [64(2.5 \text{ cm})^3(22)(2368 \text{ N cm}^{-1})]/(0.7 \text{ cm})^4$$

$$= 216 \times 10^6 \text{ N cm}^{-2}$$

Therefore, strain energy produced (U_s)

$$U_s = 0.5\,(GD^4/64.R_s^3.n)x^2$$

$$= 0.51216 \times 10^6 \text{ N cm-2 } (0.7 \text{ cm})^4/64\,(2.5 \text{ cm})^3 (22)](15 \text{ cm})^2$$

$$= 265 \times 10^3 \text{ Joule}$$

The velocity produced (73 m s^{-1}) is fast enough to perform a free cutting. This is based on the fact that high speed of cutting could overcome the materials resistance (Mohsenin, 1970).

Force and Energy Measurements

The parameters investigated were:

1. Cutter design (T). Methods of cutting – slice cutting.
2. Cutting angle (S). Angle of the knife travel with respect to the frond longitudinal. The angle tested were 90" (Sl), 60" (S2) and 45" (S3).
3. Frond maturity (F). Three levels of frond maturity were used: (i) F1, the second frond below a ripe bunch (the most matured frond), (ii) F2, the frond above the ripe bunch, and (iii) F3, the frond above F2. All fronds were taken from palms of similar age and type.

Spring Powered Sickle Cutter

A prototype spring powered sickle cutter was designed and developed. This sickle was powered by a specially designed extension spring from which the cutting energy was sourced.

The advantages of this concept are summarized as follows:

- No countershear is required, thus reduce the weight of tool.
- Employing slicing method as it requires lower cutting force.
- Cutting force acts in one direction, thus avoiding the tool from vibrating.

- Fronds and bunch stalks are made up of fibre bundles which contain silica. Thus, it needs a right method of cutting as to maintain the sharpness of the cutting edge. Slicing method offers this advantage in that lesser number of contact of the cutting edge to the fibre bundles.
- Overcome the problem of little accessibility of tool between the frond and the fruit stalk.

Test Procedures

A test rig was developed to carry out the experiment (Figure 3). The spring was pulled downwards by means of a pneumatic cylinder. The top end of the spring was bolted to the sickle while another end was clamped to the cylinder rod. A stopper was used to hold the sickle after the spring was pulled to a desired length. A pair of bearing was located on each side of the pneumatic cylinder as to allow the cutter to move freely in the vertical direction

Before cutting, the sample of frond was gripped by a gripper at a desired cutting angle. The cutting angle could be varied by adjusting the height adjusters. The frond was set to touch the edge of the sickle and this point was set at the beginning of the knife curvature. In the cutting process, a trigger was used to release the stopper and consequently, the spring which carried a sickle moved downwards and cut the material into two halves. A load cell (model Kyowa 500-KF) which was placed at the bottom of the test cutter was used to sense the vertical reaction force during that cutting process. This load cell was connected to an amplifier to record the maximum force sensed by the load cell.

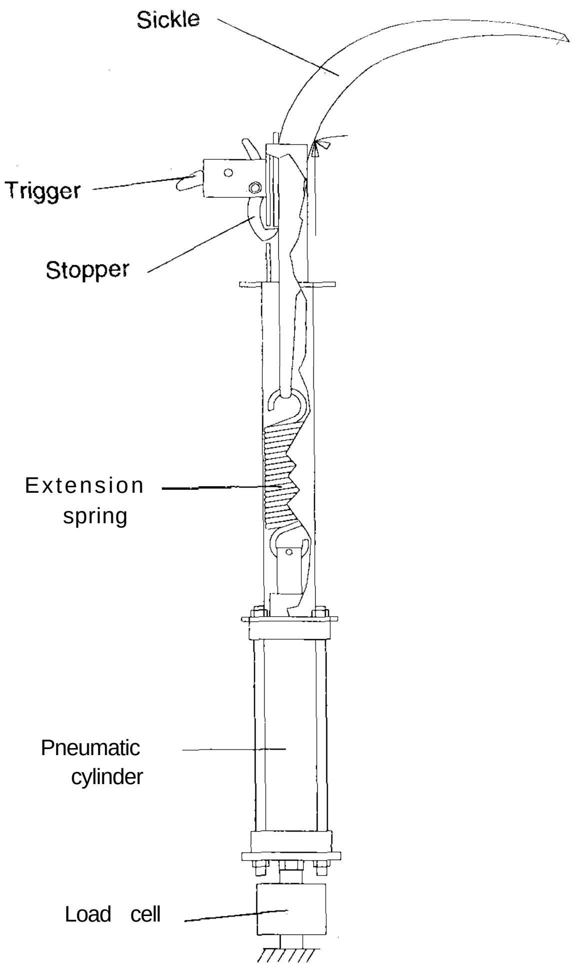

Figure 3. Experimental set-up to measure the reaction cutting force.

RESULTS AND DISCUSSION

An analysis of variance for the specific reaction force (ROCSA) per unit cut area, specific reaction energy (RENCSA) per unit cut area, and the ratio of reaction force to maximum cutting force (R/Fc_{max}) is shown in *Table 1*. It indicates significant effect of cutting angle for ROCSA and ROCSA, while cutting angle and frond maturity were found to affect R/Fc_{max}.

Effect of Cutting Angle

The effect of cutting angle on reaction force (R), specific cutting force (ROCSA) and energy (RENCSA) per unit cut area is shown in *Figures* 4 to 7. Their relationships are represented by the following equations (*Figure* 4):

$R = 2.8168 + 224.8;\ r^2 = 0.649$ (F1) [1]
$R = 2.5428 + 211.3;\ r^2 = 0.570$ (F2) [2]
$R = 4.162S + 62.5;\ r^2 = 0.703$ (F3) [3]

These equations were derived from the curve in *Figure 5:*

$ROCSA = 0.231S + 3.32;\ r^2 = 0.922$ (F1) [4]
$ROCSA = 0.2448 + 3.01;\ r^2 = 0.906$ (F2) [5]
$ROCSA = 0.3498 \cdot 4.59;\ r^2 = 0.967$ (F3) [6]

TABLE 1. ANALYSIS OF VARIANCE FOR SPECIFIC REACTION FORCE (ROCSA) AND ENERGY (RENCSA) PER UNIT CUT AREA

Source of variation	DF	Anova SS	Mean squares	F value	Pr>F
ROCSA					
S	2	14.35	7.17	24.34”	0.0001
F	2	0.05	0.02	0.09	0.9172
. S*F	4	0.62	0.16	0.53	0.7159
RENCSA					
S	2	239	119.5	36.3*	0.0001
F	2	0.45	0.22	0.07	0.9343
S*F	4	12.55	3.14	0.96	0.4415
R/Fc_{max}					
S	2	3 960	1 980	7.19”	0.0020
F	2	7 903	3 951	14.34*	0.0001
S*F	4	1 321	330	1.20	0.3246

Notes: weight of tool = 14 kg.
* Significant at 1% level.
Cutting angle = 10°.
Speed of cutting = 55 m s^{-1}.

While these equations were derived from the curve in ***Figure 6:***

RENCSA = 1.072S + 16.31; r^2 = 0.963 (F1) [7]

RENCSA = 0.9528 + 23.28; r^2 = 0.969 (F2) [8]

RENCSA = 1.47058 - 11.51; r^2 = 0.97 (F3) [9]

where the range of cutting angle is from 45” to 90”.

Both ROCSA and RENCSA were minimum at the cutting angle of 45” and maximum at 90” cutting angle.

Ratio of Reaction Force to the Maximum Cutting Force (R/Fc_{max})

The ratio of R to Fc_{max} shows the percentage of the reaction force compared to the cutting force that will be exerted onto the harvesters. This ratio indicates the percent of the cutting force being transferred to the harvester. Data of the reaction force were obtained from the above experiment, while data of the maximum cutting force were obtained from the experiment carried out by Razak (1997) for a similar characteristic of testing (frond maturities and cutting angles). LSD test carried out showed that both cutting angle and frond maturity gave significant effect on R/Fc_{max}

It was found that the maximum ratio was about 35% at 70” cutting angle for cutting F3, while the minimum was about 14% given by F1 at 45” cutting angle. The relationship of cutting angle and R/F_{cmax} is represented by the following equations (Figure 7):

R/F_{cmax} = -0.0068S^2 + 0.84958 - 12.232 (F1) [10]

R/F_{cmax} = -0.0196S^2 + 2.77348 -69.79 (F2) [11]

R/F_{cmax} = -0.00216S^2 + 3.12668 -76.821 (F3) [12]

where the range of S is from 45” to 90”.

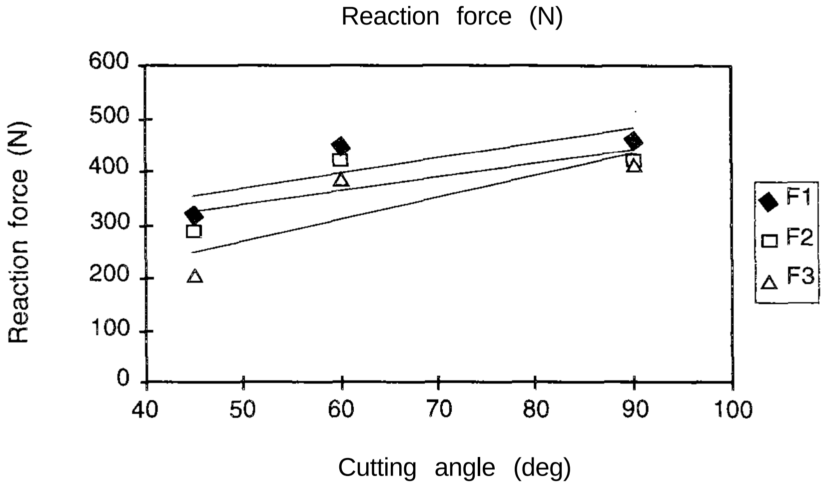

Figure 4. Effect of cutting angle on reaction force.

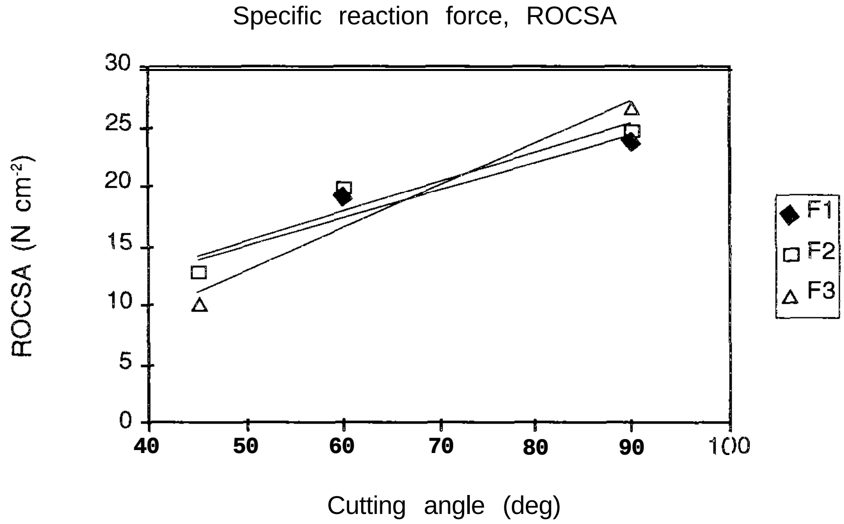

Figure 5. Effect of cutting angle on ROCSA.

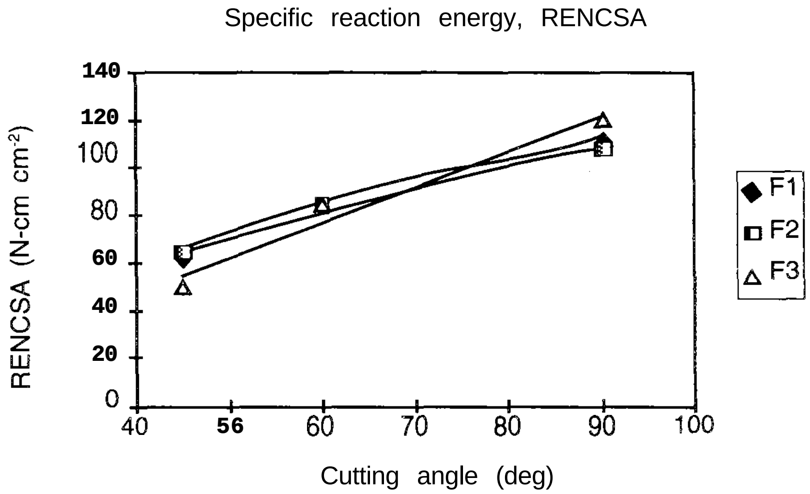

Figure 6. Effect of cutting angle on RENCSA.

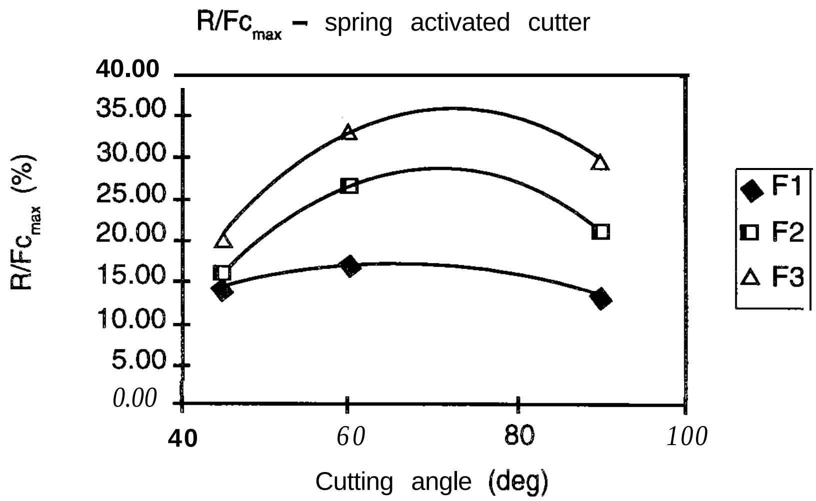

Figure 7. Effect of cutting angle on R/Fc_{max}.

SUMMARY AND CONCLUSION

The significant findings generated from this study are summarized below:

1. Only the cutting angle significantly affected the specific reaction force (ROCSA) and energy (RENCSA). On the other hand, frond maturity and the interaction ofcutting angle and frond maturity were not affecting the ROCSA and RENCSA. This is shown from the shape of the regressions curve which was found similar. Both ROCSA and RENCSA were linear functions of cutting angle. Increasing the cutting angle from 45” to 90” would increase the ROCSA and RENCSA to about 72% and 62% respectively. The maximum value of ROCSA and RENCSA recorded were about 23.7 N cm^{-2} and 107.9 N-cm cm^{-2} respectively, while the minimum were 10.8 N/cm^{-2} and 66.7 N-cm cm^{-2} respectively.
2. Cutting angle and frond maturity were found to affect the ratio of R/Fc_{max} significantly. However, it was found that the mature the frond, the lower the ratio of R/Fc_{max}. This gives an advantage to the harvester since the lowest fronds (normally two fronds) are to be cut as they hinder the fruit stalk.
3. The reaction force is a linear function of the cutting angle. The reaction force increased as the cutting angle was increased. Increasing the cutting angle from 45” to 90” would increase the reaction force by 79%. The minimum and the maximum value of the reaction force were 245.2 N and 470.9 N respectively.

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